1 General

Ferrium S53 is a corrosion resistant, secondary hardening, ultra-high strength martensitic steel that exhibits good toughness, good general corrosion resistance, high resistance to stress corrosion cracking, excellent resistance to fatigue and notch fatigue, and very high bearing strength with an ultimate tensile strength of 280 ksi or greater. Ferrium S53 was designed as a replacement for 300M in landing gear components. The increased general corrosion resistance and high resistance to stress corrosion cracking allows for the elimination of cadmium coating of components. Greater general corrosion resistance leads to less component condemnations by allowing the component to be reworked within the dimensional tolerance limits for the component. The high resistance to stress corrosion cracking reduces the number of failures for components. Another benefit of Ferrium S53 is the high-temperature resistance of the alloy. The high-temperature resistance of Ferrium S53 reduces the amount of condemnations during processing due to grinding damage. In addition to landing gear components, Ferrium S53 has been applied to oil and gas applications and can be used in other applications requiring high strength with good corrosion resistance. (Refs. 1-3, 7, 10)

1.1 Commercial Designation
Ferrium S53

1.2 Alternate Designation
UNS S10500

1.3 Specification
AMS 5922

1.4 Composition

The nominal composition of Ferrium S53 is: Fe-10Cr-5.5Ni-14Co-2Mo-1W-0.3V-0.21C wt%. (Ref. 4)

1.5 Heat Treatment

1.5.1 General: Heat treatment of S53 is typically completed in vacuum to reduce the amount of decarburization. However, the second temper step may be completed in air. The normalized, cryogenic treatment, and anneal cycle were developed for optimal machinability. During the normalizing and solution treatment cycles (austenitizing), it is important to minimize the time between 600F and 1650F in order to minimize carbide precipitation and growth, as large carbides will be difficult to dissolve during austenitizing hold time; retained carbides lead to a reduction of strength by secondary carbide precipitation. (Refs. 3, 4, 7)

1.5.2 Normalizing: Heat to 1940–2012F, air cool, cool below -100F, hold 1 hour or longer, air warm.

1.5.3 Annealing: Heat to 1231–1281F, air cool.

1.5.4 Austenitizing: Heat to 1958–2012F, hold 60–70 minutes, oil quench or equivalent, cool below -100F, hold 1–3 hours, air warm.

1.5.5 Tempering: Heat to 922–946F, hold 2.5–3 hours, oil quench or equivalent, cool below -100F, hold 1–3 hours, air warm, heat to 882–918F, hold 11–14 hours, air cool.

1.6 Hardness
The hardness of Ferrium S53 after heat treatment is 52–55 Rockwell C. (Refs. 3, 7)

1.7 Forms and Conditions Available

Ferrium S53 is available in the form of bar, billet, and forging in the normalized and annealed condition. The microstructure of the mill annealed product is a combination of austenite and martensite. (Refs. 2, 4)

2.0 Physical and Chemical Properties

2.1 Thermal Properties

2.1.1 Melting Range: 2485F to 2630F (Refs. 3)

2.1.2 Phase Changes

2.1.2.1 Continuous cooling transformation diagram (Ref. 3)

2.1.2.2 Phase diagram (Refs. 3, 6)
2.1.2.3 The grain size of forged barstock is bimodal with an average grain size of ASTM No. 4 or finer with a range of ASTM No. 12 to ASTM No. 1. (Refs. 3, 4)  
2.1.2.4 Table The grain size of die forged components as a function of hot-fire temperature (Refs. 3, 7)  

2.1.3 Thermal Conductivity  
2.1.3.1 [Figure] Thermal conductivity of Ferrium S53 as a function of temperature (Refs. 5, 7)  

2.1.4 Thermal Expansion  
2.1.4.1 [Figure] Mean coefficient of thermal expansion between room temperature and 1100°F (Refs. 5, 7)  

2.1.5 Specific Heat  
2.1.5.1 [Figure] Specific heat of Ferrium S53 as a function of temperature (Refs. 5, 7)  

2.1.6 Thermal Diffusivity  
2.1.6.1 [Figure] Thermal diffusivity of Ferrium S53 as a function of temperature (Ref. 9)  

2.1.7 Enthalpy  

2.2 Other Physical Properties  
2.2.1 Density: 0.288 lbs/in³ (Refs. 3, 5)  

2.2.2 Electrical Properties  

2.2.3 Magnetic Properties—Paramagnetic  

2.2.4 Emittance  

2.2.5 Damping Capacity  

2.3 Chemical Properties  
2.3.1 General Corrosion  
Ferrium S53 has good general corrosion resistance in the presence of an outdoor environment. S53 has a tendency to form isolated spots of thin corrosion scale (rust) with a shallow underlying pit. The pit depth arrests at 0.001 to 0.004 inches after formation of a passive chromium oxide layer that forms at the bottom of the pit. From anodic polarization testing, the estimated corrosion rate of S53 in 3.5 wt% NaCl solution was found to be 0.5 mils per year. In addition, a one-year corrosion study in a marine atmosphere at an oceanfront test stand at Kure Beach, NC was completed on test panels prepared using various techniques representative of landing gear manufacturing. The above results are representative of the post-test examination. A surface protection scheme is recommended to minimize corrosion and generation of hydrogen for extended outdoor applications. (Ref. 3)  

2.3.2 Stress Corrosion  
2.3.2.1 [Figure] Stress corrosion cracking threshold K_{Lscc} in 3.5%NaCl solution as a function of applied cathodic potential (Refs. 1, 3, 7)  

2.3.3 Nuclear Properties  

3.0 Mechanical Properties  

3.1 Specified Mechanical Properties  

3.2 Mechanical Properties at Room Temperature  

3.2.1 Tension Stress-Strain Diagrams and Tension Properties  
While the 0.2% yield strength of Ferrium S53 is lower than that of other ultra high-strength alloys due to instability of retained austenite, note that the measured plastic strain between the proportional limit and 0.2% offset strain is not by “slip mechanism” in the traditional sense; the strain reflects the volume expansion of transformation from austenite to martensite. The effect is more pronounced in uniaxial tension compared to uniaxial compression tests and does not exhibit an adverse effect on fatigue cyclic life. (Refs. 1, 3)  

3.2.1.1 [Figure] Stress-strain curves (Refs. 3, 5, 7)  

3.2.1.2 [Table] Typical room temperature mechanical properties compared with minimums for bar. (Refs. 3–5, 7)  

3.2.2 Compression Stress-Strain Diagrams and Compression Properties (see Table 3.2.1.2)  

3.2.3 Impact  

3.2.3.1 [Figure] Effect of sample thickness of Charpy V-notch impact energy (Ref. 3, 7)  

3.2.4 Bending.  

3.2.5 Torsion and shear (see Table 3.2.1.2).  

3.2.6 Bearing (see Table 3.2.1.2).  

3.2.7 Stress Concentration  
3.2.7.1 Notch Properties  

3.2.7.1.1 [Table] Notch tensile strength of 2150°F die forging in longitudinal orientation heat treated per: 1985°F, 1 hr, 10Bar He quench, -100°F, 1 hr, AW(RT), 934°F, 3 hr, 4Bar He quench, -100°F, 1 hr, AW(RT), 900°F, 12 hr, AC (Refs. 3, 7, 11)  

3.2.7.2 Fracture Toughness (see Table 3.2.1.2).  

3.2.8 Tempering response  

3.2.8.1 [Figure] Single-step temper response (Ref. 3)  

3.2.8.2 [Figure] Multi-step temper response (Ref. 3)
3.3 Mechanical Properties at Various Temperatures
3.3.1 Tension Stress-Strain Diagrams and Tension Properties
  3.3.1.1 Effects of Temperature on Tensile Properties
    3.3.1.1.1 Effect of temperature on the 0.2% yield stress of Ferrium S53 (Ref. 9)
    3.3.1.1.2 Effect of temperature on the ultimate tensile strength of Ferrium S53 (Ref. 9)
    3.3.1.2.1 Effect of temperature on modulus (Ref. 9)
    3.3.1.2.2 Typical stress-strain curves as a function of temperature (Ref. 9)
3.3.2 Compression Stress-Strain Diagrams and Compression Properties
3.3.3 Impact Properties
  3.3.3.1 Effect of temperature on Charpy V-notch impact energy for barstock (Refs. 3, 7)
  3.3.3.2 Effect of temperature on Charpy V-notch impact energy for die forging (Refs. 3, 7)
3.3.4 Bending
3.3.5 Torsion and Shear
3.3.6 Bearing
3.3.7 Stress Concentration
  3.3.7.1 Notch Properties
  3.3.7.2 Fracture Toughness
    3.3.7.2.1 Effects of temperature on fracture toughness (Ref. 7)
3.4 Creep and Creep Rupture Properties
3.4.1 Creep and Creep Rupture Curves
3.5 Fatigue Properties
  3.5.1 Conventional High-Cycle Fatigue
    3.5.1.1 Smooth bar axial fatigue according to ASTM E466 (Refs. 3, 5, 7)
    3.5.1.1.1 Smooth bar axial fatigue for barstock according to ASTM E466 (Refs. 3, 5, 7)
    3.5.1.2.1 Smooth bar axial fatigue for die forging according to ASTM E466 (Refs. 3, 5, 7)
  3.5.1.2 Notch fatigue according to ASTM E466 (Refs. 3, 5, 10)
    3.5.1.2.1 Notch Fatigue, Kt = 1.4, forged at 2050F (Refs. 5, 10)
    3.5.1.2.2 Notch fatigue, Kt = 2.0, forged at 2050F (Refs. 5, 10)
3.5.2 Conventional Low-Cycle Fatigue
  3.5.2.1 Unnotched Strain controlled fatigue (Refs. 3, 5, 7, 8)
3.5.3 Fatigue Crack Growth Rate
  3.5.3.1 Fatigue crack growth rate of Ferrium S53 (Refs. 3, 5, 7, 8)
3.5.4 Effect of Corrosion on Fatigue Life Cycle
  3.5.4.1 Effects of corrosion on fatigue life cycle (Refs. 3, 7)
3.6 Elastic Properties
  3.6.1 Poisson’s Ratio
  3.6.2 Modulus of Elasticity: 29.6 x 10^6 psi in tension; 30.7 x 10^6 psi in compression. (Refs. 3, 5)
  3.6.3 Modulus of Rigidity

4.0 Fabrication
4.1 Forming
  4.1.1 Ferrium S53 is typically forged in the temperature range of 1950 to 2150F. Material flow behavior is similar to that of other high alloy steels. (Ref. 3)
    4.1.1.1 Gleeble testing of mill annealed Ferrium S53 (Ref. 9)
    4.1.1.2 Effects of forging temperature on mechanical properties (Ref. 3, 7)
4.2 Machining and Grinding
  4.2.1 Ferrium S53 can be readily machined in the normalized and annealed condition. Hardening causes isotropic permanent growth of 0.003in/in. Material which has been fully hardened is also machinable and can be precision ground. The high temperature stability will reduce the vulnerability to induced microstructure change, from abusive grinding, i.e., “burn” damage during manufacturing. (Ref. 3)
4.3 Joining

4.3.1 Welding

Initial weld demonstration of Ferrium S53 plates, 0.4” thickness, was completed using the gas tungsten arc manual welding method and incorporating the use of a filler alloy of the same composition. No cracking or weld defects were detected. Results from this study indicate Ferrium S53 is readily weldable either with or without post-weld thermal bake. Tensile testing transverse to weld following the full heat treatment process revealed no debit in strength properties of the base and weldment. (Ref. 2)

4.3.2 Inertia and Friction Welding

The medium level of carbon, and the moderate strength of annealed condition and of the fresh formed martensitic condition would suggest applicability to these solid state joining processes.

4.4 Surface Treatment

4.4.1 While Ferrium S53 is corrosion resistant, protective coatings should be considered for the application environment. Commercially available specifications, platings of the defense industry, such as chromium, aluminum, nickel, cadmium and the chromium replacement WC-Co powder coating by HVOF thermal spray, are designed ready for S53. The conventional bake at 375F following electroplating removes the embrittling absorbed hydrogen. Recommended passivation techniques are covered by AMS 2700B. If prime and paint is the desired protection scheme, a grit blast (30–45 psig to minimize grit embedding) followed by a film application (spray) is recommended of “Boegel” AC-131 BB on a clean and prepared surface to ensure high adhesion between the intrinsic chrome oxide of steel surface and the primer coating. (Refs. 3, 7)

4.4.2 Nitriding has been demonstrated on Ferrium S53 and achieved a 67 Rockwell C hardness to a depth of 0.005”. (Ref. 2)
References


5. MMPDS-05 (anticipated release date of 2009).


9. QuesTek Innovations LLC unpublished data.


<table>
<thead>
<tr>
<th>Element</th>
<th>Weight Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min</td>
</tr>
<tr>
<td>C</td>
<td>0.19</td>
</tr>
<tr>
<td>Mn</td>
<td>0.10</td>
</tr>
<tr>
<td>Si</td>
<td>0.10</td>
</tr>
<tr>
<td>P</td>
<td>0.008</td>
</tr>
<tr>
<td>S</td>
<td>0.005</td>
</tr>
<tr>
<td>Cr</td>
<td>9.50</td>
</tr>
<tr>
<td>Ni</td>
<td>5.20</td>
</tr>
<tr>
<td>Co</td>
<td>13.50</td>
</tr>
<tr>
<td>Mo</td>
<td>1.80</td>
</tr>
<tr>
<td>W</td>
<td>0.80</td>
</tr>
<tr>
<td>Ti</td>
<td>0.015</td>
</tr>
<tr>
<td>Al</td>
<td>0.010</td>
</tr>
<tr>
<td>V</td>
<td>0.25</td>
</tr>
<tr>
<td>O</td>
<td>0.0020</td>
</tr>
<tr>
<td>N</td>
<td>0.0015</td>
</tr>
</tbody>
</table>

Table 4.1: Composition
Table 1.7.1 Forms and conditions (Refs. 2, 4)

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Form</th>
<th>Condition</th>
<th>Hardness (Max)</th>
<th>Hardness (Standard)</th>
<th>UTS, ksi (Max)</th>
<th>UTS, ksi (Typical)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMS 5922</td>
<td>Bars and Forgings</td>
<td>Normalized and</td>
<td>372 BHN</td>
<td>327 BHN</td>
<td>182</td>
<td>157.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Annealed</td>
<td>40 Rc</td>
<td>35.5 Rc</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 2.1.2.1 Continuous cooling transformation diagram (Ref. 3)
Figure 2.1.2.2: Phase diagram (Refs. 3, 6)
Table 2.1.2.4 The average prior austenite grain size of die forged components as a function of hot-fire temperature (Refs. 3, 7)

<table>
<thead>
<tr>
<th>A10 MLG Piston Die-Foring</th>
<th>Forging Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1975F (1079C)</td>
</tr>
<tr>
<td>ASTM Grain Size No.</td>
<td>7.5</td>
</tr>
</tbody>
</table>
Figure 2.1.3.1 Thermal conductivity of Ferrium S53 as a function of temperature (Refs. 5, 7)
Figure 2.1.4.1 Mean coefficient of thermal expansion from room temperature to temperature indicated (Refs. 5, 7)
Figure 2.1.5.1: Specific heat of Ferrium S53 as a function of temperature (Refs. 5, 7)
Figure 2.1.6.1 Thermal diffusivity of Ferrium S53 as a function of temperature (Ref. 9)
Figure 2.3.2.1 Stress corrosion cracking threshold $K_{Iscc}$ in 3.5% NaCl solution as a function of applied cathodic potential (Refs. 1, 3, 7)
Table 2.3.2.2 Stress corrosion cracking threshold \( K_{\text{SCC}} \) in 3.5%NaCl solution as a function of applied cathodic potential for various hot-fire temperatures of die forgings (Ref. [3, 7])

<table>
<thead>
<tr>
<th>Hot Fire Temperature</th>
<th>Heat Treatment</th>
<th>Air (ksi)</th>
<th>V vs. SCE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>-0.7</td>
<td>-0.85</td>
</tr>
<tr>
<td>2050F</td>
<td>1985F, 1hr, OQ, -100F, 1hr, AW(RT), 934F, 3 hr, WQ, -100F, 1 hr, AW(RT), 900F, 12 hr, AC</td>
<td>67</td>
<td>37.1</td>
</tr>
<tr>
<td>2050F</td>
<td>2012F, 1hr, OQ, -100F, 1hr, AW(RT), 941F, 3 hr, WQ, -100F, 1 hr, AW(RT), 918F, 12 hr, AC</td>
<td>68.3</td>
<td>--</td>
</tr>
<tr>
<td>2150F</td>
<td>1985F, 1hr, OQ, -100F, 1hr, AW(RT), 934F, 3 hr, WQ, -100F, 1 hr, AW(RT), 900F, 12 hr, AC</td>
<td>63.4</td>
<td>--</td>
</tr>
</tbody>
</table>
Figure 3.2.1.1 Stress-strain curves (Refs. 3, 5, 7)

Ferrum S53 Bar
Longitudinal and Transverse
1.750" dia x 8.000" long

Ramberg-Osgood
n=7.1
TYS 225ksi
<table>
<thead>
<tr>
<th></th>
<th>Typical (Ref. 7)</th>
<th>AMS Minimum (Ref. 5)</th>
<th>A basis</th>
<th>B basis</th>
<th>A basis</th>
<th>B basis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Longitudinal</td>
<td>Transverse</td>
<td>Longitudinal</td>
<td>Transverse</td>
<td>Longitudinal</td>
<td>Transverse</td>
</tr>
<tr>
<td>FTU ksi</td>
<td>288.3</td>
<td>288.6</td>
<td>280</td>
<td>280</td>
<td>284</td>
<td>280</td>
</tr>
<tr>
<td>FTY ksi</td>
<td>225.2</td>
<td>226</td>
<td>213</td>
<td>213</td>
<td>218</td>
<td>211</td>
</tr>
<tr>
<td>%elong</td>
<td>15</td>
<td>15</td>
<td>11</td>
<td>11</td>
<td>--</td>
<td>11</td>
</tr>
<tr>
<td>%RA</td>
<td>57</td>
<td>55</td>
<td>44</td>
<td>44</td>
<td>--</td>
<td>44</td>
</tr>
<tr>
<td>FCY ksi</td>
<td>257.9</td>
<td>264.7</td>
<td>n/a</td>
<td>n/a</td>
<td>245</td>
<td>250</td>
</tr>
<tr>
<td>KIC ksi*in*0.5</td>
<td>66.3</td>
<td>63.0</td>
<td>50</td>
<td>50</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>BUS (e/D=1.5) ksi</td>
<td>451.9</td>
<td>450.9</td>
<td>n/a</td>
<td>n/a</td>
<td>440</td>
<td>446</td>
</tr>
<tr>
<td>BYS (e/D=1.5) ksi</td>
<td>370.6</td>
<td>369.3</td>
<td>n/a</td>
<td>n/a</td>
<td>351</td>
<td>359</td>
</tr>
<tr>
<td>BUS (e/D=2.0) ksi</td>
<td>587.1</td>
<td>590.5</td>
<td>n/a</td>
<td>n/a</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>BYS (e/D=2.0) ksi</td>
<td>445.7</td>
<td>458.0</td>
<td>n/a</td>
<td>n/a</td>
<td>417</td>
<td>426</td>
</tr>
<tr>
<td>FSU ksi</td>
<td>180.9</td>
<td>181.2</td>
<td>n/a</td>
<td>n/a</td>
<td>176</td>
<td>178</td>
</tr>
</tbody>
</table>

Table 3.2.1.2: Typical room temperature mechanical properties compared with minimums for bar (Refs. 3–5, 7)
Figure 3.2.2.1 Stress-strain curves (Refs. 3, 5, 7, 8)
Figure 3.2.3.1  Effect of sample thickness of Charpy V-notch impact energy (Refs. 3, 7)

Tested in T-L @ RT0

Impact Energy (ft-lb)

Thickness (in)
Table 3.2.7.1.1 Notch tensile strength of 2150F die forging in longitudinal orientation heat treated per: 1985F, 1hr, 10Bar He quench, -100F, 1 hr, AW(RT), 934F, 3 hr, 4Bar He quench, -100F, 1 hr, AW(RT), 900F, 12 hr, AC (Refs [3, 7, 11])

<table>
<thead>
<tr>
<th>Specimen Pedigree*</th>
<th>Notch Tensile Strength (ksi)</th>
<th>200 hr sustained load at 75% notch tensile strength per ASTM F519</th>
</tr>
</thead>
<tbody>
<tr>
<td>baseline</td>
<td>421.4</td>
<td>--</td>
</tr>
<tr>
<td>stress relief of 515F, 4 hr, AC; Ni-plated (Sulfamate process) 0.004&quot; thick; bake of 375F, 23 hr, AC</td>
<td>411.9</td>
<td>passed</td>
</tr>
<tr>
<td>stress relief of 515F, 4 hr, AC; Ni-strike plated (&lt;0.0001&quot;) + Cd plated 0.0005&quot; thick</td>
<td>398.3</td>
<td>passed</td>
</tr>
<tr>
<td>stress relief of 515F, 4 hr, AC; Activated in HF+H2SO4 acid solution; Cr-plated 0.004&quot; thick; bake of 375F, 23 hr, AC</td>
<td>385.3</td>
<td>No 200 hr test for this specimen</td>
</tr>
<tr>
<td>stress relief of 515F, 4 hr, AC; Activated in HF+H2SO4 acid solution; Cr-plated 0.004&quot; thick; bake of 375F, 23 hr, AC</td>
<td>401.5</td>
<td>passed</td>
</tr>
<tr>
<td>stress relief of 515F, 4 hr, AC; Activated in chromic acid solution; Cr-plated 0.004&quot; thick; bake of 375F, 23 hr, AC</td>
<td>399.1</td>
<td>passed</td>
</tr>
<tr>
<td>stress relief of 515F, 4 hr, AC; Activated in chromic acid solution; Cr-plated 0.004&quot; thick; No bake after plating</td>
<td>254.1</td>
<td>No 200 hr test for this specimen</td>
</tr>
</tbody>
</table>

*Grit blasted at 30-45 psig Alumina prior to acid activaton; $K_t=3.1$
Figure 3.2.8.1 Single-step temper response (Ref. 3)
Figure 3.2.8.2 Multi-step temper response (Ref. 3)
Figure 3.3.1.2.1 Effect of temperature on the 0.2% yield stress of Ferrium S53 (Ref. 9)
Figure 3.3.1.2.2 Effect of temperature on the ultimate tensile strength of Ferrium S53 (Ref. 9)
Figure 3.3.1.2.3 Effect of temperature on modulus (Ref. 9)
Figure 3.3.1.2.4 Typical stress-strain curves as a function of temperature (Ref. 9)
Figure 3.3.3.1: Effect of temperature on Charpy V-notch impact energy for barstock (Refs. 3, 7)
Figure 3.3.3.2: Effect of temperature on Charpy V-notch impact energy for die forging (Refs. 3, 7)
Figure 3.3.7.2.1  Effects of temperature on fracture toughness (Ref. 7)

Ferrium S53 8-inch Bar
1985F, 1 hr, OQ, -100F, 1 hr, AW(RT), 934F, 3 hr, WQ,
-100F, AW(RT), 900F, 12 hr, AC

-65 and 0F are average of 2 samples;
75F is a single data point
Figure 3.5.1.1 Smooth bar axial fatigue for barstock according to ASTM E466 (Refs. 3, 5, 7)
Figure 3.5.1.1.2 Smooth bar axial fatigue for die forging according to ASTM E466 (Refs. 3, 5, 7)
Figure 3.5.1.2.1 Notch Fatigue, $K_t = 1.4$, forged at 2050°F (Refs. 5, 10)
Figure 3.5.1.2.2 Notch fatigue, $K_t = 2.0$, forged at 2050°F (Refs. 5, 10)

Ferrium S53 die-forging
Notch Fatigue (ASTM E466) $K_t = 2.0$
1985°F, 70min, 10bar He quench + -100°F, 1hr, AW(RT) + 934°F, 3hr, 4bar He quench + -100°F, 1hr, AW(RT) + 900°F, 12hr, AC

$\bullet$ $R = 0.33$
$\triangle$ $R = -0.33$
$\square$ $R = -1$

$\square$ = Longitudinal
$\square$ = Transverse

$S_{st}$ (ksi)

Cycles to Failure

$1.0 \times 10^3$ $1.0 \times 10^4$ $1.0 \times 10^5$ $1.0 \times 10^6$ $1.0 \times 10^7$ $1.0 \times 10^8$
Figure 3.5.1.2.3 Notch Fatigue, $K_t = 3.24$, longitudinal barstock vs. 2050F die-forging (Refs. 3, 5, 10)
Figure 3.5.1.2.4 Notch fatigue, $K_t = 3.24$ for transverse barstock (Refs. 3, 5, 10)
Figure 3.5.1.2.5 Notch fatigue, $K_t = 5.0$ for longitudinal 2050F die forging (Refs. 5, 10)
Figure 3.5.1.3 Effects of peening on rotating-bending fatigue as a function of maximum cycle stress (Refs. 3, 7)
Figure 3.5.2.1 Unnotched Strain controlled fatigue
(Refs. 3, 5, 7, 8)
Figure 3.5.3.1 Fatigue crack growth rate of Ferrium S53
(Refs. 3, 5, 7, 8)
Figure 3.5.4.1 Effects of corrosion on fatigue life cycle (Refs. 3, 7)
Figure 4.1.1: Gleeble testing of mill annealed Ferrium S53 (Ref. 9)
Table 4.1.1.2-A Typical effect of hot fire temperature (preheat) for 5" diameter die forging from 8" RCS barstock on mechanical properties (Refs. 3, 7)

<table>
<thead>
<tr>
<th>Mechanical Property</th>
<th>Forging</th>
<th>Forging</th>
<th>1975°F</th>
<th>2050°F</th>
<th>2050°F</th>
<th>2050°F</th>
<th>2150°F</th>
<th>2150°F</th>
<th>2150°F</th>
<th>2150°F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stock: 8&quot; RCS; HT per (a)</td>
<td>Stock: 8&quot; RCS; HT per (d)</td>
<td>Preheat (prototype) HT per (a)</td>
<td>Preheat (prolongation) HT per (a)</td>
<td>Preheat (Piston zone) HT per (a)</td>
<td>Preheat (Piston zone) HT per (a)</td>
<td>Preheat (All of forging) HT per (b)</td>
<td>Preheat (Piston zone) HT per (b)</td>
<td>Preheat (Piston zone) HT per (c)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T (ksi)</td>
<td>-</td>
<td>-</td>
<td>284 (282-285)</td>
<td>286 (282-286)</td>
<td>-</td>
<td>284 (282 &amp; 285)</td>
<td>288 (286-289)</td>
<td>293 (293 &amp; 293)</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>L (ksi)</td>
<td>231 (230 &amp; 232)</td>
<td>234 (234 &amp; 234)</td>
<td>233 (229 &amp; 234)</td>
<td>233 (227-237)</td>
<td>234 (231-235)</td>
<td>235 (234 &amp; 236)</td>
<td>231</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T (ksi)</td>
<td>-</td>
<td>-</td>
<td>230 (229-230)</td>
<td>231 (231)</td>
<td>-</td>
<td>232 (232)</td>
<td>234 (233-235)</td>
<td>237 (237 &amp; 237)</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Elongation (1 in) L (%)</td>
<td>16 (16 &amp; 16)</td>
<td>16 (17-17)</td>
<td>-</td>
<td>-</td>
<td>16</td>
<td>16 (15-17)</td>
<td>-</td>
<td>15 (15-16)</td>
<td>14 (14 &amp; 14)</td>
<td>14</td>
</tr>
<tr>
<td>T (%)</td>
<td>-</td>
<td>-</td>
<td>15 (14-15)</td>
<td>15 (15)</td>
<td>-</td>
<td>15 (14-15)</td>
<td>15 (14-16)</td>
<td>14 (14 &amp; 14)</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Reduction-in-Area L (%)</td>
<td>59 (58 &amp; 61)</td>
<td>57 (55 &amp; 60)</td>
<td>-</td>
<td>-</td>
<td>59</td>
<td>63 (60-65)</td>
<td>-</td>
<td>55 (54-57)</td>
<td>57 (56 &amp; 58)</td>
<td>53</td>
</tr>
<tr>
<td>T (%)</td>
<td>-</td>
<td>-</td>
<td>58 (56-60)</td>
<td>62 (61-62)</td>
<td>-</td>
<td>61 (60-61)</td>
<td>52 (48-56)</td>
<td>56 (55 &amp; 57)</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

Notch-Tensile Strength L (ksi) | - | - | - | - | 430 (425-438) | - | 421 (408-430) | - |
| T (ksi) | - | - | - | - | - | - | - | - |

Charpy V-Notch (ft-lb) L-T (L-R for cyl.) 21 (21 & 22) | 16 (15 & 17) | - | - | 18 (18 & 18) | 15 (13-18) | - | 9 (7-10) | - |
| T-L (R-L for cyl.) | - | - | 21 (18-22) | 20 (18-22) | - | - | 17 (12-21) | 8 (7-10) | - | 10 (8-11) |
| T-T (R-R for cyl.) | - | - | - | - | - | - | 8 (8) | - |

Fracture Toughness (ksi/in) L-T (L-R for cyl.) 69 (65-72) | 59 (58-61) | - | - | 70 (64-75) | 65 (56-74) | - | 61 (58-64) | - | 63 (62-65) |
| T-L (R-L for cyl.) | - | - | 75 | - | - | - | 61 (61-82) | - |
| T-T (R-R for cyl.) | - | - | - | - | - | - | 62 (62) | - |

Hardness: Rockwell C HT run - Lot A 53.2 (52.9-53.4) | 53.9 (53.8-54.0) | 54.7 (54.3-54.8) | 55.0 (54.8-55.1) | 53.4 (53.2-53.6) | 54.8 (54.0-56.0) | 54.8 (54.8) | 54.5 (54.3-54.9) | N/A | 55 (54.5-55.4) |
| HT run - Lot C | - | - | - | - | - | - | 55 (54.7-56.3) | - |
| HT run - Lot D | - | - | - | - | - | - | 54.9 (54.4-55.4) | - |

Hardening heat treatment temperature cycles, °F: "SHT/Age 1/Age 2" (Cryo cooling after SHT and Age 1 for all)
(a) 2012°F, 70 min, OQ, -100°F, 1 hr, AW(RT), 941°F, 3 hr, WQ, -100°F, 1 hr, AW(RT), 918°F, 12 hr, AC
(b) 1985°F, 1 hr, 10Bar He quench, -100°F, 1 hr, AW(RT), 934°F, 3 hr, 4Bar He quench, -100°F, 1 hr, AW(RT), 905°F, 12 hr, AC
(c) 2012°F, 70 min, OQ, -100°F, 1 hr, AW(RT), 943°F, 3 hr, WQ, -100°F, 1 hr, AW(RT), 900°F, 12 hr, AC
(d) 1985°F, 70 min, OQ, -100°F, 1 hr, AW(RT), 934°F, 3 hr, WQ, -100°F, 1 hr, AW(RT), 900°F, 12 hr, AC
## Table 4.1.1.2-B

Typical effect of hot fire temperature (preheat) for 5" diameter die forging from 8" RCS barstock on mechanical properties (Refs. 3, 7)

<table>
<thead>
<tr>
<th>Product</th>
<th>Location</th>
<th>Heat Treatment</th>
<th>Flu (ksi)</th>
<th>Fly (ksi)</th>
<th>% Elongation</th>
<th>% Reduction-in-Area</th>
<th>Notch Tensile (ksi)</th>
<th>CVN (ft-lbs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8&quot; RCS Barstock</td>
<td>0.5R</td>
<td>2012F, 70 min, OQ, -100F, 1 hr, AW(RT), 941F, 3 hr, WQ, -100F, 1 hr, AW(RT), 918F, 12 hr, AC</td>
<td>285</td>
<td>231</td>
<td>15</td>
<td>59</td>
<td>-</td>
<td>21</td>
</tr>
<tr>
<td>8&quot; RCS Barstock</td>
<td>0.5R</td>
<td>2012F, 70 min, OQ, -100F, 1 hr, AW(RT), 941F, 3 hr, WQ, -100F, 1 hr, AW(RT), 918F, 12 hr, AC</td>
<td>292</td>
<td>234</td>
<td>15</td>
<td>57</td>
<td>-</td>
<td>16</td>
</tr>
<tr>
<td>1975F Die forging piston</td>
<td>2012F</td>
<td>70 min, OQ, -100F, 1 hr, AW(RT), 941F, 3 hr, WQ, -100F, 1 hr, AW(RT), 918F, 12 hr, AC</td>
<td>-</td>
<td>284</td>
<td>230</td>
<td>15</td>
<td>-</td>
<td>21</td>
</tr>
<tr>
<td>2050F Die forging piston</td>
<td>1985F</td>
<td>70 min, OQ, -100F, 1 hr, AW(RT), 941F, 3 hr, WQ, -100F, 1 hr, AW(RT), 918F, 12 hr, AC</td>
<td>286</td>
<td>231</td>
<td>15</td>
<td>59</td>
<td>-</td>
<td>18</td>
</tr>
<tr>
<td>2150F Die forging piston</td>
<td>2012F</td>
<td>70 min, OQ, -100F, 1 hr, AW(RT), 941F, 3 hr, WQ, -100F, 1 hr, AW(RT), 918F, 12 hr, AC</td>
<td>292</td>
<td>233</td>
<td>15</td>
<td>63</td>
<td>430</td>
<td>15</td>
</tr>
<tr>
<td>2150F Die forging piston</td>
<td>1985F</td>
<td>1 hr, 10Bar He quench, -100F, 1 hr, AW(RT), 934F, 3 hr, 4Bar He quench, -100F, 1 hr, AW(RT), 905F, 12 hr, AC</td>
<td>291</td>
<td>231</td>
<td>15</td>
<td>53</td>
<td>-</td>
<td>10</td>
</tr>
<tr>
<td>2150F Die forging piston</td>
<td>2012F</td>
<td>70 min, OQ, -100F, 1 hr, AW(RT), 941F, 3 hr, WQ, -100F, 1 hr, AW(RT), 918F, 12 hr, AC</td>
<td>-</td>
<td>286</td>
<td>231</td>
<td>15</td>
<td>-</td>
<td>20</td>
</tr>
<tr>
<td>2150F Die forging piston</td>
<td>1985F</td>
<td>1 hr, 10Bar He quench, -100F, 1 hr, AW(RT), 934F, 3 hr, 4Bar He quench, -100F, 1 hr, AW(RT), 905F, 12 hr, AC</td>
<td>-</td>
<td>284</td>
<td>232</td>
<td>15</td>
<td>-</td>
<td>17</td>
</tr>
<tr>
<td>2150F Die forging all of forging</td>
<td>1985F</td>
<td>1 hr, 10Bar He quench, -100F, 1 hr, AW(RT), 934F, 3 hr, 4Bar He quench, -100F, 1 hr, AW(RT), 905F, 12 hr, AC</td>
<td>288</td>
<td>233</td>
<td>15</td>
<td>55</td>
<td>52</td>
<td>421</td>
</tr>
</tbody>
</table>

Table: 4.1.1.2-B:  Typical effect of hot fire temperature (preheat) for 5" diameter die forging from 8" RCS barstock on mechanical properties (Refs. 3, 7)