Tritium Aging Effects on Forged Stainless Steel

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Pressure vessels for tritium service are constructed from stainless steel forgings.

Tritium and its decay product, helium, change the structural properties of stainless steels and make them more susceptible to cracking.

Material and forging specifications have been developed for optimal material compatibility with tritium. They include: Composition, tensile properties, and select microstructural characteristics like grain size, flow line orientation, inclusion content, and ferrite distribution and content.

For years, the forming process of choice was high-energy-rate forging (HERF).

Today, some reservoir forgings are being made that use a conventional, more common process known as press forging (PF or CF).

Conventional hydraulic or mechanical forging presses deform metal at 4-8 ft/s, about ten-fold slower than the HERF process.

The material specifications continue to provide successful stockpile performance by ensuring that the two forging processes produce similar reservoir microstructures.
The purpose of this study was to measure and compare the fracture toughness properties of Type 21-6-9 stainless steel for:

- High-energy-rate and conventional forgings; in the
- Unexposed, hydrogen-exposed and tritium-exposed-and-aged conditions.
Effect of Tritium Exposure on Stainless Steels

Unexposed

Tritium-Exposed & Aged
Helium Hardened Microstructure
<table>
<thead>
<tr>
<th>Material Forging</th>
<th>Sample ID</th>
<th>Cr</th>
<th>Ni</th>
<th>Mn</th>
<th>P</th>
<th>Si</th>
<th>Co</th>
<th>Mo</th>
<th>C</th>
<th>S</th>
<th>N</th>
<th>O</th>
<th>Al</th>
<th>Cu</th>
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</thead>
<tbody>
<tr>
<td>HERF* 21-6-9</td>
<td>A4582</td>
<td>19.4</td>
<td>6.4</td>
<td>8.5</td>
<td>0.021</td>
<td>0.33</td>
<td></td>
<td></td>
<td>0.04</td>
<td>&lt;.001</td>
<td>0.28</td>
<td>0.0022</td>
<td>&lt;.001</td>
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<tr>
<td>CF** 21-6-9</td>
<td>B7073</td>
<td>19.1</td>
<td>6.7</td>
<td>9.9</td>
<td>0.01</td>
<td>0.41</td>
<td></td>
<td></td>
<td>0.03</td>
<td>0.004</td>
<td>0.28</td>
<td>0.001</td>
<td>0.005</td>
<td></td>
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<tr>
<td>CF** 21-6-9</td>
<td>B6275</td>
<td>19.3</td>
<td>6.7</td>
<td>9.9</td>
<td>0.01</td>
<td>0.38</td>
<td></td>
<td></td>
<td>0.03</td>
<td>0.001</td>
<td>0.28</td>
<td>0.002</td>
<td>0.004</td>
<td></td>
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<tr>
<td>Filler Wire 308L</td>
<td>308L 98-X</td>
<td>20.5</td>
<td>10.3</td>
<td>1.56</td>
<td>0.006</td>
<td>0.5</td>
<td>0.068</td>
<td>&lt;0.01</td>
<td>0.028</td>
<td>0.012</td>
<td>0.055</td>
<td>-</td>
<td>-</td>
<td>0.015</td>
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*High-Energy-Rate Forged
**Conventionally Forged
Manufacturers’ supplied compositions
Forging and Sample Orientation

Forging A4582 - - 21-6-9 SS
<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Yield Strength psi</th>
<th>Ultimate Strength psi</th>
<th>% EL</th>
<th>Grain Size</th>
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<tbody>
<tr>
<td>F9 (CF)</td>
<td>87100</td>
<td>131400</td>
<td>48.3</td>
<td>10/7; 7 &lt; 5%</td>
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<tr>
<td>H94 (CF)</td>
<td>99400</td>
<td>139300</td>
<td>44.3</td>
<td>10/7; 7 &lt; 5%</td>
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<tr>
<td>F97 (HERF)</td>
<td>104800</td>
<td>139400</td>
<td>37.6</td>
<td>5/3</td>
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</tbody>
</table>
Sample Cartridge and Aging Calculation

- Hydrogen and Tritium exposures conducted at 350 C for three weeks
- Tritium samples aged at -40C to build-in decay helium
- All samples were tested at ambient temperature in air
Fracture Toughness Testing

[Graphs showing load vs. displacement and normalized voltage across crack mouth]
J-R Curves for CF and HERF Steels

- Conventionally Forged (CF)
- High-Energy-Rate Forged (HERF)

J, lbs / in.

da, in.
Fracture Appearance Unexposed Heats

Conventionally Forged

High-Energy-Rate Forged
Conventionally Forged Microstructures

90 ksi Y.S. Heat

100 ksi Y.S. Heat
HERF Microstructures

[Images of microstructures with labeled scales of 40 µm and 20 µm]
J-R Curves for As-Received and Heat-Treated Steels

- Conventionally Forged (CF)
- High-Energy-Rate Forged (HERF)
- CF Heated 650 C 5 Min
- HERF Heated 650 C 5 Min
Fracture Appearance Heat Treated Steels

Conventionally Forged

High-Energy-Rate Forged
Effect of Hydrogen Exposure on J-R Behavior

Conventionally Forged Type 21-6-9 Stainless Steel
Effect of Hydrogen on Fracture Appearance

Conventionally Forged Type 21-6-9 Stainless Steel
Effect of Hydrogen, Tritium, and Decay Helium on J-R Behavior

Conventionally Forged Type 21-6-9 Stainless Steel
Effect of Decay Helium on Fracture Toughness

![Graph showing the effect of decay helium on fracture toughness. The graph plots JQ Value (in lbs/in.) against Helium Content (in appm.). Different symbols represent different materials: CF 21-6-9 with 100 ksi yield strength heat, CF 21-6-9 with 90 ksi yield strength heat, and HERF 21-6-9 with 100 ksi yield strength heat.]
Tritium Aging Effects on Fracture Appearance

253 appm Helium

627 appm Helium
Tritium Aging Effects on Fracture Appearance

253 appm Helium

627 appm Helium
Fracture Appearance of Tritium Exposed HERF Type 21-6-9 Stainless Steel

627 appm Helium
Fracture Toughness of Heat Treated 21-6-9 SS

Fracture Toughness, lbs/in.

Time @ 647 C, h
Comparison of Fracture Appearance – Heat Treated vs. Tritium-Exposed-and-Aged

Heat Treated 650 C 24 h

Tritium-Exposed-Aged for Seven Years (627 appm helium)
Conclusions

- HERF Type 21-6-9 stainless steels had lower fracture toughness values than Conventionally Forged Type 21-6-9 steel because of its larger grain size and sensitization that occurred during the forging process.
- Hydrogen and tritium exposures lowered the JQ values and J-da curves. The degree of sensitization did not seem to affect the fracture toughness at high helium levels.
- Fracture modes of the forged steels were dominated by the dimpled rupture process in unexposed, hydrogen-exposed and tritium-exposed steels and welds.
- Heavily sensitized steels had a similar fracture appearance as tritium-exposed-and-aged steels