Diffusion of hydrogen in pipeline steel API 5L X65

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Hydrogen will play an important role in the decarbonisation of sectors that cannot rely exclusively in electrification (e.g. transportation, energy and carbon intensive industries) [1]. However, hydrogen economies will require a reformation and expansion of the current gas transportation and storage infrastructure, to accommodate high volumes of pure or blended hydrogen.

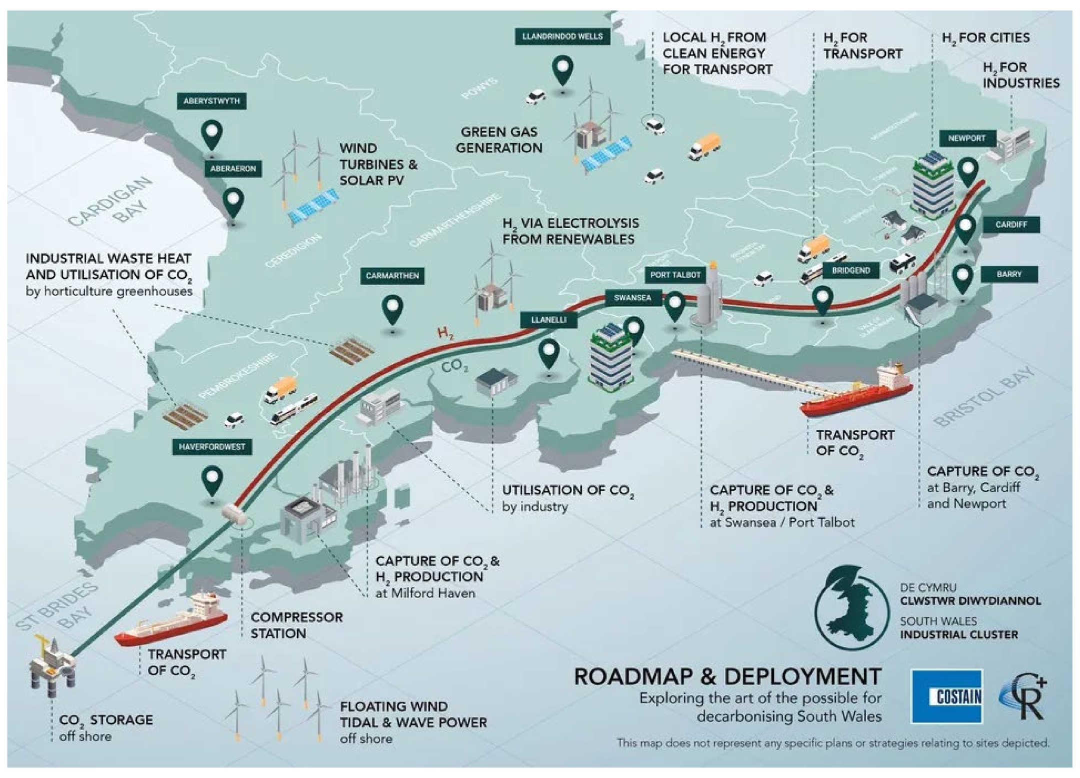


Figure 1: Roadmap of South Wales Industrial Cluster (SWIC) project [2].

Pipelines are a crucial element of that infrastructure, which are particularly susceptible to ***hydrogen induced failure*** (HIF), an unpredictable phenomena that often leads to substantial economic losses and environmental damages.

Table 1: Chemical composition and mechanical properties of X65 pipeline steel. $\sigma_{y0.2}$ – Offset yield strength at 0.2%, UTS – Ultimate Tensile Strength

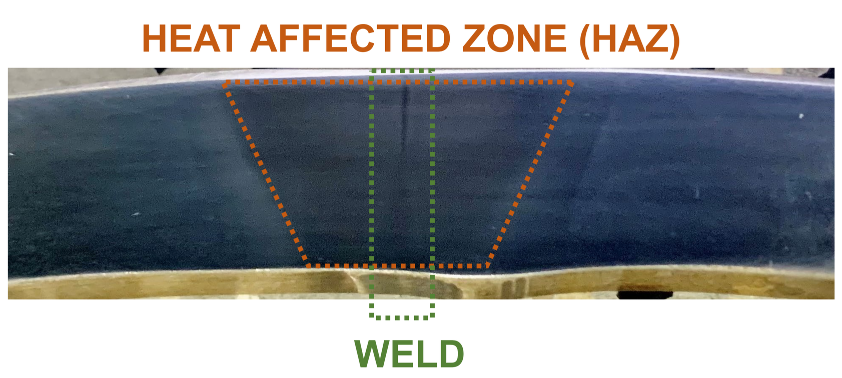
Mass fraction (%), max. value					Mechanical properties				
C	Mn	P	S	Si	Orientation	$\sigma_{y0.2}$ (MPa)	UTS (MPa)	Elongation at fracture (%)	Fracture strength (MPa)
0.075	1.55	0.02	0.003	0.225	**Longitudinal**	502 ± 6	574 ± 9	32.0 ± 0.3	261 ± 5
					Transverse	513 ± 0.5	580 ± 8	33.5 ± 0.3	266 ± 2

High Frequency Induction (HFI) welded pipelines

Grade: **API 5L X65**

Diameter: 508 mm

Thickness: 15.9 mm



Factors that lead to pipeline failure:
- Higher strength
- Elevated internal pressure
- Cyclic stresses
- Corrosion

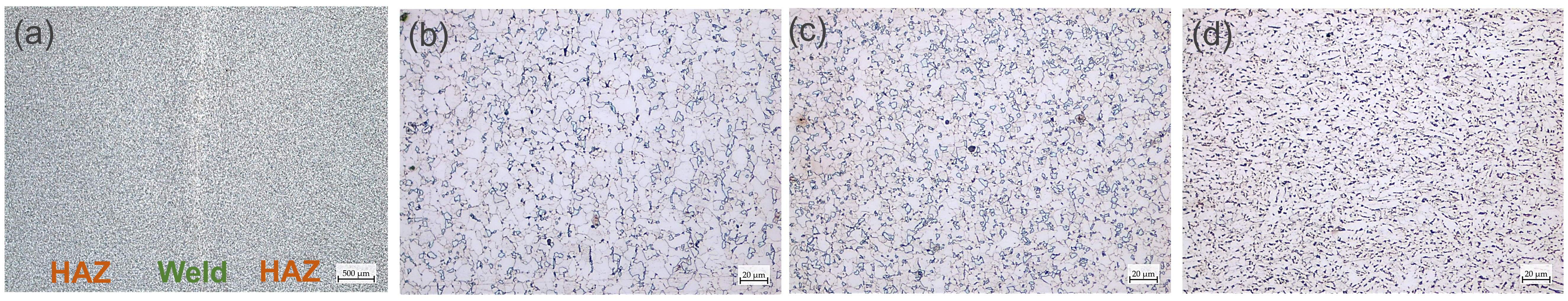


Figure 2: Optical microscope images of X65 microstructure (a) weld and HAZ cross-section (b) weld (c) HAZ (d) base material Microstructure composed of ferrite matrix (grey) with pearlite (black).

INTERACTION OF HYDROGEN WITH METALS

Hydrogen transport into a certain critical location can be described by the following reaction steps [3, 4]:

Reaction 1
Gas – phase diffusion of molecular hydrogen (H_2) to the crack surface

$$r_1 = k_1 P$$

k_1 – rate constant
P – H_2 pressure

Reaction 2
H_2 dissociation at metal surface and physical adsorption of atoms

$$r_2 = k_2 P^{\frac{1}{2}}(1-\theta)$$

θ - H surface coverage

Reaction 3
Adsorbed atoms migrate across the metal surface and consequent chemisorption

$$r_3 = k_3\, grad\, u$$

$grad\, u$ – gradient in surface hydrogen concentration

Reaction 4
Adsorbed atoms dissolve into the metal

$$r_4 = k_4\, \theta\, [1 - \left(\frac{u}{u_s}\right)]$$

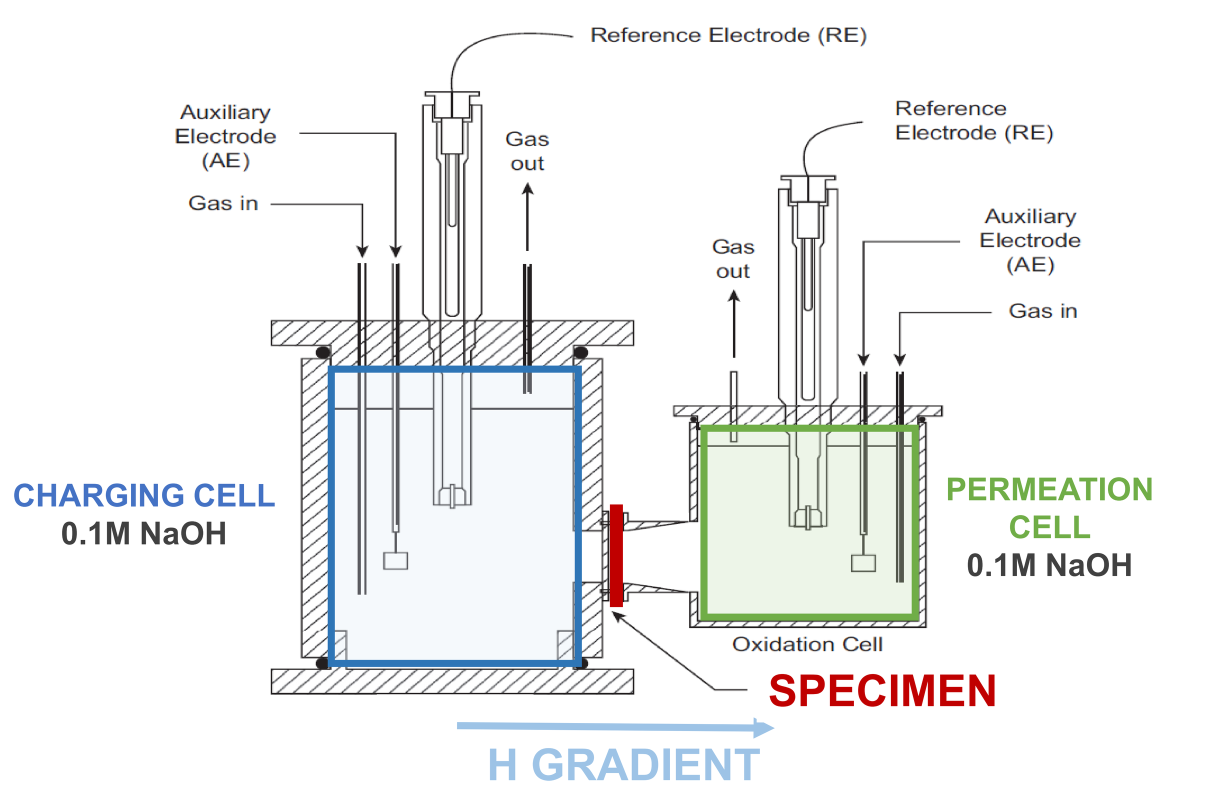
u – hydrogen concentration just inside the metal surface
u_s – saturation concentration of hydrogen in the metal

Reaction 5
Atoms diffuse to the critical location, causing embrittlement

$$r_5 = D\left(u - \frac{u_l}{l}\right)$$

D – diffusion coefficient
u_l – hydrogen concentration at the critical location at l distance from the metal surface

HYDROGEN PERMEATION TESTING (ISO 17081:2014) [5]



Different cathodic charging conditions
- **Galvanostatic charging** (fixed current), creates a flux of H towards the surface
- **Potentiostatic charging** (fixed potential), promotes the concentration of H at the surface

The overall transport reaction will be the sum of the individual reactions and can involve reactions occurring in opposite directions, consecutively and in parallel. If any of the reaction steps is hindered or eliminated, the structure will be less susceptible to embrittlement.

REFERENCES

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