Selection and Evaluation of Stainless Steel
## Type 304L and 316L Stainless Steel

<table>
<thead>
<tr>
<th>Grade</th>
<th>C</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
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</tr>
</thead>
<tbody>
<tr>
<td>304L</td>
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<td>2.0</td>
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</tr>
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</table>

Based on the ASTM A 24 requirements
Stainless Steel Production

• High cost of raw materials
  – Producers always want to reduce inventory costs
  – Reluctant to produce a new grade or variation of and existing grade

• Energy intensive process
  – Producers rely on economy of scale (large production facilities run at capacity)
Stainless Steel Production

Scrape and alloy additions are melted in an electric arc furnace
Stainless Steel Production

Molten metal is transferred to an AOD for subsequent processing
Stainless Steel Production

Typical AOD holds about 120 tons of stainless steel
Stainless Steel Production

After casting slabs are cut for processing into plate or coil product. Each slab weighs about 8 - 12 tons.
Important Process Parameters

- Typical size of an AOD heat $\approx 120$ tons (240,000 lbs)
- Typical slab $\approx 8 - 12$ tons
- An average sized mill will produce about 500,000 tons stainless steel per year
Who are the Larger Customers for Stainless Steel?

• Distributors
  – In North America about 60 - 70% of all stainless steel is sold through distributors
    • Distributor are very price sensitive and demand lowest possible price

• Large projects often purchase “mill direct”
  • Constrains on minimum size of an order and plate sizes
  • Typical mill order - 200 tons and up
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Based on the ASTM A 240 requirements
Special Order – Enhanced 304L or 316L Compositions for High Purity Applications

Is it practical?
Cost of “Special” 316L Composition
Example - Increase Mo% by 0.4%

- At the current price of Mo ($17.80/lb) the cost = $0.071 per pound of 316L or $17,088 per 120 ton heat

- The 0.4% increase in Mo will require an increase in Ni of approximately 0.5% to maintain the equivalent ferrite content
Cost of “Special” 316L Composition
Example - Increase Mo% by 0.4%

- At the current price of Ni ($10.50/lb) cost = $0.052 per lb of 316L or $12,600 per 120 ton heat

- Total cost of the modification - $29,688 per 120 ton heat
Example
Cost of “Special” 316L Composition

– For most applications it is more practical to select a higher grade of stainless steel such as 2205 duplex stainless steel
– Advantages of moving to a higher alloyed grade
  • Possible Lower costs
  • Higher strength
  • Better corrosion resistance
  • Shorter lead times
Special Processing

• Users often consider special processing requirements to enhance properties
  – Electroslag Remelting (ESR)
  – Vacuum Arc Remelting (VAR)
Remelting

VAR

ESR
Electroslag Remelting (ESR)

- ESR is done on a per slab bases (8 -12 tons)
- Remelt capacity is typically fully utilized for processing higher alloys for aerospace applications
  - Long lead times and high costs
Stainless Steel Production

After casting slabs are cut for processing into plate or coil product. Each slab weighs about 8 - 12 tons.
Electroslag Remelting (ESR)

• For types 304L and 316L, ESR typically not necessary
  – Most producers’ continuous casters are very effective at reducing inclusions in stainless steels

  – Critical applications should avoid the first and last slab of the heat
Factors to Consider When Choosing a Stainless Steel

• Corrosion resistance
• Fabrication characteristics
  – Weldability, formability, machinablity electropolishing (EP) properties
• Mechanical properties
• Cost
• Availability
CPT (ASTM G 150) vs. PREn

PREn = Pitting Resistance Equivalent number

PREn = %Cr + 3.3%Mo + 16%N
Other Factors

• Sulfur content
• Ferrite content
• Surface condition
Sulfur Content

• Detrimental to corrosion resistance
  – Sulfide inclusions serve as initiation sites for pits
• Detrimental to electropolishing
• Beneficial for autogenous welding
  – ASME BPE Standard requires 0.005 - 0.017% S for automatic welding
• Improves machinability
  – Type 304L and 316L bar products typically contain 0.020 - 0.030% S
What Effect Does Sulfur Have?

(A) LOW SULFUR
<0.001% S
Shallow Penetration

(B) HIGH SULFUR
0.016% S
Deep Penetration
Effect of S Content on Pitting Resistance

Brennert & Eklund Scandinavian J. of Met. 5 (1976)
### Type 304L and 316L Stainless Steel

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<tr>
<td>303</td>
<td>0.15</td>
<td>2.0</td>
<td>0.20</td>
<td>0.15 Min.</td>
<td>1.00</td>
<td>17.0</td>
<td>8.0</td>
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Based on the ASTM A 240/A 314 requirements
Type 303 Stainless Steel

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<td>1.00</td>
<td>17.0</td>
<td>8.0</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>PRODEC® 304</td>
<td>0.03</td>
<td>2.0</td>
<td>0.045</td>
<td>0.030</td>
<td>0.75</td>
<td>18.0</td>
<td>8.0</td>
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Based on the ASTM A 240 requirements
Ferrite Content
Ferrite Content

• Presence of ferrite improves hot cracking resistance and hot workability

• Increased ferrite levels lower the pitting resistance and increase corrosion rates in strong acids

• Ferrite may reduce the EP properties on the end grain of bar product
Selecting Optimal 304L/316L for High Purity Applications

– Optimize selection requirements without seriously limiting availability
– Selection criterion should be based on product form
  • Plate/Sheet
  • Bar
  • Pipe/tubing
Selecting 304L/316L Plate and Sheet (no autogenous welding)

- Sulfur content - 0.003% maximum
- % Ferrite range - 3% maximum
- Electropolishing Applications
  - Procure product produced on a state of the art caster
  - Avoid first and last slabs of the melt sequence
Selecting Welded Pipe and Tubing
(welding applications)

- ASME BPE requires a sulfur content - 0.005 - 0.017%
  - For optimal corrosion and EP properties the sulfur level should be near the bottom of this range with a 0.010% max.
- % Ferrite range - 5% maximum
- Electropolishing Applications
  - Procure product produced in a state of the art melt shop
  - Avoid product from the first and last slabs of the melt sequence
Selecting Bar Product

• If possible, avoid type 303 stainless steel
  – Select a modern machining grade such as 304 PRODEC

• For maximum Corrosion Resistance
  – Sulfur content - 0.013% maximum
  – % Ferrite range - 5% maximum
Case Study - Type 304 Railings

Rail Station

Bus Station

May 18, 2010
Rail Station - Gate

Type 304/No.4 Polish

May 18, 2010
Bus Station - Handrail

Type 304/320 Grit Finish
## Chemical Composition

<table>
<thead>
<tr>
<th>Element</th>
<th>Rail Station Gate (wt%)</th>
<th>Bus Station Handrail (wt. %)</th>
<th>ASTM A 554, MT-304 Composition (wt. %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cr</td>
<td>18.00</td>
<td>18.18</td>
<td>18.0 – 20.0</td>
</tr>
<tr>
<td>Mn</td>
<td>1.74</td>
<td>1.77</td>
<td>2.00 (max.)</td>
</tr>
<tr>
<td>Ni</td>
<td>8.11</td>
<td>8.13</td>
<td>8.0 – 11.0</td>
</tr>
<tr>
<td>P</td>
<td>0.030</td>
<td>0.033</td>
<td>0.040 (max.)</td>
</tr>
<tr>
<td>S</td>
<td>0.014</td>
<td>0.013</td>
<td>0.030 (max.)</td>
</tr>
<tr>
<td>Si</td>
<td>0.42</td>
<td>0.46</td>
<td>1.00 (max.)</td>
</tr>
<tr>
<td>C</td>
<td>0.055</td>
<td>0.023</td>
<td>0.08 (max.)</td>
</tr>
</tbody>
</table>
## Roughness

### Rail Station - Gate

<table>
<thead>
<tr>
<th>Location</th>
<th>Ra Readings (micro inches)</th>
<th>Average Ra (micro inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top Horizontal Tube</td>
<td>52, 41, 40, 33</td>
<td>41.5</td>
</tr>
<tr>
<td>Vertical Tube (hinge side)</td>
<td>35, 32, 32</td>
<td>33.0</td>
</tr>
<tr>
<td>Vertical Tube (latch side)</td>
<td>52, 49, 52</td>
<td>51.0</td>
</tr>
<tr>
<td>Vertical Bar</td>
<td>19, 17, 19, 21, 19, 19</td>
<td>19.0</td>
</tr>
<tr>
<td>Latch Plate</td>
<td>52, 49, 52</td>
<td>51.0</td>
</tr>
</tbody>
</table>

### Bus Station - Railing

<table>
<thead>
<tr>
<th>Location</th>
<th>Ra Readings (micro inches)</th>
<th>Average Ra value (micro inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal Tube</td>
<td>42, 40, 48, 52</td>
<td>45.5</td>
</tr>
<tr>
<td>Horizontal Tube</td>
<td>159, 98, 77, 97</td>
<td>112.7</td>
</tr>
</tbody>
</table>

May 18, 2010

3-A Educational Program
## Surface Chloride - Chlor*Test™

<table>
<thead>
<tr>
<th>Site - Test Area</th>
<th>Chloride Concentration (µg/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rail Station - Top tube on sheltered gate</td>
<td>40</td>
</tr>
<tr>
<td>Rail Station - Top tube on exposed railing</td>
<td>10</td>
</tr>
<tr>
<td>Rail Station - Top tube on exposed railing</td>
<td>12</td>
</tr>
<tr>
<td>Bus Station - Top tube on sheltered handrail</td>
<td>40</td>
</tr>
<tr>
<td>Bus Station - Top tube on exposed railing</td>
<td>55</td>
</tr>
</tbody>
</table>
Surface Morphology

Bus Station

Rail Station
Corrosion Attack On a Mechanically Polished surface
What does Passivation Mean?

• Process by which stainless steel will spontaneously form a protective film

• Chemical treatment to remove free iron or other foreign matter that could interfere with the spontaneous formation of a protective film on a stainless steel
  – Typically an oxidant such as a nitric acid solution which enhances the spontaneous formation of a protective film
Methods for Characterizing the Quality of a Passive Surface

- Measure the Cr/Fe ratio in on the passive surface using surface techniques such as Auger and XPS
- Electrochemical measurements that measure open circuit potentials or critical pitting potentials in a controlled test environment
  - Test.Clinox by Nitty Gritty
  - Passivation Tester 2026 by Koslow
  - Modified ASTM G 61 test
Passivation Study - Test methods

Cyclic Polarization (modified ASTM G 61)

- Test Solution - 1000 ppm Cl⁻/pH 5.0
- Electrode potential was scanned in the more noble direction from -25 mV below open circuit potential until the current reached a value of 500 µA/cm²
- Critical Pitting Potential was defined as the potential where the current reaches a level of 100 µA/cm²
Passivation Study - Test Conditions

- Type 316L stainless steel with sulfur in the range of 0.005 - 0.017%

- Welded (full penetration GTAW) by DCI - (AWS Weld Discoloration Level 2 - 3)
  - As-welded - no post-weld cleaning
  - Color Cleaned using a Scotch Bright pad
  - Ground to 120 Grit finish

- Passivation treatment - 30 minutes in 9.5% nitric acid at 55 ºC
## Summary of Test: Clinox

<table>
<thead>
<tr>
<th>Sample</th>
<th>Unpassivated</th>
<th></th>
<th>Passivated</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Run #1</td>
<td>Run #2</td>
<td>Run #1</td>
<td>Run #2</td>
</tr>
<tr>
<td>As Welded (HAZ)</td>
<td>Pass</td>
<td>Fail</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>Color Cleaned (HAZ)</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>Ground (HAZ)</td>
<td>Pass</td>
<td>Fail</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>Base Metal (2B Finish)</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
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</tr>
</tbody>
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## Summary of the Koslow Passivation Test

<table>
<thead>
<tr>
<th>Sample</th>
<th>Unpassivated</th>
<th>Passivated</th>
</tr>
</thead>
<tbody>
<tr>
<td>As Welded (HAZ)</td>
<td>-780 mV</td>
<td>-215 mV</td>
</tr>
<tr>
<td>Color Cleaned (HAZ)</td>
<td>-450 mV</td>
<td>-322 mV</td>
</tr>
<tr>
<td>Ground (HAZ)</td>
<td>-220 mV</td>
<td>-298 mV</td>
</tr>
<tr>
<td>Base Metal (2B Finish)</td>
<td>-221 mV</td>
<td>-258 mV</td>
</tr>
</tbody>
</table>

0 to -400 mV = Passive, -400 to -500 mV = Indeterminate, -500 to -1100 mV = Unpassivated
# Summary Of The 316L CPP Measurements

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<th>Unpassivated</th>
<th>Passivated</th>
</tr>
</thead>
<tbody>
<tr>
<td>As Welded (HAZ)</td>
<td>276 mV</td>
<td>525 mV</td>
</tr>
<tr>
<td>Color Cleaned (HAZ)</td>
<td>230 mV</td>
<td>475 mV</td>
</tr>
<tr>
<td>Ground (HAZ)</td>
<td>343 mV</td>
<td>495 mV</td>
</tr>
<tr>
<td>Base Metal (2B Finish)</td>
<td>506 mV</td>
<td>494 mV</td>
</tr>
<tr>
<td>Weld (ground)</td>
<td>---</td>
<td>603 mV</td>
</tr>
</tbody>
</table>
Mechanically Polished Surfaces

- Mechanically polished surfaces typically are not as corrosion resistant as a 2B mill surface
- The smoother the surface finish the better the corrosion resistance
- Avoid micro crevices
- For maximum Corrosion Resistance Passivate after mechanical polish
Passivation

- Removes free iron, sulfides, and other foreign matter
- Does not affect the stainless steel
- Will not remove scale, heat tint, or chromium depleted areas
- Can assist in the formation of passive film with superior corrosion resistance
Passivation Treatments

- See ASTM A 380 and A 967 for details on commonly used passivation processes

- Nitric and citric acid solutions are the commonly used
The Effects Of Passivation On A Mechanically Ground Surface

Cyclic Polarization Scan

Cyclic Polarization Scan - Type 316L SST
As-ground vs. As-ground & Passivated
Test Solution 1000 ppm Cl-/pH=5

Blue - ground 60/80/120 grit
Red - ground (60/80/120 grit) & passivated

CPP = 770 mV
CPP = 427 mV

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Thank You!
Missed Joint if Difference in Sulfur > 0.012%

Tungsten Electrode centered over Joint

Cross Section of Tube Wall

Actual Cross Section of Weld Between Elbow & Tube (20X)

Low Sulfur Elbow

High Sulfur Tube

LOW SULFUR HIGH SULFUR
Ferrite Content

\[ \%\text{Ferrite} = 3.34(\text{Cr}_{\text{equiv.}}) - 2.46(\text{Ni}_{\text{equiv.}}) - 28.6 \]

Where

\[ (\text{Cr}_{\text{equiv.}}) = 1.5(\%\text{Si}) + \%\text{Cr} + \%\text{Mo} + 2(\%\text{Ti}) + 0.5(\%\text{Nb}) \]

\[ (\text{Ni}_{\text{equiv.}}) = 30(\%\text{C}+\%\text{N}) + \%\text{Ni} + 0.5(\%\text{Mn}+\%\text{Cu}+\%\text{Co}) \]
Why Clean Stainless Steels

- Restore corrosion properties after fabrication or repair procedures
- Meet the hygienic requirements of the application
- Meet the required aesthetic requirements
Typical Defects/Contaminants

- Weld defects - undercut, pores, slag, inclusions, weld spatter, arc strikes, heat tint, and chromium depletion fabrication
- Free iron contamination
- Rough surface
- Sulfides
- Organic contamination
Pitting Potential vs. Roughness
(Type 316L Stainless Steel)
Weld Corrosion Resistance

Improving Pitting Resistance

- Parent Material
- Weld, Ground
- Weld, Ground and Pickled
Surface Roughness vs. Grit Finish

The graph shows the relationship between surface roughness (Ra) in microinches and grit finish number. The x-axis represents the grit finish number, while the y-axis shows the surface roughness. Two categories are plotted: Weld: Ground, indicated by red circles, and Weld: Ground and Pickled, represented by green triangles.

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Influence of Pickling/Blasting On the Pitting Resistance of a Welded 6% Mo Stainless Steel

(A. H. Tuthill NiDI Tech Series No. 10 068)
Influence of Mechanical Cleaning/Pickling

(JF Grubb, Int. Conf. On Stainless Steel 1991)

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Passivation

Sample passivated in 9.5% HNO3 at 50 C

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Passivation

Sample passivated in 9.5% HNO3 at 50 C

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Pickling

- Aggressive chemical method for removing oxides (descaling) and free iron contamination
- Removes chromium depleted areas and some of the stainless steel surface
- Nitric-hydrofluoric acid solutions are most widely used
  - See ASTM A 380 for recommendations on acid concentrations, temperatures, and dwell times
Pickled Surface

Magnification = 600X

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Pickling Methods

- **Dip pickling**
  - Composition of the acid, temperature, and dwell time depends on stainless steel grade

- **Spray methods**
  - Used for large surfaces that can not be dipped

- **Pickle Paste**
  - HNO$_3$/HF solution with added binding agents
  - Not very effective at low temperatures (5 - 10 ºC)
  - Avoid drying the past - keep temperatures below 40 ºC
Electropolishing

- Controlled corrosion process
- Removes all free iron and the chromium depleted zone
- Smooth bright surface
- Typically provides the optimum corrosion resistance
Conclusions

• Producers are very reluctant to produce new grades or new variations of an existing grade.
• The pharmaceutical industry is a relatively small market for stainless steels and producers probably will not make an alloy variation solely for this sector.
• Users can special order a modified 316L composition but this will increase lead times and this must be done on a per heat bases. (120 tons!!)
Conclusions

• Often it is more practical to specify a higher grade of stainless steel than special order a modified 316L heat.

• Improved EP properties can be achieved by selecting 316 SST that is produced on a state of the art caster and avoiding the first and last slabs of the melt sequence.

• Within any given product form users can maximize performance through careful section of sulfur and ferrite levels.
Thank You!
Relative Pitting resistance

![Graph showing critical pitting temperature for different stainless steels]

- 304L
- 316L
- S32205
- CPT 304L
- CPT 316L
- CPT S32205
- CPT 6% Mo

Critical Pitting Temperature (°C)

Stainless steels

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Type 304L and 316L Stainless Steel

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<tr>
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<td>0.030</td>
<td>0.030 max</td>
</tr>
<tr>
<td>Mn</td>
<td>2.00 max.</td>
<td>2.00 max.</td>
</tr>
<tr>
<td>P</td>
<td>0.045 max.</td>
<td>0.045 max.</td>
</tr>
<tr>
<td>S</td>
<td>0.030 max.</td>
<td>0.030 max.</td>
</tr>
<tr>
<td>Si</td>
<td>0.75 max.</td>
<td>0.75 max.</td>
</tr>
<tr>
<td>Cr</td>
<td>17.5 – 19.5</td>
<td>16.0 – 18.0</td>
</tr>
<tr>
<td>Ni</td>
<td>8.0 – 12.0</td>
<td>10.0 – 14.0</td>
</tr>
<tr>
<td>Mo</td>
<td>---</td>
<td>2.00 – 3.00</td>
</tr>
<tr>
<td>N</td>
<td>0.10</td>
<td>0.10</td>
</tr>
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Based on the ASTM A 24 requirements
# ASTM A 240 Compositional Ranges

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May 18, 2010 3-A Educational Program