Hydrogen Isotope Permeation and Trapping in Additively Manufactured Stainless Steel

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Tritium Focus Group, PNNL
May 2017

- Customers
- How and why AM
- Permeation process, capabilities
- Examples of diatomic gas-driven permeation in AM steel
- Trapping
- Summary
Stainless Steel is Used by Many Hydrogen Customers

- Be, W, Mo, RAFM, SiC
- Barriers (Oxides, IMs)
- Zr
- SS Al Barriers (Oxides, IMs)

Fusion

GTS

Readiness

Transport

Ni, Cu
Additively Manufactured 304/316 Steel Processes

- DED/LENS (Direct Energy Deposition/Laser Engineered Net Shaping)
- PBF (Powder Bed Fusion)

Blade made from LENS

SAND2002-3539W; Laser Engineered Net Shaping; David Gill

Varying Cooling Rates

Dislocation Density

Powder Characteristics

Interstitial Nitrogen

PBF on Renishaw

http://www.renishaw.com/en
Motivation: Strength, Shaping, Repair

Balch et al. (2016)

Fig. 6 — Bore and radial repaired scratches on the surface of the weld bases.

Fig. 7 — Sample gouge in sample gas bottle. Gouges were 0.125 in. wide and either 0.010 or 0.020 in. deep.
Looked at five different builds

<table>
<thead>
<tr>
<th>ID</th>
<th>Powder</th>
<th>Process</th>
<th>Geometry</th>
<th>Ferrite</th>
</tr>
</thead>
<tbody>
<tr>
<td>LENS1</td>
<td>316</td>
<td>LENS-0.325 kW</td>
<td>Wall</td>
<td>1.1</td>
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<tr>
<td>LENS2</td>
<td>316L</td>
<td>LENS-0.5 kW</td>
<td>Plate</td>
<td>0.3</td>
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<tr>
<td>LENS3</td>
<td>304L</td>
<td>LENS</td>
<td>Wall</td>
<td>0.9</td>
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<tr>
<td>DLPD</td>
<td>304L</td>
<td>DLPD-3.8kW</td>
<td>Plate</td>
<td>2.7</td>
</tr>
<tr>
<td>PBF</td>
<td>304L</td>
<td>PBF</td>
<td>Plate</td>
<td>&lt;0.2</td>
</tr>
</tbody>
</table>
Most materials exhibit diffusion-limited permeation at sufficient pressures. Recombination is often neglected because it is fast (e.g. $KR \sim 1e-16$ cm$^4$/s for Ni).
Permeation Experiments at Sandia California

- Deuterium gas driven permeation capabilities presently in use at SNL
  - 1st generation (150 < T < 500 °C) used stainless steel construction (VCR seals), evacuated quartz outer tube to reduce D2 bypass, and low flow to prevent surface contamination.
  - 2nd generation (50 < T < 1150 °C) uses Al2O3 construction and soft, pressure loaded seals for brittle specimens (funded by “Work For Others” program to measure SiC permeation barriers for fusion blankets).

Materials studied:
- 1st Generation System: stainless steels, steel alloys, welds, aluminum alloys, nickel, AM steel
- 2nd Generation System: stainless steels, SiC, tungsten

PSiC < 10-12 mol H2 m-1 s-1 MPa-0.5
Permeability of metals

Causey, Karnesky, San Marchi, “Tritium Barriers and Tritium Diffusion in Fusion Reactors” 2012

R Karnesky, Sandia National Laboratories, TFG 2017-05
Ferritic steels are much more permeable than austenitic steels.
But modest ferrite additions don’t increase permeability
And AM steels have similar permeabilities, regardless of ferrite content.
But slow transients suggest trapping

200 °C

conventional austenitic stainless steel, $D = 10^{-12} \text{ m}^2\text{s}^{-1}$

DLPD (Penn State) 304L

$D = 10^{-14} \text{ m}^2\text{s}^{-1}$
Low apparent D, even at high T

![Graph showing apparent diffusivity vs. 1000/T (K⁻¹)]
Schematic of trapping

Young and Scully, 1998
AM shows higher energy traps
AM steels have slightly greater amounts of H

<table>
<thead>
<tr>
<th>ID</th>
<th>Hydrogen isotope content [wt. ppm]*</th>
</tr>
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<tbody>
<tr>
<td>Inventional [8]</td>
<td>140</td>
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<tr>
<td>LENS1</td>
<td>160±30</td>
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<tr>
<td>LENS3</td>
<td>150±20</td>
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<tr>
<td>DLPD</td>
<td>140±20</td>
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<tr>
<td>PBF</td>
<td>170±20</td>
</tr>
</tbody>
</table>
Summary

- Permeation of AM is within a factor of 2 of conventional, despite ferrite levels of up to 2.7%
- Greater retention/trapping in AM
  - Dislocations?