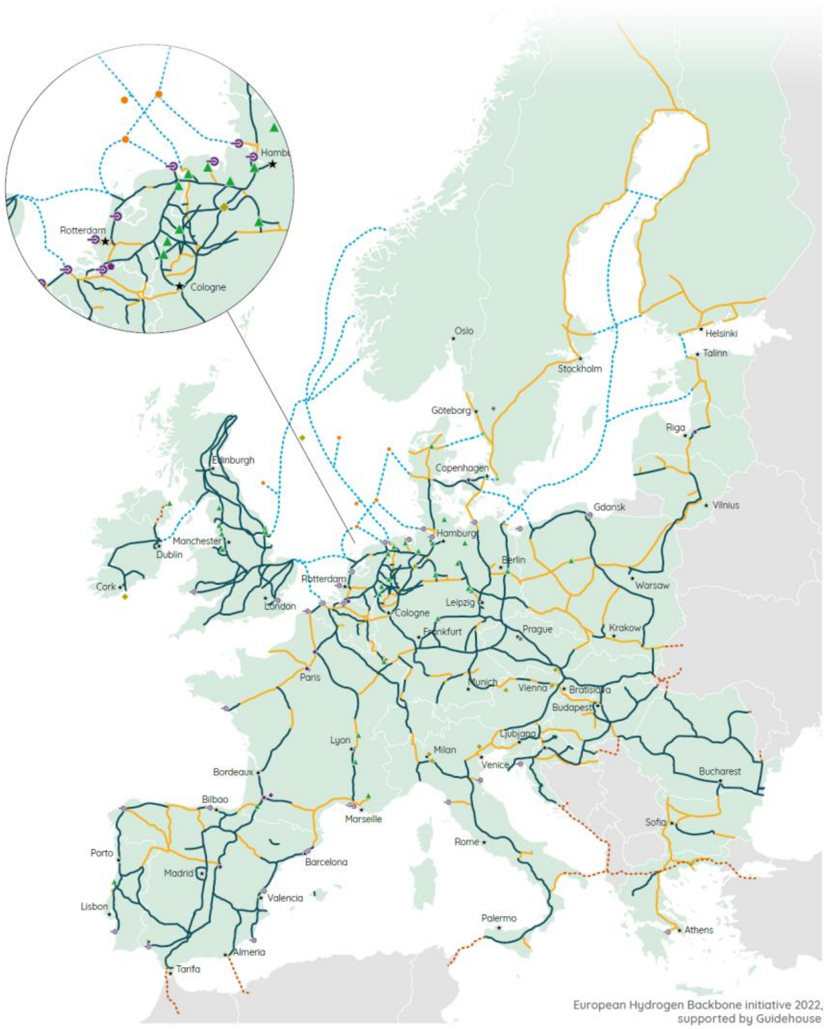
EPRG-PRCI-APGA
23rd Joint Technical Meeting
Edinburgh, Scotland • 6–10 June 2022

Manufacturers’ View on Specifying Linepipe Requirements for Hydrogen Applications

7 June 2022

European Hydrogen Backbone Initiative



European Hydrogen Backbone initiative 2022, supported by Guidehouse

status April 2022

53.000 km H_2 pipelines until 2040

60 % repurposed natural gas pipelines, 40 % new pipelines
investment of € 80 - 143 billion
€ 0.11-0.21 per kg of hydrogen when transporting over 1,000 km

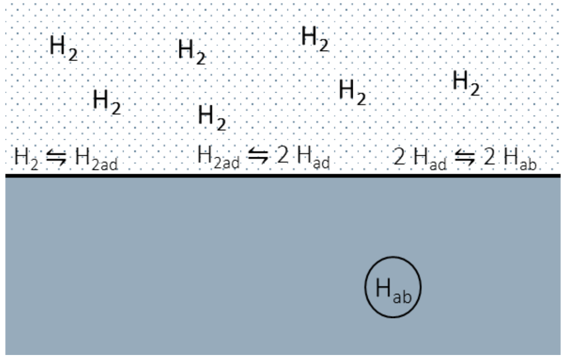
The EHB initiative has grown to 31 European network operators with infrastructure covering 25 EU Member States plus Norway, the United Kingdom, and Switzerland.

Source: The European Hydrogen Backbone (EHB) initiative

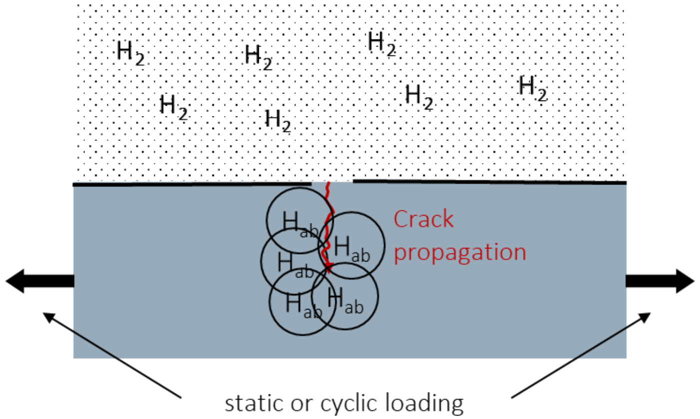
Comparison Compressed Hydrogen vs. Sour Service

Compressed Hydrogen Gas H_2

physical process of gas absorption



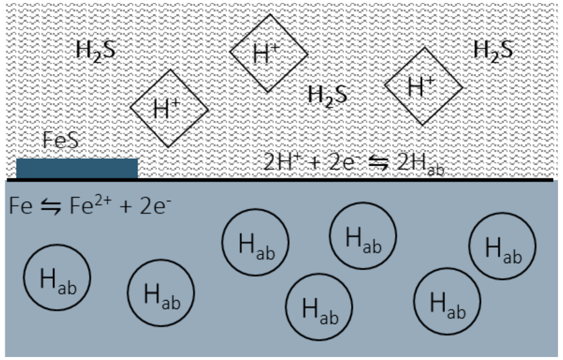
0.05 – 0.25 ppm-w H
(measured for storage in 100 bar H_2)



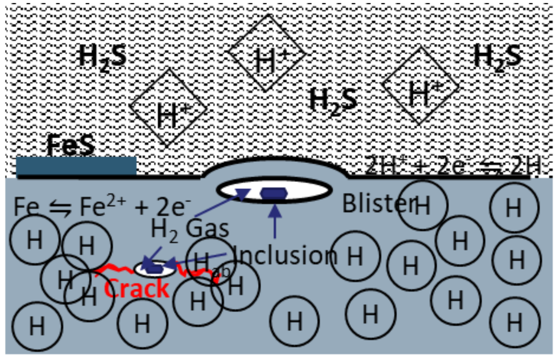
influence on ductility, crack propagation, fracture toughness, fatigue properties

Sour Service Testing H_2S

acid corrosion reaction in liquid medium



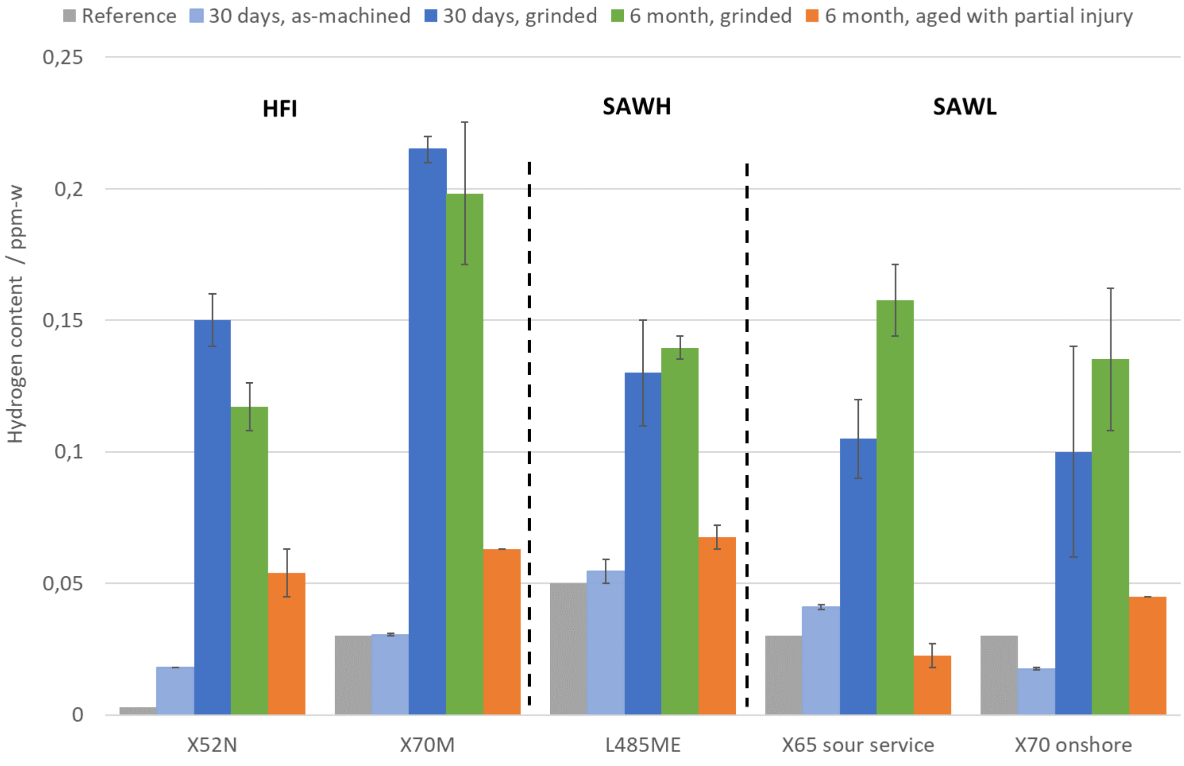
3 - 5 ppm-w H
(measured for 1 bar H_2S, pH3)



hydrogen induced cracking (HIC) or sulfide stress cracking (SSC)

significant difference in hydrogen uptake and possible failure scenario

Hydrogen Uptake in Compressed Hydrogen



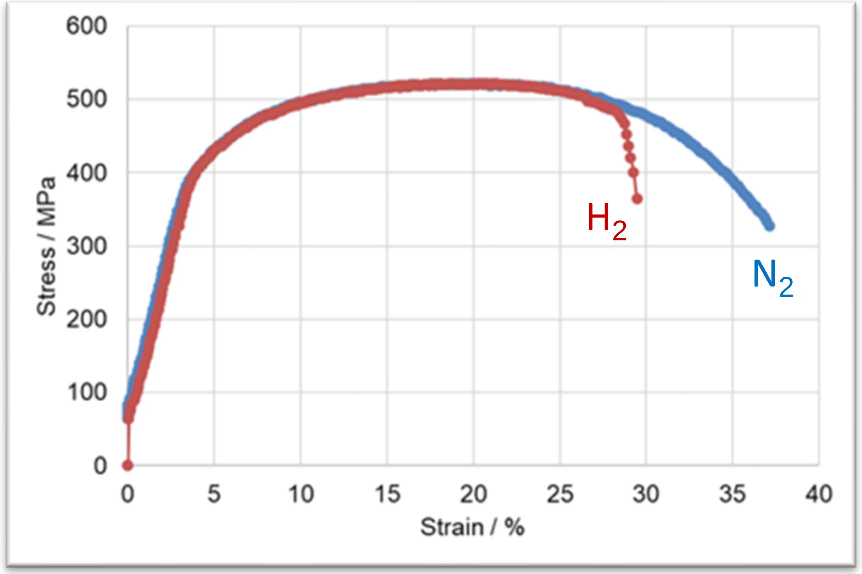
large influence of surface condition

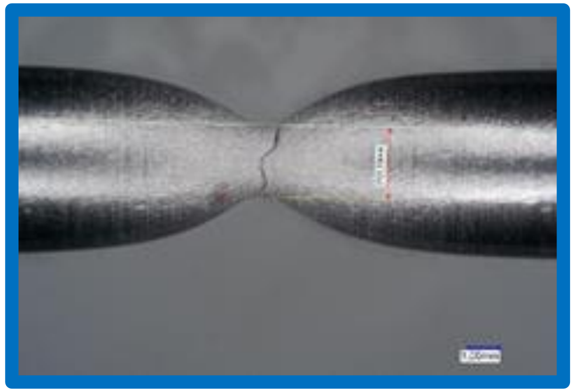
- low hydrogen uptake in case of controlled test parameters and activated surface condition only
- even less in case of aged samples injured by scratching
- low values, careful interpretation

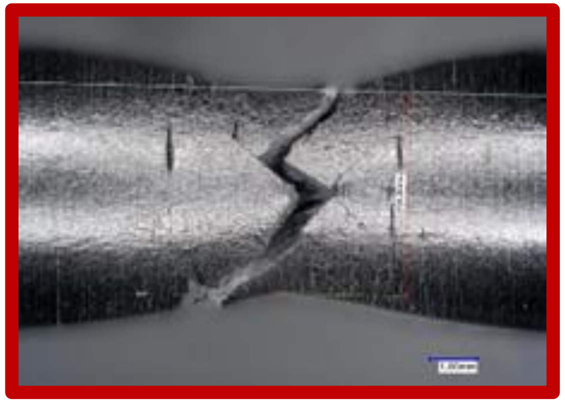
Slow Strain Rate Tensile (SSRT) Testing in Hydrogen Gas

- common to evaluate influence of corrosion reaction
- SSRT tests in compressed hydrogen avoiding any kind of oxygen contamination and in inert atmosphere for comparison
- results
  - no influence of hydrogen on yield and tensile strength
  - influence of hydrogen on ductility: reduction of area, elongation at failure
  - failure in hydrogen clearly in region of necking
  - non-representative for service condition of pipes

suitable choice for comparison of materials





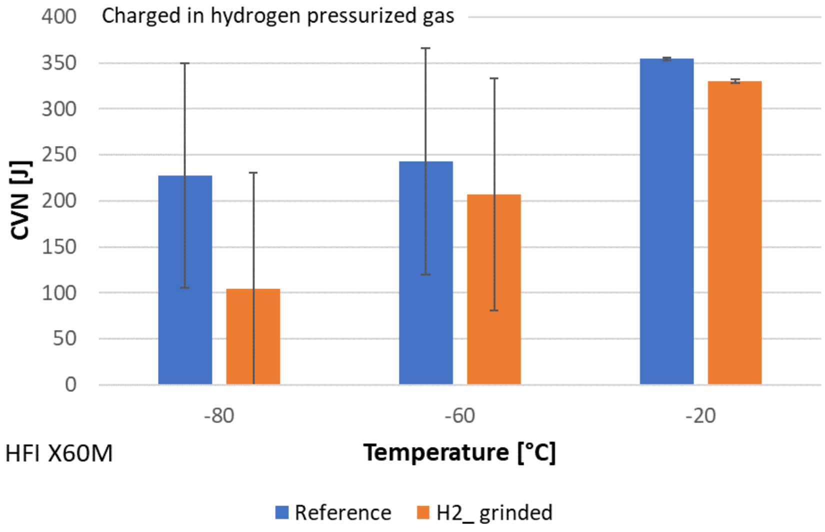


Charpy Impact Testing of Pre-Charged Samples

Pre-Charged in Compressed Hydrogen Gas

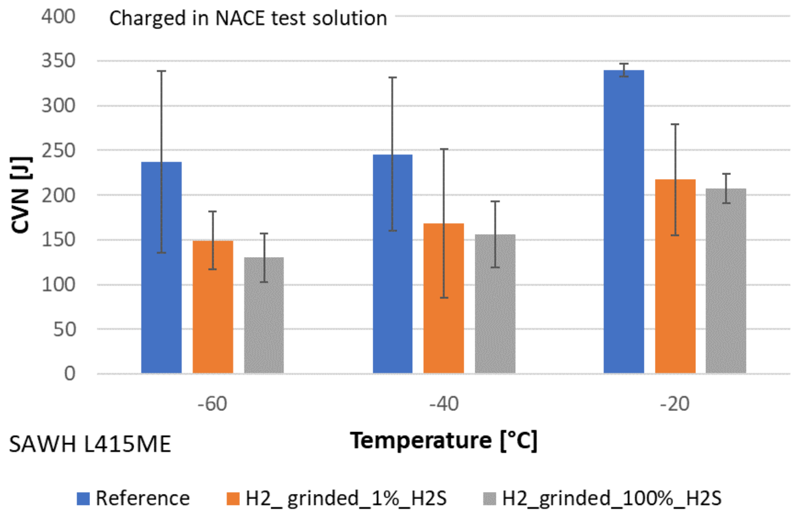
- sample storage in pressure vessel (activated surface)
- 720 h at room temperature, 100 bar H_2

⇨ 0.21 ppm-w hydrogen



Pre-Charged by Chemical Reaction

- sample immersion in acidified brine solution
- 0.01 bar H_2S ⇨ 0.2 ppm-w hydrogen (as for pre-charged in compressed hydrogen)
- 1 bar H_2S ⇨ 3 ppm-w hydrogen



no clear results for pre-charged samples, not to be considered to qualify materials

Standards

common standards of high-pressure natural gas pipelines are adopted

- high relevance of API 5L (PSL2), EN1594, and ISO 3183 (incl. Annex A)

and, if available, hydrogen-related standards, too

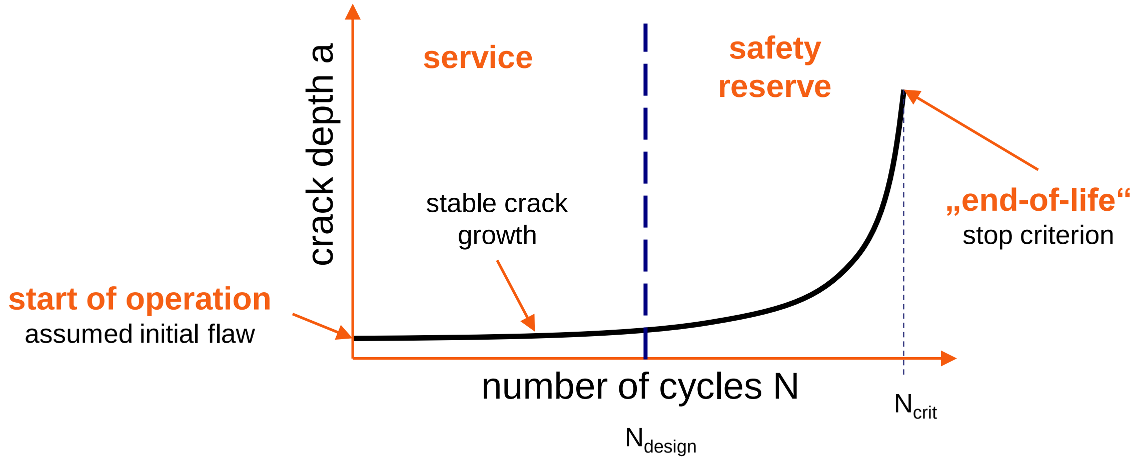
- to date base applications: EIGA IGC Doc 121/14 limited to lower strength levels and low strength utilization
- design code ASME B31.12 (2019) for higher-strength materials with safety factors, based on fracture mechanics
- technical standards of German Technical and Scientific Association for Gas and Water (DVGW)
- European and international standards and customer specifications in discussion

Consensus: pipeline design based on fracture mechanics

ASME B31.12 (2019) – Pipeline Design

start of operation

- assumed flaw at lower detection limit of nondestructive testing or identified and sized flaw
- smaller assumed flaw, i.e., lower assured detection limit (N5 instead of N10) advantageous



service

- pressure cycles characterize pipeline operation period
- da/dN - ΔK master curve reflects crack propagation behavior

end-of life

- crack reaches critical stress intensity exceeding material’s toughness limit
- safety factor determines design lifetime

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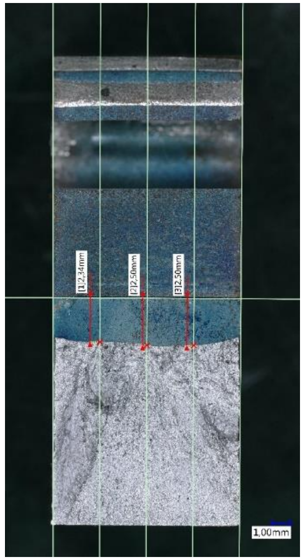
Material Qualification According ASME B31.12 (2019)

testing standards and methods

- determination of threshold stress intensity factor K_{IH} according ASME BPVC Sec. VIII Div. 3, KD-10 referring to ASTM E1681, based on linear-elastic fracture mechanics
- ASME BPVC overrules ASTM E1681, notably material suitability up to design (wall) thickness if sample thickness larger than 85 % of pipe wall
- constant load or constant displacement (currently more often used) to be applied
- qualification of 3 heats, 3 positions, 3 specimens each, in sum 27 samples
- constant displacement method, load $K_{lapp} = 2 * K_{IH}$ (limit value of 55 MPa√m), stored for 1000 hours (six weeks) in 100 bar pure hydrogen gas



results

all tested materials fulfill at least the limit value using test procedure of constant displacement

	Position	$K_{IH,min}$ MPa√m	$K_{IH,max}$ MPa√m
L415ME	BM	56	61
	WM (SAWH)	55	62
	HAZ	57	61
X52N	BM	61	63
X60M	BM	62	86
	WM (HFI)	63	85

Plausibility Check for K_{IH} Constant Displacement Tests

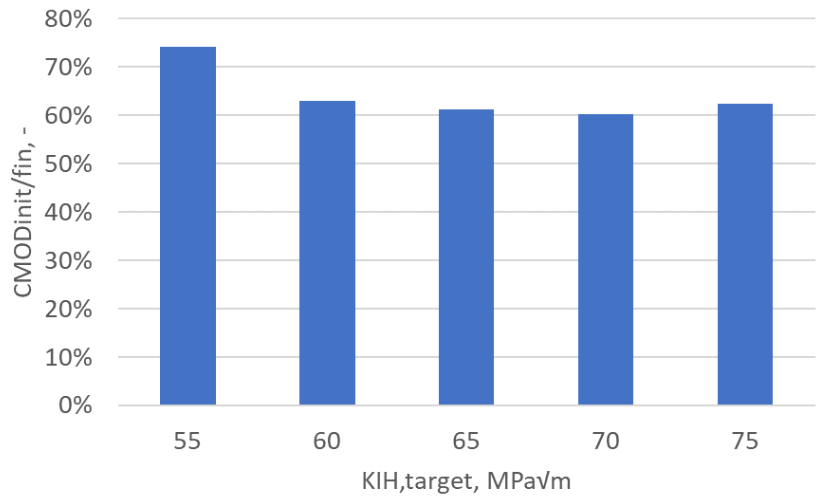
crack mouth opening displacement (CMOD) ratio

- measurement of displacement of each specimen using a crack opening displacement gauge
- ratio of CMOD during loading and unloading, >90 % mentioned in ASTM E1681

results

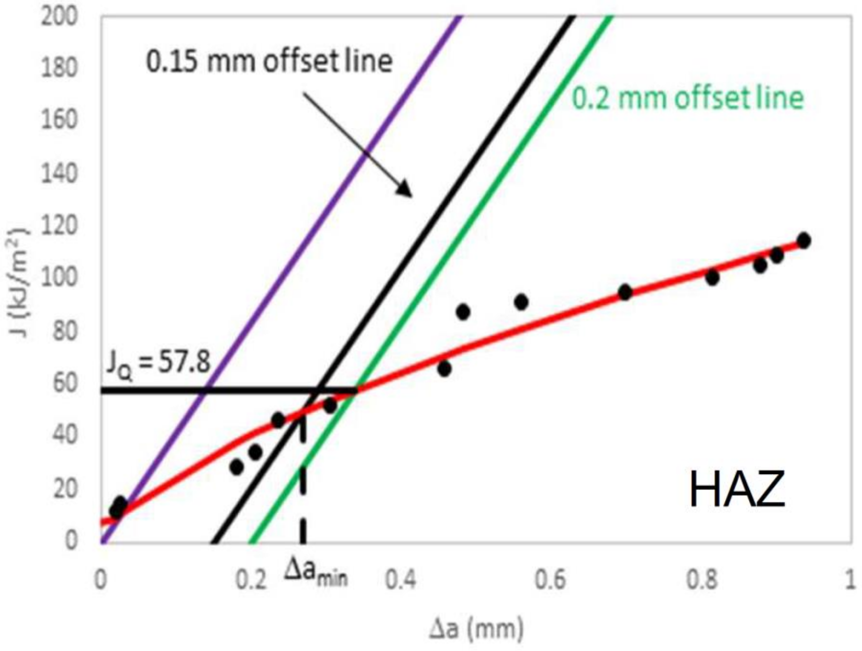
- evaluation of CMOD ratio gives average of 63 %
- increasing load levels show decreasing CMOD ratios
- side grooves in the specimens results in larger ratios, average 78 %

➔ plastic zone at the crack tip for typical line pipe materials



conditions of linear-elastic fracture mechanics not met

Material's Toughness



X70 onshore material, determination of K_{JIC} at NIST

materials characteristic value K_{JIC}

- based on elastic-plastic fracture mechanics
- determination of fracture mechanics resistance curve (J-R), applying ASTM E1820
- X70 onshore material in assumed most critical position: K_{JIC} = 114.5 MPa√m, well above limit of 55 MPa√m

reasonable test method showing high toughness potential; however, limited lab availability

Test Variants for Qualification and Toughness Testing

K_{IH} testing, constant displacement method

- current state-of-the-art testing method, medium test effort, high number of tests at a time
- basis linear-elastic fracture mechanics not met, plastic zone could be reduced by
  - side grooves or
  - reduced load where CMOD on unloading just exceeds the limit value

K_{IH} testing, constant load method

- advantageous loading conditions: constant force on crack tip, and reduced load to limit value
- linear-elastic fracture mechanics still not met, higher test effort, lower availability

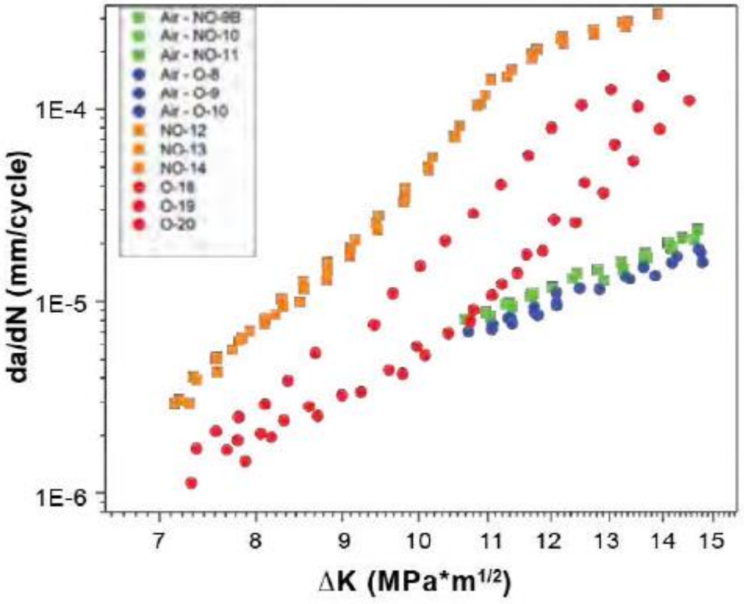
K_{JIC}, J-R curve, material toughness

- elastic-plastic fracture mechanics to determine fracture toughness of ductile materials like novel line pipe steels
- high effort of test equipment and testing, limited laboratory availability and capacity

pipeline operator needs to define the applied test procedure

Composition and Microstructure

- pipe manufacturers are faced with requirements of different international standards, API 5L, ISO 3183, and ASME B31.12
- ASME B31.12 (2019), non-mandatory appendix G, gives example rules pushing the properties to sour-service steels as fixed in API 5L Annex H
- this affects the mechanical properties of line pipes, in particular yield to tensile strength ratio, and thus can violate requirements of ISO 3183 Annex A
- pipe manufacturers control their processes and material characteristics in narrow constraints to fulfill all required properties



Source: D. Stalheim et al: Structural Steels Microstructural Homogeneity Effect on Fatigue Performance in Air and Hydrogen Environments, SEP 2021, Iron & steel technology, AIST.ORG

pipeline operators should concentrate on mechanical-technological properties relevant for the application

Conclusions

relevant properties and tests

- in hydrogen service ductility and toughness of line pipe materials might be affected
- slow strain rate tensile (SSRT) testing provides possibility to compare material's ductility properties
- no clear results of Charpy impact testing for pre-charged samples found, not to be considered to qualify materials

materials qualification to ASME B31.12 (2019)

- current testing of threshold stress intensity factor K_{IH} does not meet basis of linear-elastic fracture mechanics
- fracture mechanics of novel line pipe materials are best characterized by materials characteristic value K_{JIC}
- test effort, test aim and laboratory accessibility needs to be considered for definition of applied test procedure

materials performance of line pipes

- manufacturers tightly control their processes and material characteristics
- qualification programs should be considered valid for same grades and conditions for different pipeline operators
- focus of material qualification should lay on primary mechanical-technological properties relevant for the hydrogen application

Cooperation between pipeline operator and pipe manufacturer is necessary

Thank you for your attention.