HIGH SCHOOL INTERNSHIP PROGRAM

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Hydrogen Embrittlement in Pressure Vessel Steel Welds

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Background and Motivation

Hydrogen-induced cracking (HIC):

- During welding of carbon steels, atomic hydrogen is introduced into the weld pool and diffuses to the heat-affected zone (HAZ).
- The combination of residual stresses, a susceptible microstructure, and enough levels of diffusible hydrogen causes HIC nucleation and propagation.

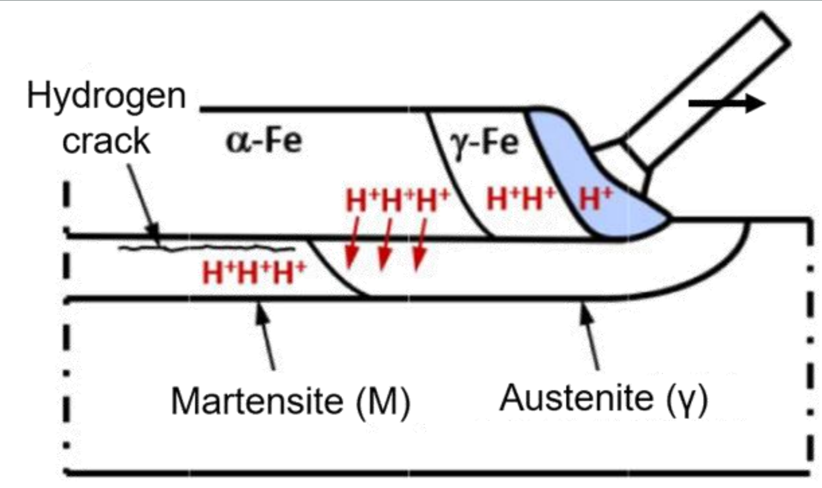
Industry application:

- SA-508 steel (quench + temper), used as a nuclear reactor pressure vessel, is susceptible to HIC because of the formation of **fresh martensite** in the HAZ.
- The **temperbead welding (TBW) technique** was developed to prevent HIC by tempering the martensite with every pass. Expected hydrogen contents are **2-4 mL/100g**.
- Pressure vessel welders must wait 48h after repair to ensure that no HIC occurred, which is cost-inefficient.

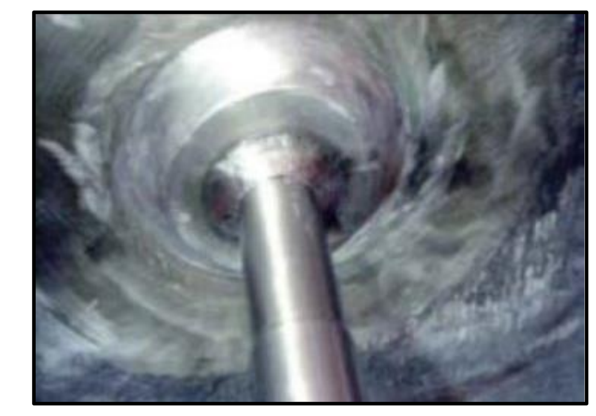
Previous Work:

- The delayed hydrogen cracking test (DHCT) was utilized to rank the HIC susceptibility in TBW HAZ microstructures by time-to-failure.

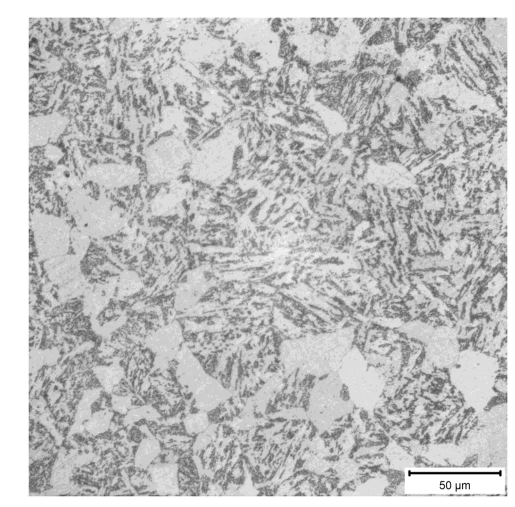
Goal: Measure critical diffusible hydrogen content in reheated SA-508 coarse-grained HAZ microstructures that caused HIC failures in previous work



Hydrogen movement during welding

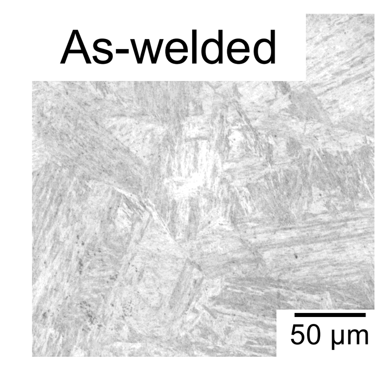


Pressure vessel nozzle TBW

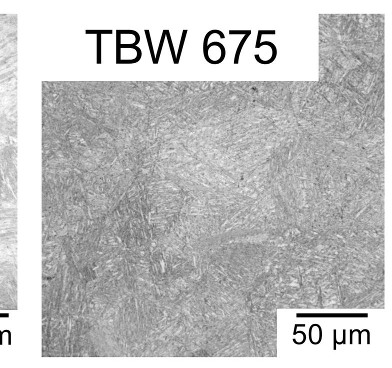


SA-508 base metal

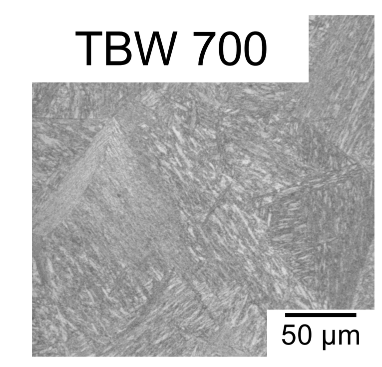
As-welded



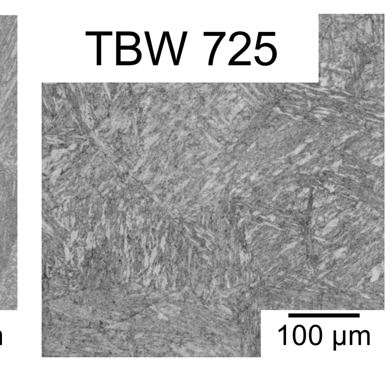
TBW 675



TBW 700

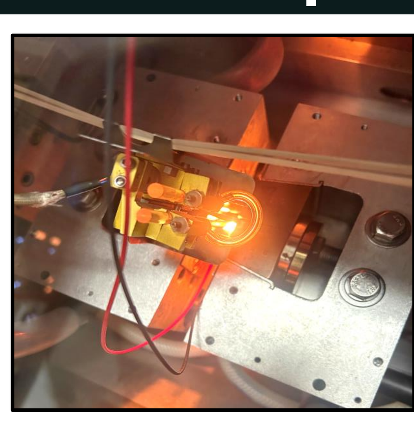


TBW 725

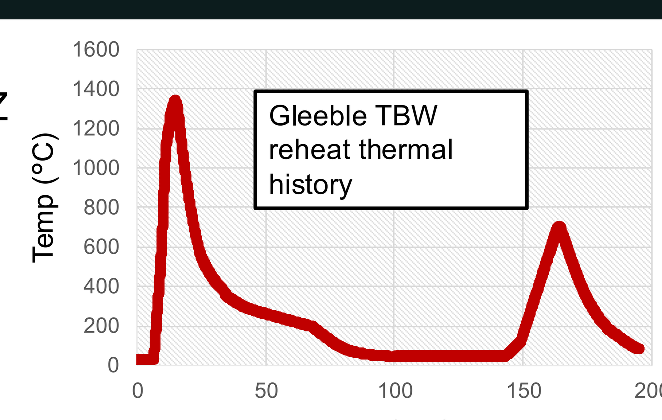


Experimental Methods

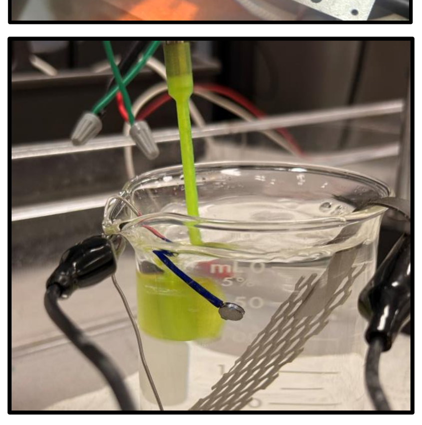
1. Weld Simulation



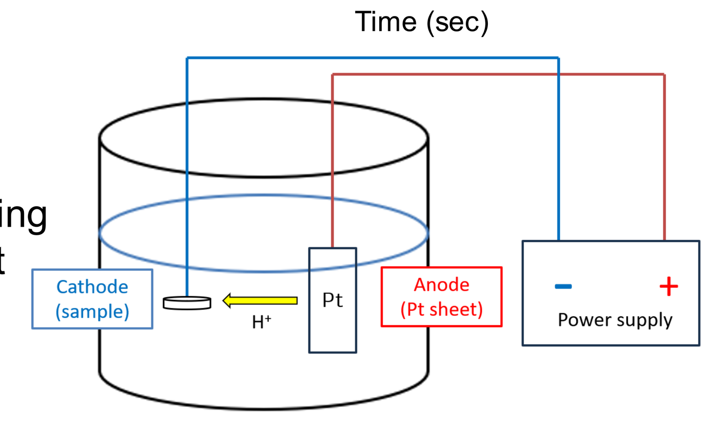
Generate TBW-HAZ microstructures in the Gleeble 3800 to replicate a single pass or reheat weld



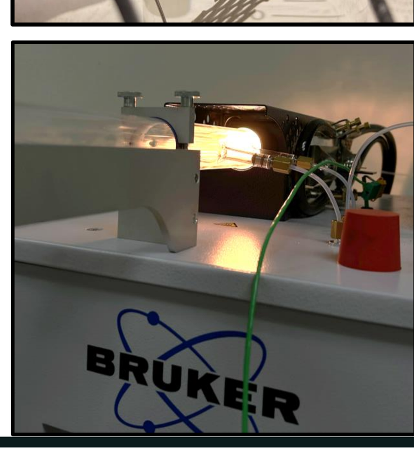
2. Electrolyte Charging



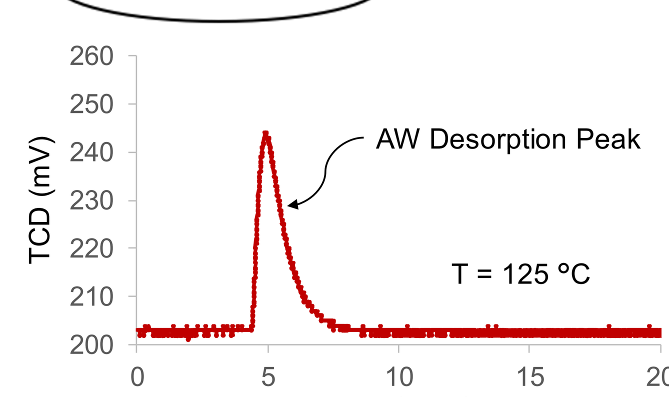
Introduce atomic hydrogen by electrolytic charging at varying current densities



3. Isothermal Outgassing



Measure diffusible hydrogen content by isothermal outgassing at 125 °C in the Bruker G4 Phoenix



Conclusions & Future Work

- As-welded condition exhibited the largest amount of hydrogen uptake, confirming its high susceptibility
- Regarding the TBW condition, tempering martensite successfully decreases the diffusible hydrogen solubility, which is associated with HIC resistance

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- Uncover more specific hydrogen data that initial tests did not:
  - Run full thermal desorption spectra on tested samples to quantify irreversible trapped hydrogen
  - Characterize HAZ microstructures to identify hydrogen traps
- Validate ferritic filler metals for welding of SA-508
  - Extract samples directly from temperbead welds using ferritic filler metals
- Test a hollow-specimen assembly to combine in-situ diffusible hydrogen measurements with DHCT mechanical testing

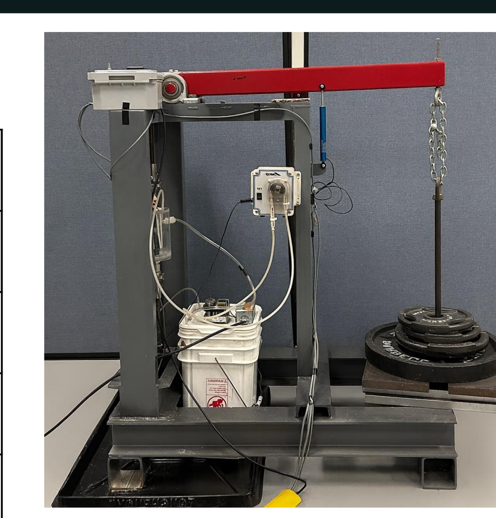
Results & Discussion

Table 1: DHCT data from previous SA-508 work.

	DHCT [Result / Test time (h)]				
Condition	1 mA/cm^2	10 mA/cm^2			
AW	F / 0.5	F / <40	F / 0.8	F / 0.9	F / 1.2
TBW675	NF	NF	F / 0.6	F / 6.2	NF
TBW700	NF	NF	NF	NF	NF
TBW725	NF	NF	NF	NF	NF

F: failed
NF: non-failed

Highest H_D failure
Lowest H_D failure



DHCT features:
- Constant load
- In-situ charging

- The AW condition consistently failed within 1h, making it the most susceptible
- The TB675 condition had unpredictable failures at 10 mA/cm^2
- The TB700 and TB725 conditions sustained the DHCT long after reaching saturation with hydrogen

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All reheated charging conditions were selected to coincide with previous DHCT outcomes, including the following:
- Minimum Critical H_D for **susceptible** specimens
- Maximum Saturation for **resistant** specimens

Above expected range
Within expected range
Below expected range

Table 2: Diffusible hydrogen content results

Test ID	Replicates	Current Density (mA/cm^2)	Charging Time (h)	Avg. H Content (mL/100g)
BM	24h Saturation	10	24	1.11
AW	24h Saturation	10	24	5.84
	Max. Critical H_D	10	1.0	8.02
	Min. Critical H_D	1	0.5	0.89*
TBW 675	24h Saturation	10	24	4.47
	Min. Critical H_D	10	0.6	2.90
	Max. Critical H_D	10	6.2	2.67
TBW 700	24h Saturation	10	26.2	3.60
	48h Saturation	10	48	3.66
TBW 725	24h Saturation	10	24	2.53
	48h Saturation	10	48	1.55

*Some DHCT failures occurred within diffusible hydrogen levels expected in low-H TBW procedures or even lower (<2 mL/100g).

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