TATA STEEL

TATA

Hydrogen Diffusion in a Range of High-Strength Steels

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Contents

Background

- Studied steels
- Hydrogen diffusion

Experimental

- Hydrogen permeation
- Slow strain-rate testing

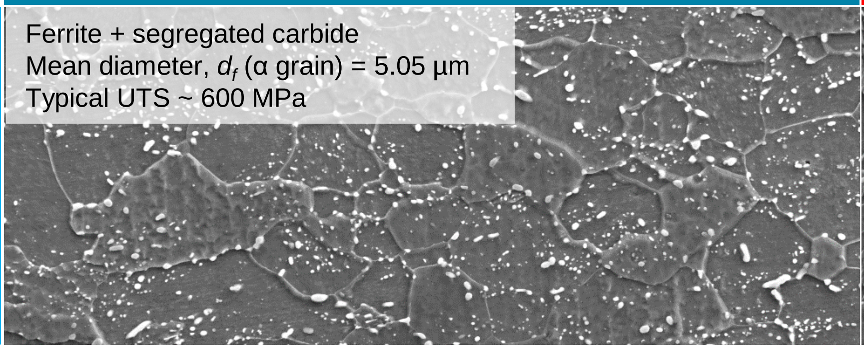
Results & Conclusions

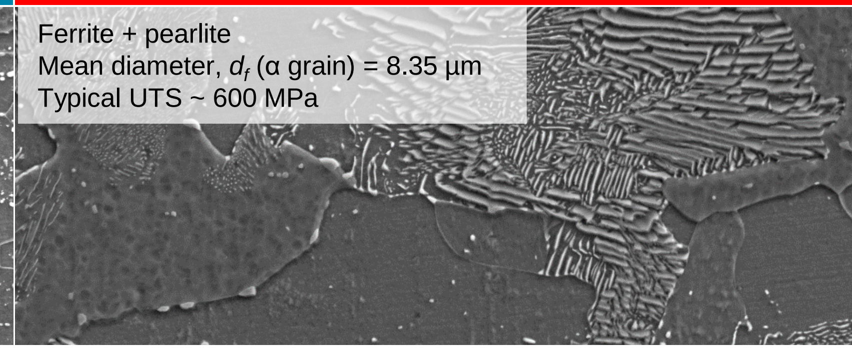
- Effects of charging potential
- Effects of microstructure
- Impacts upon mechanical properties

Overview of Products

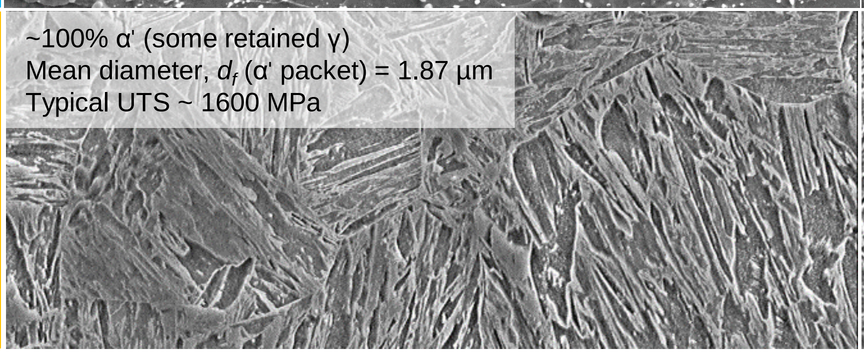
Steel A | **Steel B**

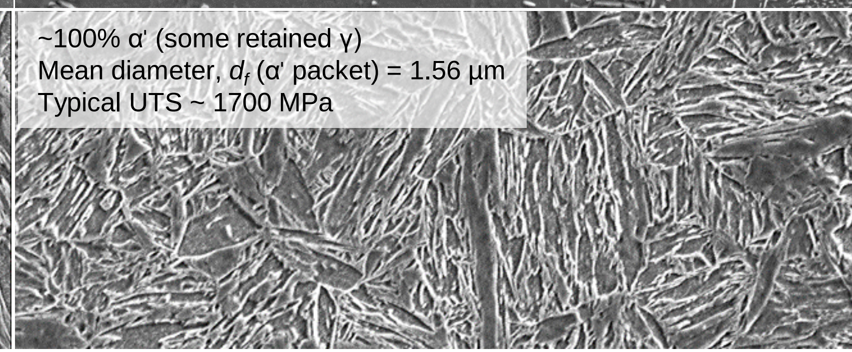
As Received





Heat-treated

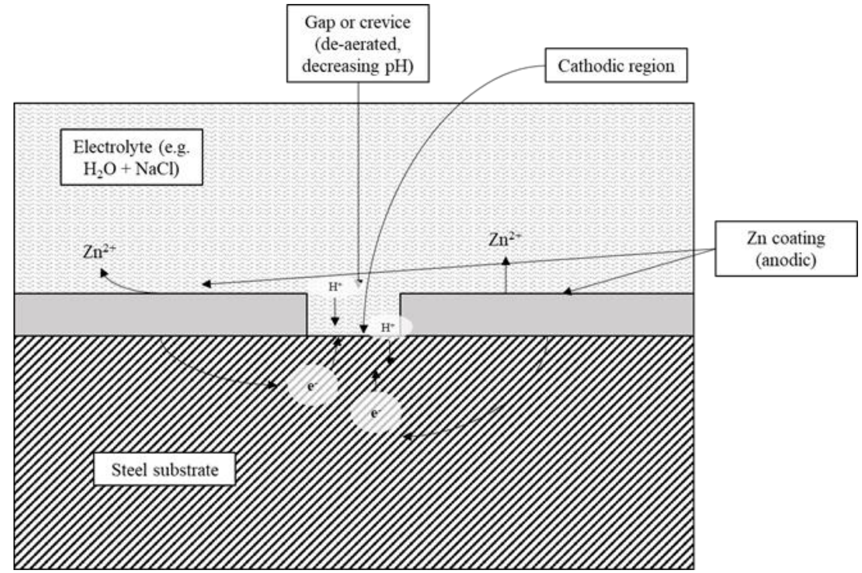




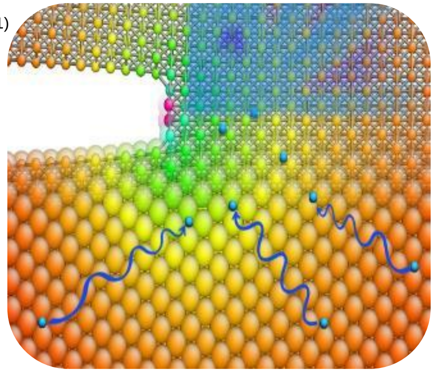
Alloy	C	Si	Mn	P	S	N	Sol. Al	Cr	Nb	Ti	B
Steel A	**0.22**	0.165	1.228	0.012	0.002	0.005	0.021	**0.288**	0.001	0.023	**0.0032**
Steel B	**0.270**	0.290	1.180	0.011	0.002	0.005	0.032	0.046	**0.029**	0.050	**0.0025**

All images @ 2500 x magnification

Why hydrogen diffusion?

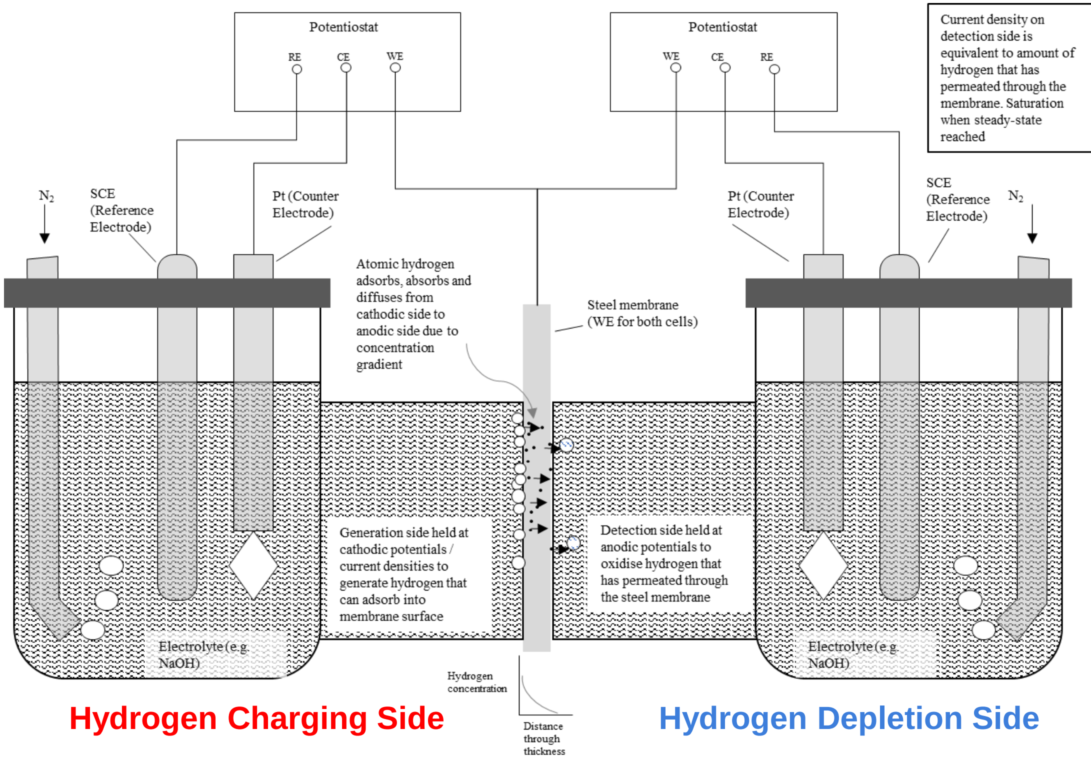


1)



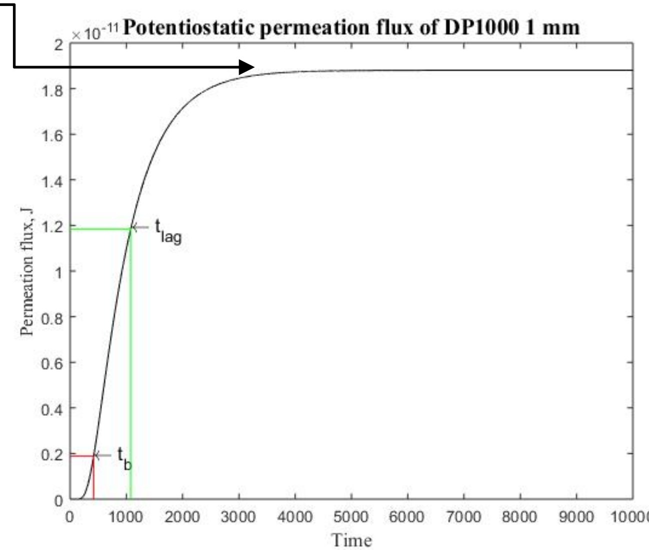
1) Materials, F. I. f. M. o. *Hydrogen embrittlement in metals - Fraunhofer IWM*, <http://www.iwm.fraunhofer.de/en/services/assessment-materials-lifetime-concepts/microstructure-residual-stresses/hydrogen-embrittlement-metals.html> (2017).

Hydrogen Transport - Diffusion



Hydrogen Charging Side **Hydrogen Depletion Side**

$$* \; J = J_{\infty}\left(1 + 2\left(\sum_{n=1}^{\infty} \cos(\pi n) \exp\left(\frac{-Dn^2\pi^2 t}{L^2}\right)\right)\right)$$

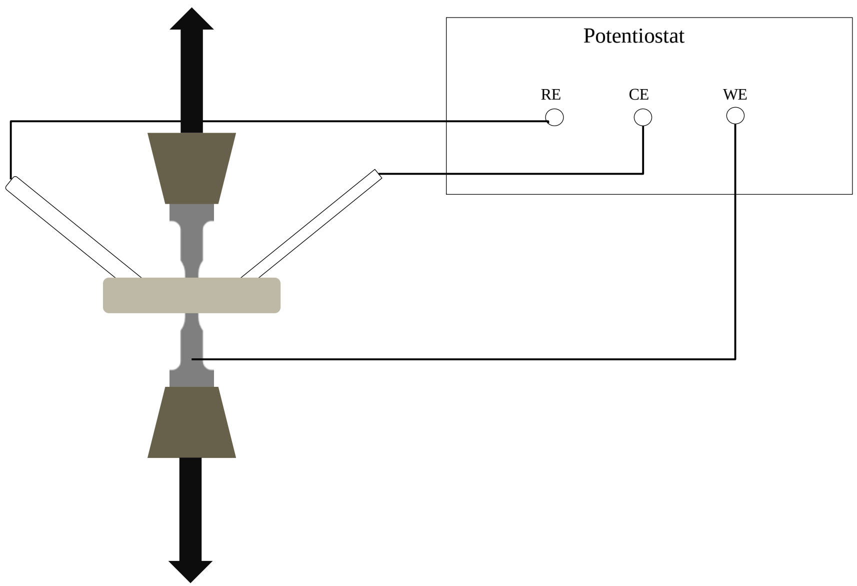


There is strong evidence that where two steels have similar strengths, the one with the higher hydrogen diffusivity will suffer more deleterious effects

However

- Usually, there are traps present
- Surface effects or concentration-dependence

Effects on Mechanical Properties



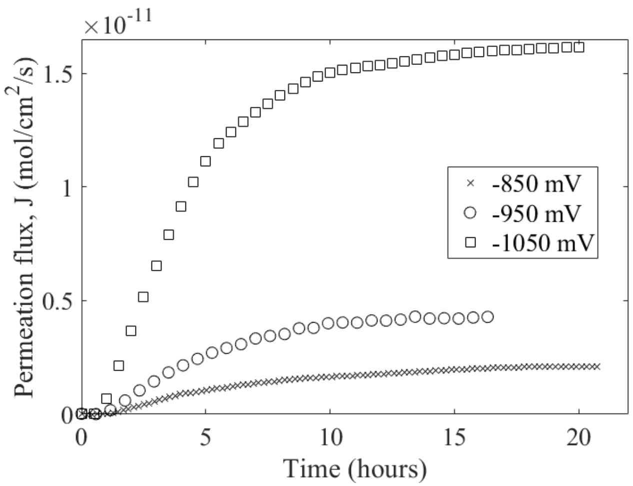
SSRT

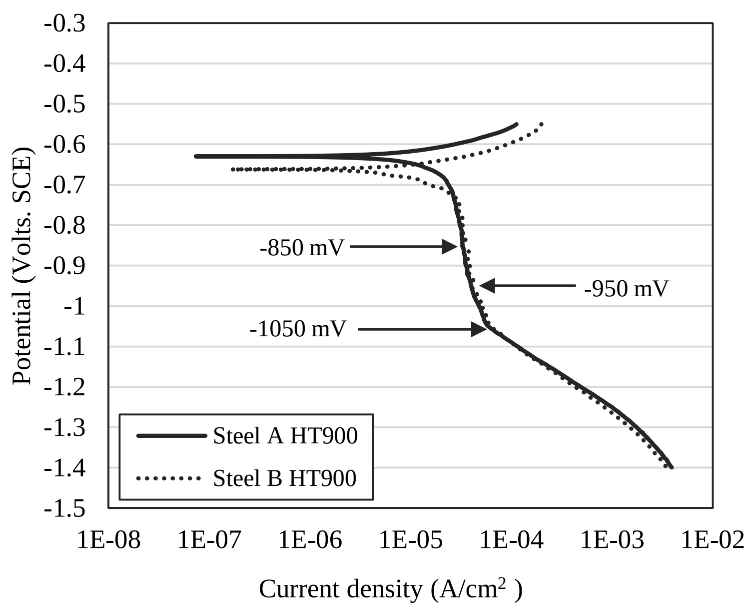
- Typical test for assessing ‘hydrogen embrittlement index’
- Sample is polarised in electrolyte to charge it with hydrogen *in situ* during tensile test at very low strain-rate ($\varepsilon/s = 9 \times 10^{-6}$ in this case)
- Comparing the elongation in air to that attained with hydrogen charging gives an estimate of a material’s susceptibility to embrittlement:

$$Embrittlement\ Index\ (EI\%) = \frac{(Elongation\ in\ air\ - Elongation\ whilst\ charging)}{Elongation\ in\ air} \times 100\%$$

Results

Effect of charging potential (concentration)





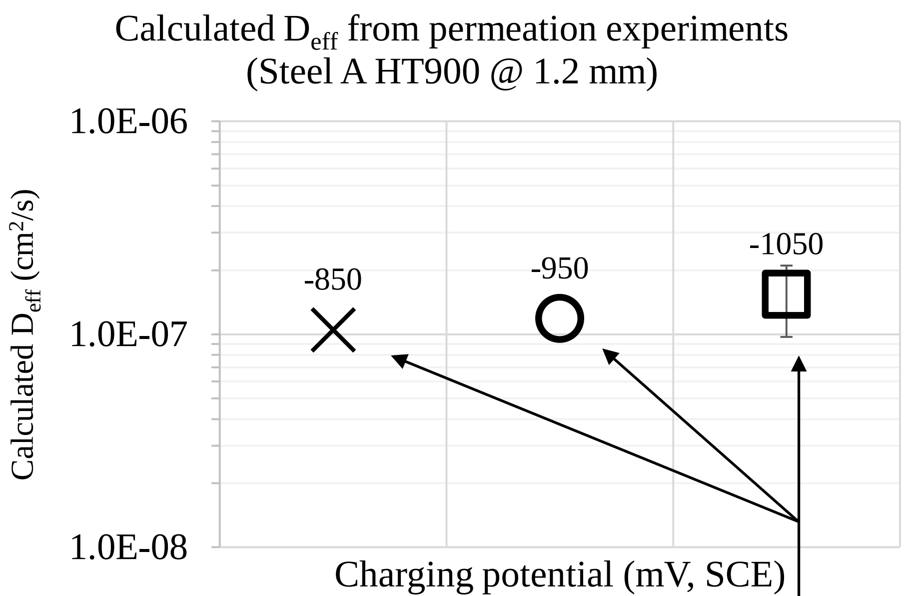
Potential vs Flux

- With increased charging overpotential comes increase in concentration at charging surface
- Correspondingly higher steady-state flux
- Sharper increase in flux when potential decreased beyond inflection point of potentiodynamic curve
  - Change in dominant cathodic reactions in favour of reduction of water ~ -1040 mV SCE

$$H_2O + e^- \rightarrow H + OH^-$$

Results

Effect of charging potential (concentration)



But:

- Little effect upon effective diffusion coefficient

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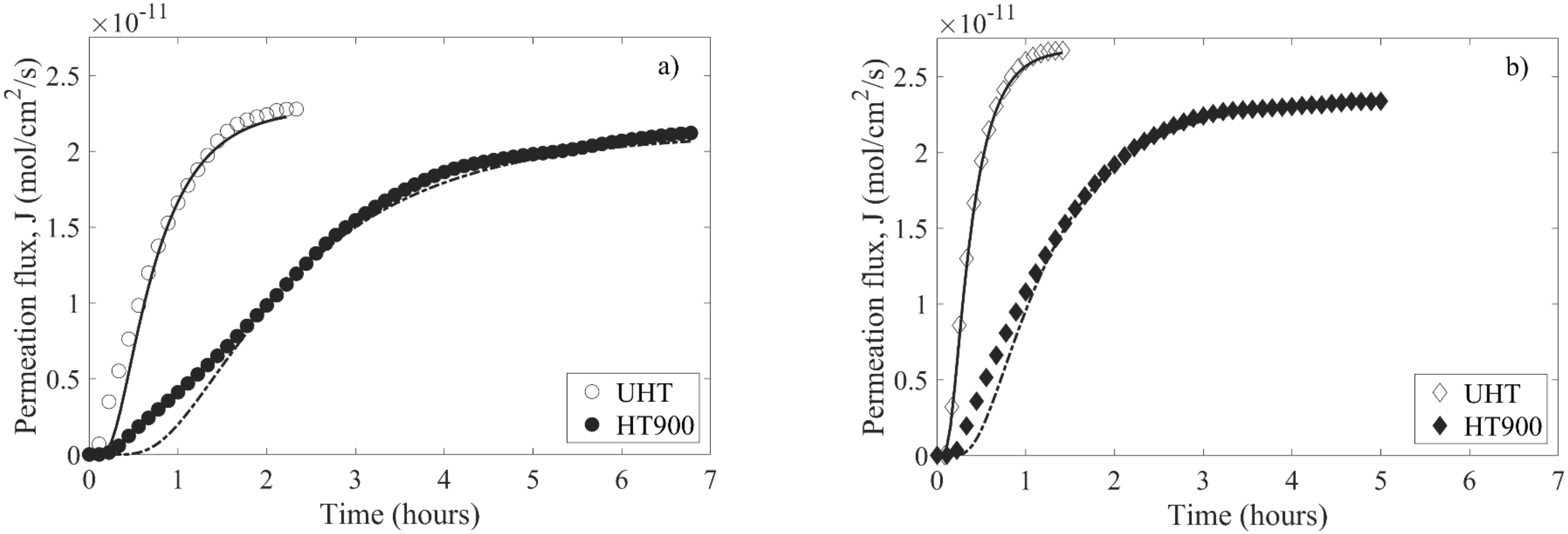
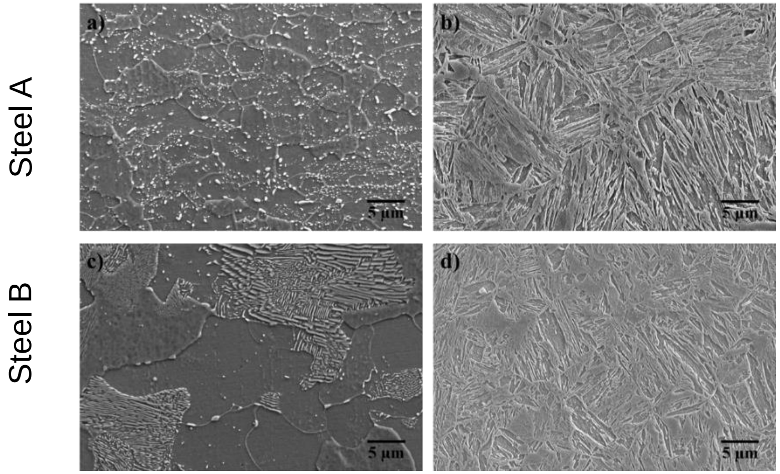
Results

Effect of microstructure



Permeation curves for a) Steel A, and b) Steel B all heat-treatment conditions, membrane thickness 0.8 mm, -1050 mV (SCE)



Permeation

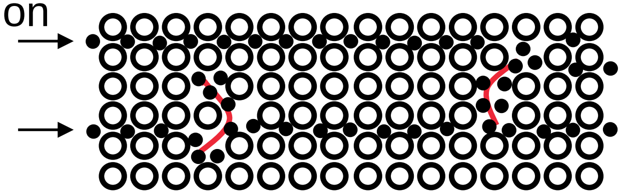
- Good fit of simulated curve implies lattice diffusion dominance
- Martensitic (heat-treated) lower steady-state flux and longer time to reach steady-state for both steels

Results

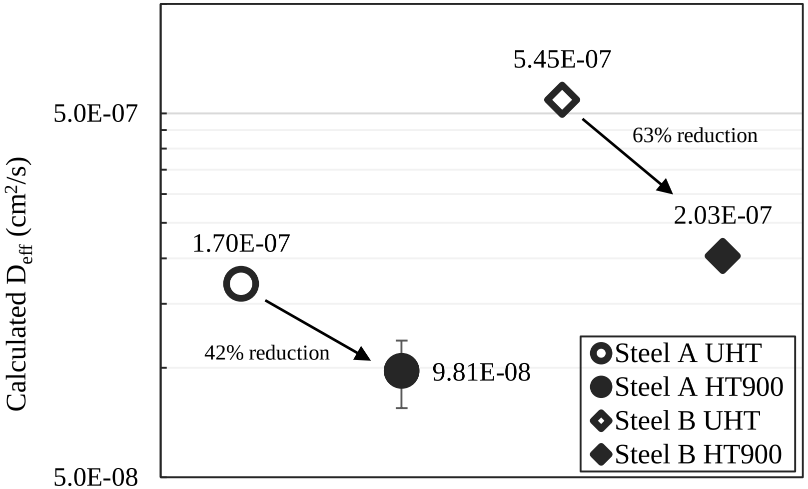
Effect of microstructure

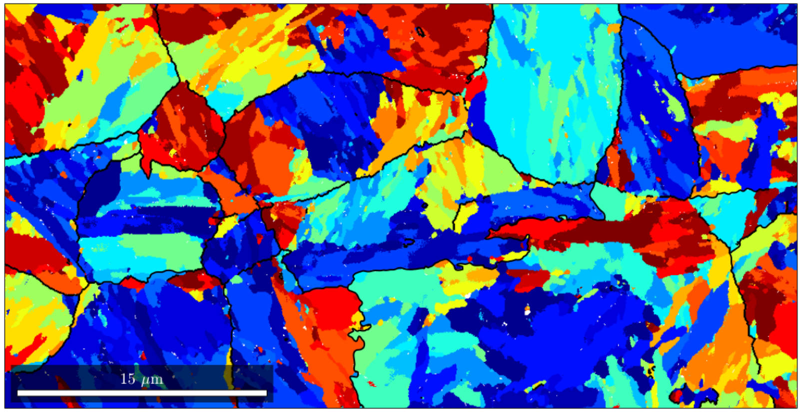
Diffusivity

- Martensite has lower overall diffusivity in both steels
- Martensite lattice has high residual strain and dislocation density – these will act as ‘reversible’ traps
  - Sieve-like affect on hydrogen diffusion



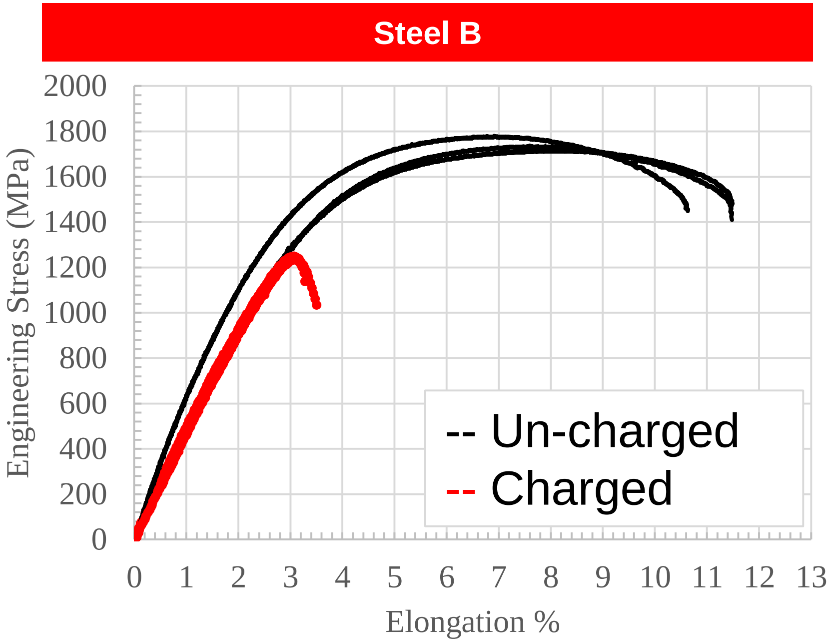
- Complex orientation relationships between martensite packets within ‘parent’ austenite grains
- Also has some retained austenite (≈ 1.5% - 2%), which has much higher solubility & lower diffusivity than ferrite or martensite, adding tortuosity to diffusion path





Results

Effect on mechanical properties



Embrittlement Index

- Steel B has (very) marginally higher EI% (@ A_{gt} & A_t) with 2-hour pre-charging
  - Indicates susceptibility of microstructure is higher in Steel B
- Requirement to test without pre-charging to truly discern effects of increased diffusivity from microstructural susceptibility

Conclusions

- For these boron steels, permeation curves simulated according to Fick's laws fitted experimental data well, indicating dominance of lattice diffusion (plus 'reversible' hydrogen traps in equilibrium) over effects of 'irreversible' trapping
- For both steels, heat-treated martensitic microstructure had a >40% lower effective diffusion coefficient than in the 'as received' microstructures
  - Effect of high dislocation density, complex orientation relationship of martensite packets, and presence of retained austenite in the martensite providing more convoluted diffusion path
- A 'jump' in steady-state flux is achieved when charging overpotential increases beyond inflection in potentiodynamic curve
  - Caused by change in balance of reactions at charging surface
  - Has minimal effect on diffusivity
- Some indication that for these steels higher diffusivity does lead to higher susceptibility to hydrogen embrittlement
  - When microstructure is saturated
  - Further testing without pre-charging required to fully discern effects of higher diffusivity

Thank you for listening. Any questions?