High-Performance Alloys for Demanding Applications

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Presentation Objectives

• A basic overview of high-performance alloys

• Trying not to get too technical!

• With a particular focus on super-duplex stainless steels

• Considering
  • their original development
  • a summary of attractive properties (and limitations)
  • examples of their applications

Unique metals for your demanding applications
Alloy comparison

Pitting corrosion resistance equivalent number (PREN)

Strength (yield strength)

Cost (per kg)

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Why select nickel alloys? nb. alloys with >30% Ni content

- They can be offer extremely high yield strengths i.e. 718
- They can offer exceptional corrosion resistance i.e. C276
- But they are also **expensive** due to the high nickel content

*Ni price has historically been more volatile than Cr – prices for Nickel alloys tend to vary far more than Stainless Steels*

So, let’s consider the reason for their original development.

Then look at their other attractive properties.

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What are Nickel Alloys?

- Nickel was isolated as an element in the mid-18th Century
- Limited applications before 1900’s due to expense

- *Monel* (Cu-Ni) alloys invented by INCO in 1901
- *Inconel* (Ni-Cr) alloys invented from 1941-onwards by Wiggins Alloys
- *Incoloy* (Ni-Fe-Cr) alloys invented by Special Metals

“The Inconel family of alloys was first developed in the 1940s by research teams at Wiggin Alloys in support of the development of the Whittle jet engine.”

Activity driven by the need for alloys that could operate at elevated temperatures.
Nickel alloys – attractive properties

• **Higher temperature service**
  Nickel alloys like 825/718/625 retain much of their strength up to 650°C
  
  \[ \textit{vs} \]
  
  Super Duplex are limited to a continuous operating temperature of 250°C

• **Low temperature toughness**
  Nickel alloys, like Austenitic stainless Steels (316L, XM-19), retain excellent impact toughness down to cryogenic temperatures (-250°C).

  \[ \textit{vs} \]
  
  Super Duplex, like Ferritic stainless steels, lose toughness below -50 to -100°C.

• Creep and oxidation resistance (at higher temperatures)
• Non-magnetic
• Corrosion resistance (in specific environments)

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Alloy comparison

- 316L
- DUPLEX
- 904L
- SUPER DUPLEX
- 6Mo/254
- 625
- C276
- 718

**PREN**
(pitting corrosion resistance equivalent number)

**Strength**
(yield strength)

**Cost**
(per kg)

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SUPER DUPLEX stainless steels offer a unique and attractive combination of

1) excellent corrosion resistance
2) high strength
3) competitive costs

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What is Stainless Steel?

• Simply put, steel that contains >10.5% chromium is considered a Stainless Steel.
• The development of Stainless Steel is claimed by many different sources.
• However, the term ‘Stainless Steel’ was captioned by Harry Brearley in 1911.

“Brearley was attempting to develop a wear-resistant steel for gun barrels. However, his initial experiments were conducted at a friends cutlery factory. Originally titled ‘Rustless Steel’, the name ‘Stainless Steel’ stuck after testing samples with vinegar.”

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Why do Stainless Steels ‘work’?

- In a ‘regular’ (carbon) steel, the iron will react with oxygen when in the presence of moisture to form iron oxides (rust)
- As this rust is flaky, it provides no protection to the underlying metal
- Eventually, over time, all of the iron will eventually corrode

- In a Stainless Steel, the chromium will react with oxygen to form a very adherent film that is chemically stable
- Although very thin (<5nm i.e. 1/20,000th of a human hair) it will self-repair in the presence of oxygen
- This passive layer can be damaged physically or chemically resulting in corrosion
The role of different elements in Stainless Steel?

<table>
<thead>
<tr>
<th>Element</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chromium (Cr)</td>
<td>Creates the ‘passive film’. <strong>More Cr means greater protection</strong></td>
</tr>
<tr>
<td>Molybdenum (Mo)</td>
<td>Improves resistance to pitting corrosion</td>
</tr>
<tr>
<td>Nitrogen (N)</td>
<td>Improves resistance to pitting corrosion (and increases strength)</td>
</tr>
<tr>
<td>Copper (Cu)</td>
<td>Improves resistance to attack by sulphuric acid</td>
</tr>
<tr>
<td>Silicon (Si)</td>
<td></td>
</tr>
<tr>
<td>Nickel (Ni)</td>
<td>Added to form ‘Austenitic’ steel. Improves resistance to acids</td>
</tr>
<tr>
<td>Manganese (Mn)</td>
<td>Added to form ‘Austenitic’ steel. Improves mechanical strength</td>
</tr>
<tr>
<td>Sulphur (S)</td>
<td>Normally <strong>undesirable</strong> as inclusions can initiate pitting corrosion</td>
</tr>
<tr>
<td>Phosphorus (P)</td>
<td></td>
</tr>
</tbody>
</table>

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PREN (Pitting Resistance Equivalent Number)

PREN = Cr + 3.3Mo + 16N

The calculated value has a qualitative relationship with resistance to pitting

Be mindful about calculating from upper or lower limits

i.e.  
304  = 17 → 21  
316  = 23 → 28  
2205 = 31 → 38  
Super Duplex  > 40  
254SMO = 42 → 48

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Different types of Stainless Steel?

Austenitic Grades
- 6Mo
- 904L
- 316
- 304

Duplex Grades
- Super Duplex 25% Cr
- Hyper Duplex 27% Cr
- Duplex 22%Cr

Martensitic Grades
- 17/4 PH
- 304
- 410
- 440

Ferritic Grades

Increasing ‘Chrome Equivalent’ content %
[Cr + 1.5Mo + 2Si + 5V + 5.5Al + 1.75Nb + 1.5Ti + 0.75W]

Increasing ‘Nickel Equivalent’ content %
[Ni + Co + 0.5Mn + 0.3Cu + 25N + 30C]

Unique metals for your demanding applications
## Different types of Stainless Steel?

<table>
<thead>
<tr>
<th></th>
<th>Ferritic</th>
<th>Austenitic</th>
<th>Duplex</th>
<th>Martensitic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corrosion resistance</td>
<td>★★★</td>
<td>★★★Std. Super</td>
<td>★★★★★</td>
<td>★★★</td>
</tr>
<tr>
<td>Stress Corrosion Cracking</td>
<td>★★★★★</td>
<td>★</td>
<td>★★★★</td>
<td>★★★★</td>
</tr>
<tr>
<td>Strength</td>
<td>★★★</td>
<td>★</td>
<td>★★★★</td>
<td>★★★★</td>
</tr>
<tr>
<td>Toughness (low temps)</td>
<td>★★</td>
<td>★★★★★</td>
<td>★★</td>
<td>★</td>
</tr>
<tr>
<td>Formability</td>
<td>★★</td>
<td>★★★</td>
<td>★★</td>
<td>★</td>
</tr>
<tr>
<td>Weldability</td>
<td>★</td>
<td>★★★★★</td>
<td>★★★★</td>
<td>★</td>
</tr>
<tr>
<td>Non-magnetic</td>
<td>★</td>
<td>★★★★★</td>
<td>★★</td>
<td>★</td>
</tr>
</tbody>
</table>

- The most widely used products are 3xx Austenitic and 4xx Ferritic alloys
- Martensitic (and Precipitation Hardened) grades provide the highest strengths
- **Duplex alloys combine HIGH corrosion resistance + HIGH strength**

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Super Duplex Stainless Steels - History

- There are a family of alloys based around 25%Cr
- Enhanced corrosion resistance and strength is only achieved by:
  - Controlling chemical composition
  - Controlling production conditions
  - Optimising the microstructure

<table>
<thead>
<tr>
<th></th>
<th>Ferralium® 255</th>
<th>Zeron® 100</th>
<th>SAF2507®</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nearest UNS</td>
<td>S32550</td>
<td>S32760</td>
<td>S32750</td>
</tr>
<tr>
<td>Nearest DIN</td>
<td>1.4507</td>
<td>1.4501</td>
<td>1.4410</td>
</tr>
<tr>
<td>Trademarked - by</td>
<td>Langley Alloys</td>
<td>Weir Materials</td>
<td>Sandvik</td>
</tr>
</tbody>
</table>

Unique metals for your demanding applications
# Super Duplex Stainless Steels

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<th>Ferralium® 255</th>
<th>S32760</th>
<th>S32750</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cr</td>
<td>24.50 – 26.50</td>
<td>24.00 – 26.00</td>
<td>24.00 – 26.00</td>
</tr>
<tr>
<td>Ni</td>
<td>5.50 – 6.50</td>
<td>6.00 – 8.00</td>
<td>6.00 – 8.00</td>
</tr>
<tr>
<td>Mo</td>
<td>3.10 – 3.80</td>
<td>3.00 – 5.00</td>
<td>3.00 – 4.00</td>
</tr>
<tr>
<td>Cu</td>
<td>1.50 – 2.00</td>
<td>&lt; 0.50</td>
<td>0.50 – 1.00</td>
</tr>
<tr>
<td>P&lt;sub&gt;max&lt;/sub&gt;</td>
<td>0.025</td>
<td>0.035</td>
<td>0.030</td>
</tr>
<tr>
<td>S&lt;sub&gt;max&lt;/sub&gt;</td>
<td>0.005</td>
<td>0.020</td>
<td>0.010</td>
</tr>
</tbody>
</table>

1. Increased Cu level, inhibits the growth of pitting corrosion
2. Reduced impurities, less inclusions where pitting can be initiated
3. Balanced composition, to optimise %Ferrite / % Austenite

Unique metals for your demanding applications
1. Pitting mainly occurs at impurity sites
2. Passive layer is broken down
3. Accelerated corrosion within the pit
4. Reduced impurities, fewer sites
5. Cu dissolution at corrosion site
6. Insoluble cover forms → slowing or stopping corrosion

Unique metals for your demanding applications
## Super Duplex Stainless Steels

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<th>Ferralium® 255</th>
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<tbody>
<tr>
<td><strong>0.2% Proof Stress</strong></td>
<td>85ksi (586N/mm²)</td>
<td>80ksi (550N/mm²)</td>
<td>80ksi (550N/mm²)</td>
</tr>
<tr>
<td><strong>Ultimate Tensile Strength</strong></td>
<td>115ksi (790N/mm²)</td>
<td>109ksi (750N/mm²)</td>
<td>109ksi (750N/mm²)</td>
</tr>
</tbody>
</table>

Higher Proof Stress (Yield Strength) allows more efficient designs
- Great loads possible
- Reduced section thickness
  - Reduced metal or Reduced suspended load

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Ferralium® 255-SD50 Case Studies - 1

Acoustic release transponders

The specification of Ferralium® 255 ensures

- Long-life in corrosive marine environment
- Physical robustness
- Increased load-carrying capability

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Pump Shafts

The specification of Ferralium® 255 ensures

- Enhanced abrasion corrosion resistance
- Higher strength
- Compatible with aggressive mediums

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Ferralium® 255-SD50 Case Studies - 3

Valves

The specification of Ferralium® 255 for stems and trim ensures

- High strength and stiffness for components subject to loading
- Compatible with aggressive mediums / wear resistant

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Ferralium® 255-SD50 Case Studies - 4

**Statue of Liberty**

Ferralium® 255 used to replace corroded support structure/armatures

- Refurbishment of iconic structure in 1986

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Summary

1. Super Duplex alloys combine many favourable characteristics
   - Corrosion Resistance
   - Strength
   - Cost

2. There are a number of different 25%Cr Super Duplex alloys
   a) Ferralium® 255 provides superior corrosion resistance
      - Increased levels of Cu additions
      - Lower level of impurities
   b) Ferralium® 255 provides increased Yield Strength
      - 85ksi (576N/mm²) cf. 80ksi (550N/mm²)

3. Continuously enhanced and used successfully for 50 years

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