DUPLEX
Stainless Steel

STI SPFA
May 15, 2008

John Grocki
What are Duplex Stainless Steels?

- A family of stainless steels whose:
- structures are approximately 50/50 austenite and ferrite
- physical properties are a combination of the ferritic and the austenitic grades
Chemistry of Duplex SS

<table>
<thead>
<tr>
<th>Name</th>
<th>UNS No.</th>
<th>C</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>N</th>
<th>Other</th>
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</thead>
<tbody>
<tr>
<td>201LN</td>
<td>S20153</td>
<td>.03</td>
<td>17</td>
<td>4.5</td>
<td>-</td>
<td>.20</td>
<td>Mn=7</td>
</tr>
<tr>
<td>2101</td>
<td>S32101</td>
<td>.04</td>
<td>21</td>
<td>1.5</td>
<td>0.5</td>
<td>.22</td>
<td>Mn=5</td>
</tr>
<tr>
<td>2202</td>
<td>S32202</td>
<td>.03</td>
<td>22</td>
<td>2</td>
<td>0.5</td>
<td>.22</td>
<td></td>
</tr>
<tr>
<td>2304</td>
<td>S32304</td>
<td>.03</td>
<td>23</td>
<td>4</td>
<td>0.5</td>
<td>.12</td>
<td></td>
</tr>
<tr>
<td>2003</td>
<td>S32003</td>
<td>.03</td>
<td>20</td>
<td>3.5</td>
<td>1.7</td>
<td>.16</td>
<td></td>
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<tr>
<td>2205</td>
<td>S31803</td>
<td>.03</td>
<td>21.8</td>
<td>5</td>
<td>2.8</td>
<td>.12</td>
<td></td>
</tr>
<tr>
<td>2205</td>
<td>S32205</td>
<td>.03</td>
<td>22.5</td>
<td>5</td>
<td>3.2</td>
<td>.16</td>
<td></td>
</tr>
<tr>
<td>2507</td>
<td>S32750</td>
<td>.03</td>
<td>25</td>
<td>7</td>
<td>4.0</td>
<td>.28</td>
<td>Cu=.5</td>
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<tr>
<td>255</td>
<td>S32550</td>
<td>.03</td>
<td>25.5</td>
<td>5.5</td>
<td>3.4</td>
<td>.20</td>
<td>Cu=2.0</td>
</tr>
</tbody>
</table>
General Corrosion

- Similar to relative austenitic alloys. (2202 and 2304 are similar to 304 & 316)
- General corrosion resistance can vary greatly with changes in concentration, pH, temperature and impurities. It is important to discuss these variables for any application!
# Duplex vs. Austenitic

<table>
<thead>
<tr>
<th>Duplex Grades</th>
<th>Austenitic Grades</th>
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</thead>
<tbody>
<tr>
<td><strong>2202 /2101</strong></td>
<td>304L</td>
</tr>
<tr>
<td><strong>2304</strong></td>
<td>316L</td>
</tr>
<tr>
<td><strong>2003</strong></td>
<td>317L</td>
</tr>
<tr>
<td><strong>2205</strong></td>
<td>317LMN</td>
</tr>
<tr>
<td><strong>255 / 2507</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>904L</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6Mo Grades</td>
</tr>
</tbody>
</table>

*(increased resistance)*
Localized Corrosion

- \{ \text{PREN} = \text{Cr} + 3.3\text{Mo} + 16\text{N} \}

<table>
<thead>
<tr>
<th>Grade</th>
<th>PREN</th>
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<tbody>
<tr>
<td>201LN</td>
<td>18</td>
</tr>
<tr>
<td>304L</td>
<td>19</td>
</tr>
<tr>
<td>316L</td>
<td>24</td>
</tr>
<tr>
<td>\textbf{2202/2101/2304}</td>
<td>\textbf{26}</td>
</tr>
<tr>
<td>317L</td>
<td>30</td>
</tr>
<tr>
<td>2003</td>
<td>30</td>
</tr>
<tr>
<td>317LMN</td>
<td>33</td>
</tr>
<tr>
<td>\textbf{2205(S32205)}</td>
<td>\textbf{35}</td>
</tr>
<tr>
<td>904L</td>
<td>35</td>
</tr>
<tr>
<td>255</td>
<td>42</td>
</tr>
<tr>
<td>2507</td>
<td>43</td>
</tr>
<tr>
<td>\textbf{6Mo Grades}</td>
<td>\textbf{45}</td>
</tr>
</tbody>
</table>
CRITICAL PITTING TEMPERATURE
IN CHLORIDE CONTAINING SOLUTIONS (E:+300mV/SCE)

CPT (°C)

NaCl (M)

304L
316L and 2304
2205
THRESHOLD CHLORIDE vs TEMPERATURE FOR WHICH PITTING DOES NOT OCCUR

Temperature, °C / °F

0 / 32
25 / 77
50 / 122
75 / 167
100 / 212

0.01
0.1
1
100
1000
10000

Cl⁻, % weight ppm

304 L
316 L
S 32304
S31803
Chloride Stress Corrosion Cracking

- The greatest advantage for duplex stainless steels is their improved resistance to CSCC when compared to the austenitic grades.

- Only the 25% Nickel grades have similar CSCC resistance.
STRESS CORROSION CRACKING RESISTANCE vs TEMPERATURE and Cl-

Temperature, °C (°F)

300 (570)
200 (390)
100 (210)
0 (32)

Cl- (% weight)

0.001 0.1 10

No SCC

SCC

304/316L

S31803
S31500
S32304

No SCC for 25Cr Super-Duplex

STRESS CORROSION CRACKING RESISTANCE vs TEMPERATURE and Cl-

No SCC

SCC

304/316L

S31803
S31500
S32304

No SCC for 25Cr Super-Duplex

STRESS CORROSION CRACKING RESISTANCE vs TEMPERATURE and Cl-

No SCC

SCC

304/316L

S31803
S31500
S32304

No SCC for 25Cr Super-Duplex

STRESS CORROSION CRACKING RESISTANCE vs TEMPERATURE and Cl-

No SCC

SCC

304/316L

S31803
S31500
S32304

No SCC for 25Cr Super-Duplex
Mechanical Properties

• Duplex Stainless Steels have roughly twice the yield strength of their counterpart austenitic grades.

• This allows equipment designers to use thinner gauge material for vessel construction!
## Room Temperature Strength

<table>
<thead>
<tr>
<th>Grade</th>
<th>Min Tensile (KSI)</th>
<th>Min Yield (KSI)</th>
<th>%Elong.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2101</td>
<td>95</td>
<td>65</td>
<td>30</td>
</tr>
<tr>
<td>2202</td>
<td>94</td>
<td>65</td>
<td>30</td>
</tr>
<tr>
<td>2304</td>
<td>87</td>
<td>58</td>
<td>25</td>
</tr>
<tr>
<td>2003</td>
<td>90</td>
<td>65</td>
<td>25</td>
</tr>
<tr>
<td>2205</td>
<td>95</td>
<td>65</td>
<td>25</td>
</tr>
<tr>
<td>2507</td>
<td>116</td>
<td>80</td>
<td>15</td>
</tr>
<tr>
<td>255</td>
<td>110</td>
<td>80</td>
<td>15</td>
</tr>
<tr>
<td>201LN</td>
<td>95</td>
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</tr>
<tr>
<td>304</td>
<td>70</td>
<td>25</td>
<td>40</td>
</tr>
<tr>
<td>316L</td>
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<td>25</td>
<td>40</td>
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<tr>
<td>317LMN</td>
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<td>35</td>
<td>40</td>
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<td>6Mo</td>
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<tr>
<td>Grade</td>
<td>@100F</td>
<td>200F</td>
<td>300F</td>
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<td>------</td>
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<tr>
<td>2304</td>
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<tr>
<td>6Mo</td>
<td>24.9</td>
<td>23.2</td>
<td>21.3</td>
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</table>
Hardness

- High hardness provides better wear resistance in abrasive environments.

<table>
<thead>
<tr>
<th>Grade</th>
<th>Hardness (BHN)</th>
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<tbody>
<tr>
<td>201LN</td>
<td>241</td>
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<tr>
<td>304L</td>
<td>215</td>
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<tr>
<td>316L</td>
<td>217</td>
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<tr>
<td>317L</td>
<td>217</td>
</tr>
<tr>
<td>317LMN</td>
<td>223</td>
</tr>
<tr>
<td>904L</td>
<td>220</td>
</tr>
<tr>
<td>6Mo</td>
<td>240</td>
</tr>
<tr>
<td>2202/2101</td>
<td>290</td>
</tr>
<tr>
<td>2304</td>
<td>290</td>
</tr>
<tr>
<td>2003/2205</td>
<td>293</td>
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<tr>
<td>255</td>
<td>302</td>
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<td>2507</td>
<td>310</td>
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<td>Grade</td>
<td>@212°F</td>
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<td>----------</td>
<td>--------</td>
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<tr>
<td>C- Steel</td>
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<td>2202</td>
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<td>2205</td>
<td>7.22</td>
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<td>6.72</td>
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<tr>
<td>304L</td>
<td>9.10</td>
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</table>
Heat Transfer

• Provides a 5% advantage compared to austenitic grades.

• This advantage is increased when design strength is used to decrease wall thickness!
Fatigue Strength

• Higher strength means higher cyclic-stresses can be applied without fatigue failures.

• This holds true even in corrosion fatigue environments!
Fatigue and fatigue corrosion resistance of stainless steels are enhanced by the use of duplex grades (higher mechanical properties, chromium content and duplex microstructure).

Synthetic sea-water rotating beam bending of smooth samples

**MPa**

- **Cycle to rupture**
- **KSI**

- 31803
- 32304
- 317 LN
- 316L 2.5 Mo
- 316L
Fracture Toughness

• Due to the high ferrite content the Duplex SS have a ductile – brittle transition temperature of -50°F.

• This restricts the minimum operating temperature to -50°F.

• In certain circumstances the Duplex SS may be used down to -100°F.
Possible precipitations in super duplex stainless steels
2304 ~8 hours for significant sigma vs. 2205 ~1 hour
Fabrication
Cutting

• Duplex SS may be cut by any of the standard methods.

• Sawing will be more difficult than carbon steel!

• Shearing is limited to thinner thickness when compared to 304L/316L. Maximum 85% for 2202/2304/2205 and 65% for 2507/255.

• Plasma and laser cutting can be done using parameters similar to 304L/316L.
Machining

• Machining will require higher cutting forces than 304L/316L.

• 2304 can be machined at higher rates than 304L/316L with similar tool wear.

• The degree of machining difficulty increases with the more highly alloyed grades as does tool wear.

.
Hot Forming

• The temperature for hot forming must be well controlled.
• 1750 to 2050°F for 2202/2304/2205.
• 1875 to 2175º for 2507/255.
• Too low a temperature will result in cracking of the ferrite phase!
• Too high a temperature will result in hot tearing of the ferrite phase!
• Parts must be annealed after forming.
Cold Forming

- Duplex SS can be formed to the same shapes as the austenitic grades.
- Additional equipment strength is required due to the higher strength of the Duplex SS.
- Springback is greater with the Duplex SS requiring greater over bending than the austenitic grades.
- Cold work will harden the Duplex SS requiring intermediate and/or final annealing depending on the amount of cross section reduction.
Bending Compared to Austenitics

- Bending radii should be more generous than for austenitic grades (3T or greater).
- When compared to a thickness of 304L/316L, Duplex SS maximum forming thickness are: $2304 = 65\%$, $2202/2205 = 50\%$ and $2507/255 = 40\%$
- Springback will require over bending to $115^\circ$ to achieve a $90^\circ$ compared to $98^\circ$ for 304L/316L
Annealing Requirements

- Final anneal is required if cold working exceeds 10 – 15%.
- For cold working exceeding 15% an intermediate anneal is required.
Welding

• Welding procedures must be developed to achieve acceptable corrosion resistance and mechanical properties/toughness in the weld zone.

• Welding of Duplex SS is not difficult. It is just different!

• 2304 is welder friendly!
WHAT ABOUT WELDED STRUCTURES?

WE NEED

- CORROSION RESISTANCE
- TOUGHNESS AT LOW TEMPERATURE

CONTROL OF FERRITE
  in HAZ < 70%
  in welds 20-40% SAW, SMAW
  25-60% TIG, MIG, PLASMA

CONTROL OF OXYGEN CONTENT
  SAW with appropriate flux basicity

CONTROL OF HYDROGEN CONTENT
  Degasing of welding consummables...
  No hydrogen in shielding gas

CONTROL OF NITROGEN LEVEL

CONTROL OF THERMAL CYCLE
  Heat input adapted to plate thickness/weld geometry
WHAT ABOUT WELDED STRUCTURES?

WE NEED

- CORROSION RESISTANCE

- TOUGHNESS AT LOW TEMPERATURE

CONTROL OF FERRITE
Not required for 2304 when using fully austenitic 309L filler metal

CONTROL OF OXYGEN CONTENT
SAW with appropriate flux basicity

CONTROL OF HYDROGEN CONTENT
Degasing of welding consummables...
No hydrogen in shielding gas

CONTROL OF NITROGEN LEVEL
Not required for 2304 when using 309L filler metal

CONTROL OF THERMAL CYCLE
Thermal stability minimizes potential for sigma phase from slow cooling
# Standard Specifications

<table>
<thead>
<tr>
<th>Grade</th>
<th>ASTM</th>
<th>ASME</th>
<th>(Sect VIII Div I)</th>
</tr>
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<tbody>
<tr>
<td>201LN</td>
<td>A240</td>
<td>A240</td>
<td></td>
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<tr>
<td>2202</td>
<td>A240</td>
<td></td>
<td>in 2008</td>
</tr>
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<td>2304</td>
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<td>2101/2003</td>
<td>A240</td>
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<td>Code Case</td>
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<tr>
<td>2205(S31803)</td>
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<td>2205(S32205)</td>
<td>A240</td>
<td>--</td>
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<tr>
<td>255</td>
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<td>SA240</td>
<td>yes</td>
</tr>
<tr>
<td>2507</td>
<td>A240</td>
<td>SA789/790</td>
<td>tube/pipe</td>
</tr>
</tbody>
</table>
ASTM A923

• Tests used to verify acceptable thermal history of Duplex SS (no sigma phase).
• Normally used to qualify plate mill product.
• May be used to qualify weld procedures.
• Requires G48 CPT corrosion test.
• Requires -40°F charpy test
• Pass/Fail requirements are given for 2205 material only. Requirements for other materials must be agreed upon.
Cost Comparison

Cost ratio based on 304L=1.0 (pattern mill plate)

Duplex
• 22022101 = 0.73
• 2304 = 0.93

Austenitic
• 201LN = .70
• 304L = 1.00

• 2003 =
• 2205 = 1.28

• 316L = 1.39
• 317L = 1.81

• 255 = 1.83
• 2507 = 2.04

• 317LMN = 2.21
• 904L = 2.90
• 6Mo = 4.00
Cost Advantage

- If a vessel design uses the Duplex SS’s additional strength to decrease wall thickness savings of up to 25% may be achieved for the fabrication vs. a comparable austenitic grade.
- Machining cost savings may be considerable.
- Physical property advantages must be evaluated for process and fabrication cost savings.
If you save weight (wall thickness reductions):

- You reduce the amount of material needed for the project
- You reduce the labor costs (weldings of thinner plates)
- You reduce transportation costs
- You reduce erection costs
- You reduce structural costs (concrete…)

THINK ABOUT TOTAL COSTS
Some Duplex SS Precautions

• Thermal history control, to reduce the risk of forming secondary phases (sigma and alpha prime), is minimized for 2202 and 2304.

• Good procedures must be developed for welding, forming, machining and heat treatment. Duplex SS are not difficult to work with but they are different! And 2202 and 2304 are the easiest!

• Duplex SS must be used for applications which operate between -50°F and +600°F.
What DUPLEX Means!

• A family of excellent engineering materials!
• A family of excellent cost effective materials!

• Comparable to austenitics in corrosion resistance – with improved CSCC.
• Twice the strength of austenitics.
• Advantageous physical properties.
• Covered by standard and end user specifications.
• Advantages with both material cost and engineered fabrication cost.
Thank you for Your Attention
... You really deserve a DRINK now!

LETS HAVE ONE MORE
AND THEN WELLL GO!!