Cast Stainless Steel Technology Developments

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Figure 1.2 Schaeffler diagram showing the amount of ferrite and austenite present in weldments as a function of Cr and Ni equivalents. (4)
Calculation of Chromium Equivalent and Nickel Equivalent

\[ \text{Cr}_E = \%\text{Cr} + 2 \times \%\text{Si} + 1.5 \times \%\text{Mo} \]
\[ + 5 \times \%\text{V} \]

\[ \text{Ni}_E = \%\text{Ni} + 0.5 \times \%\text{Mn} + 30 \times \%\text{C} \]
\[ + 0.3 \times \%\text{Cu} \]
• Chemistry: C=0.07, Mn=0.56, Si=1.30, P=0.028, S=0.009, Cr=19.5, Ni=10.7, Mo=2.18 (Cb ~ 0.05 and N ~ 0.04)

• ASTM A800 predicts 10.5 volume percent ferrite with a range of 6.5 to 14.5 (chromium equivalent to nickel equivalent = 1.19)
Means of Calculating Ferrite

- Severn Gage: 11
- Feritscope: 7
- Magne-Gage: 2
- *Two different instruments*: 5
- Manual point count
- ASTM A800
- 1949 Schaeffler Diagram
- WRC Diagram

Unit of measure:
- FN: 8 (all 4 of the non-foundry)
- Volume percent: 7
- *Use both methods*: 2
Identification of Phases by Composition
# Stainless Steels - Strength

<table>
<thead>
<tr>
<th>Grade</th>
<th>Yield (ksi)</th>
<th>UTS (ksi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CF8</td>
<td>70</td>
<td>30</td>
</tr>
<tr>
<td>CF3MN</td>
<td>75</td>
<td>37</td>
</tr>
<tr>
<td>4A(2205)</td>
<td>90</td>
<td>60</td>
</tr>
<tr>
<td>6A(Zeron 100)</td>
<td>100</td>
<td>65</td>
</tr>
</tbody>
</table>
## Stainless Steel - Corrosion

<table>
<thead>
<tr>
<th>Grade</th>
<th>Critical pitting temperature °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>CF8</td>
<td>5 (calculated)</td>
</tr>
<tr>
<td>CF3MN</td>
<td>29 (calculated)</td>
</tr>
<tr>
<td>4A(2205)</td>
<td>35 - 40</td>
</tr>
<tr>
<td>6A(Zeron100)</td>
<td>45 – 55</td>
</tr>
</tbody>
</table>
Pseudo Phase Diagram for 68% Fe – Cr Ni
Figure 1.6 Temperature-time precipitation curves for various phases observed in alloy U50. (9)
CCT Diagram - CD3MN

TTT curves (initial & final)

CCT curves (non-equil. initial & final)

Cooling Rate=1°C/min, σ phase << 1%

Cooling Rate=0.5°C/min, σ phase < 1%

Cooling Rate=0.1°C/min, σ phase = 8.72% ± 3.38

Cooling Rate=0.01°C/min, σ phase = 17.62% ± 3.46
CCT Diagram - CD3MWCuN

- **Bridgman furnace**
  - V=0.1 mm/sec, σ phase < 1%

- **Cooling Rate=5°C/min**
  - σ phase = 3.61% ± 2.64

- **Cooling Rate=2°C/min**
  - σ phase = 7.10% ± 2.12

- **Cooling Rate=1°C/min**
  - σ phase = 10.09% ± 1.13

**TTT curves**
- (initial & final)

**CCT curves**
- (non-equil. initial & final)
PROBLEM - Corrosion of High Alloy (6 wt% Mo) Stainless Steel Castings

Current minimum required heat treatment
- 1150 °C/ 1hr (ASTM Standards A743 and A351)

Cast alloys and welds not as corrosion resistant due to:
- microsegregation
- presence of σ phase

OBJECTIVE: Develop heat treating schedules and welding procedures that restore the corrosion resistance of castings and welds to a level comparable to that of wrought counterpart alloys.
Typical Homogenization Results

- 1205 °C/4 hours needed for complete homogenization
CN3MN Corrosion Results – ASTM G48A

Weight Loss (%)

- AL6XN: 5.4%
- As Cast CN3MN: 22.3%
- 1150 1 Hour: 18.0%
- 1150 2 Hour: 13.8%
- 1150 4 Hour: 18.3%
- 1205 1 Hour: 13.2%
- 1205 2 Hour: 5.0%
- 1205 4 Hour: 1.7%
$\lambda = 80 \varepsilon^{-0.33}$

Model can be used as a predictive tool to determine effective heat treatment times for CN3MN prepared with various cooling rates.
Need to establish acceptable cooling rate from the heat treating temperature to avoid formation of brittle secondary phase

Collaboration with Scott Chumbley (Iowa State)

Results from C. Muller and Scott Chumbley, Iowa State University

Impact toughness decreases significantly with time at 870 °C, which could occur for large castings cooled slowly from the heat treating temperature

Need to establish critical cooling rates in order to avoid embrittlement.
Charpy Impact Toughness decreases significantly with an extremely slow cooling rate (0.01°C/sec). Charpy Impact Toughness is unaffected by cooling rate above 1°C/sec.

Corrosion Performance decreases at an extremely slow cooling rate (0.01°C/sec). Corrosion Performance is unaffected by cooling rate above 1°C/sec.

Slow cooling rate sample shows evidence of grain boundary attack.
Corrosion of Welds in Super Austenitic Stainless Steel Castings

<table>
<thead>
<tr>
<th></th>
<th>CN3MN 1205°C/4 hrs with Autogenous Weld</th>
</tr>
</thead>
<tbody>
<tr>
<td>CN3MN As-Cast</td>
<td>Basal Metal</td>
</tr>
<tr>
<td>CN3MN 1205°C/4 hrs</td>
<td>Weld</td>
</tr>
</tbody>
</table>

Welding reintroduces the microsegregation profile

<table>
<thead>
<tr>
<th>Percent Mass Loss</th>
<th>CN3MN As-Cast</th>
<th>CN3MN 1205°C/4 hrs</th>
</tr>
</thead>
<tbody>
<tr>
<td>22%</td>
<td>2%</td>
<td>14%</td>
</tr>
</tbody>
</table>

Percent Mass Loss
Corrosion performance increases with decreasing dilution level.
Corrosion performance of weld can restored to level of cast material at dilution levels below ~ 50%.
Corrosion Resistance as a Function of Dilution
(IN72 Filler Metal Welds on CN3MN)

Corrosion performance increases with decreasing dilution level
IN72 Filler metal unable to avoid localized corrosion in weld

- **ASTM G48a**
- **Temperature:** 75°C
- **Solution:** FeCl₃ (Ferric Chloride)
Corrosion Results: IN686 Filler Metal

Heat Treatments have a significant effect on corrosion performance

Post weld heat treatments (PWHT) will mitigate negative effects of dilution

Heat treatments should be done after welding, if possible (no need to control dilution)

Post Weld Heat Treatment at 1205°C/4hr produces the best corrosion resistance
Air-Set Pouring
Nondestructive Examination

• Surface
  – Visual
  – Magnetic particle examination (MT)
  – Liquid penetrant examination (PT)

• Volume
  – Radiographic examination (RT)
  – Ultrasonic examination (UT)
Examination

- Visual
  - ASTM A802
  - MSS SP55

- Magnetic Particle
  - ASTM E709
  - ASTM E125
  - MSS SP53

- Liquid Penetrant
  - ASTM E165 Method
  - ASTM E433 Acceptance
  - MSS SP93
Visual Examination

- Equipment required: surface comparator, pocket rule, straight edge, workmanship standards
- Enables detection of: surface flaws – cracks, porosity, slag inclusions, adhering sand, scale, etc.
- Advantages: low cost, can be applied while work is in process to permit correction of faults
- Limitations: applicable to surface defects only, provides no permanent record
- Remarks: should always be the primary method of inspection, no matter what other techniques are required
Liquid Penetrant Examination

- Equipment required: commercial kits containing fluorescent or dye penetrants and developers, application equipment for the developer, a source of ultraviolet light – if fluorescent method is used
- Enables detection of: surface discontinuities not readily visible to the unaided eye
- Advantages: applicable to magnetic and nonmagnetic materials, easy to use, low cost
- Limitations: only surface discontinuities are detectable
Methodology

• To determine the resolution of the process
  – Only data from a minimum of three inspections per casting for each inspector was used.
  – An indication must be detected at least 50% of the time or the data was not considered so results are a best case situation.

• The results were grouped by casting type, if multiple geometries were used, and also by inspector (to eliminate variation from inspector to inspector).

• Sample standard deviation was used as a measure of resolution.
Foundry 3

- High alloy steel, visible liquid penetrant.
- One casting shape, 10-15 lb cast weight.
- Three Inspectors.
- Twenty-four pieces per part type.
- Three runs per inspector
- Measured length and sketched location of indications on part drawing.
- A total of 216 inspections were made.
Casting Geometry 1

Box-and-Whisker Plot

| Standard Deviation | 95% confidence interval for mean | 0.0” to 0.04” |

Box-and-Whisker Plot

| Standard Deviation | 95% confidence interval for mean | 0.0” to 0.2” |

Box-and-Whisker Plot

| Standard Deviation | 95% confidence interval for mean | 0.0” to 0.02” |

Box-and-Whisker Plot

| Standard Deviation | 95% confidence interval for mean | 0.01” to 0.5” |

Punch Line – The resolution for all inspectors is about 0.4”.
Radiographic Examination

• Equipment required: commercial x-ray or gamma units made especially for inspecting welds, castings, and forgings with film and processing facilities
• Enables detection of: internal macroscopic flaws – cracks, porosity, blow holes, non-metallic inclusions, shrinkage, etc.
• Advantages: when the indications are recorded on film, gives a permanent record
• Limitations: cracks difficult to detect, requires safety precautions, requires skill in choosing angles of exposure, operating equipment, and interpreting indications
• Remarks: radiographic inspection is required by many codes and specifications, useful in qualification of processes, its use should be limited to those areas where other methods will not provide the assurance required because of cost
Results for Unanimous Agreement in X-Ray Ratings

- **Unanimous agreement in shrinkage type:** 37% (47/128)
  - 14 Level 0 (no type)
  - 20 CB
  - 7 CA
  - 6 CC

- **Unanimous agreement in shrinkage level:** 17% (22/128)
  - 14 Level 0
  - 1 Level 1
  - 1 Level 2
  - 1 Level 3
  - 5 Level 5

- **Unanimous agreement in level and type:** 12.5% (16/128)
  - 14 Level 0
  - 2 CB5
Casting Simulation

– Each trial plate was simulated with recorded casting conditions

– Niyama values ($N_y$) were measured
  
  • minimum $N_y$
  • area of $N_y$  
  $< 0.1 \ (K\cdot s)^{1/2} \ mm^{-1}$

\[
N_y = \frac{G}{\sqrt{T}}
\]

$G$: temperature gradient ($K/mm$)
$T$: cooling rate ($K/s$)
Casting Simulation

– Combine trial and simulation results:

- Trial results: X-ray level vs. FL
- Simulation of trials: Ny_{min} vs. FL
- Combine by eliminating FL → X-ray level vs. Ny_{min}

Mean Minimum Niyama Values
+/- One Standard Deviation

<table>
<thead>
<tr>
<th>W/T</th>
<th>Material</th>
<th>Plates</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>CF-8M</td>
<td>20</td>
</tr>
<tr>
<td>5.5</td>
<td>CF-8M</td>
<td>50</td>
</tr>
<tr>
<td>8</td>
<td>CF-8M</td>
<td>30</td>
</tr>
<tr>
<td>8</td>
<td>HH</td>
<td>20</td>
</tr>
<tr>
<td>8</td>
<td>HP</td>
<td>20</td>
</tr>
<tr>
<td>12</td>
<td>CF-8M</td>
<td>25</td>
</tr>
</tbody>
</table>

Level 5: 25 Plates
Level 4: 6 Plates
Level 3: 12 Plates
Level 2: 15 Plates
Level 1: 24 Plates
Level 0: 83 Plates
TOTAL: 165 Plates
Variation in the Ratings:
Confidence intervals of x-ray level ratings grouped by average x-ray level

Data from all foundries

Average one-sided student-t 95% confidence interval for all 128 x-rays = 1.42
Background

- The root cause of leaks in fluid-containing castings can be shrinkage porosity that extends through a wall.
- Sometimes, porosity is so small that it cannot be detected using industrial radiography.
- No method available to assure quality.
The Niyama criterion, a common output from a casting computer simulation, can be used to predict shrinkage porosity.

\[ Ny = \frac{G}{\sqrt{T}} \]
Background

- What is the critical Niyama below which shrinkage porosity forms? (especially for high-Ni alloys)
  - Micro-porosity, $N_{y_{micro}}$ (not visible on radiograph)
  - Macro-porosity, $N_{y_{macro}}$ (visible on radiograph)

\[ Ny = \frac{G}{\sqrt{T}} \]
Case Study #3: Valve B

- CG8M steel valve cast in a silica sand shell mold

- After machining, 22% leaked around gasket on flange face during pressure testing

- No shrinkage visible on x-rays
Case Study #3: Valve B

- leaking castings were sectioned, and photomicrographs were taken

- microporosity evident in leaking area

\( \sim 0.1 \text{ mm} \)
Case Study #3: Valve B

original rigging

revised rigging

- padding added
- chill setup changed
Case Study #3: Valve B

revised rigging flange face

Ny = 1.38
Ny = 1.36

$Ny_{\text{min}} = 1.4$
Case Study #3: Valve B

- Microporosity caused leaks in original rigging with $N_{y_{\text{min}}} = 0.5 - 0.7$
- $N_{y_{\text{min}}} = 1.4$ for revised rigging
- Valves cast since rigging revised:
  - none have leaked
  - none have had any shrinkage indications on x-ray
Leaker Case Study #1

• Leaker was a 20# investment cast M35-1 valve
• 8 valves were cast and shipped to the customer, and one leaked during the customer’s pressure testing
• Leaker was returned to the foundry, with leak area circled
• Metallographic analysis (John Griffin, UAB)
Photographs of Defects in Leak Area

- Outer diameter (OD) of leak area:

  - 18 mm below mid-plane
  - Mid-plane
Photographs of Defects in Leak Area

- Casting through-thickness toward inner diameter (ID) of leak area:
Photographs of Defects in Leak Area

• Polished through-thickness specimen toward ID of leak area, showing shrinkage porosity:
Niyama Values in Entire Valve
Niyama Values in Region of Leak

Niyama values are in units of ($^\circ$C-s)$^{1/2}$/mm
Niyama Values in Region of Leak

photos and simulation results are from the valve mid-plane
Case Study #1 Summary

• Simulation suggests potential for leak in valve
  – At valve mid-plane:
    \( N_{y\text{min}} = 0.58 \ (°\text{C-s})^{1/2}/\text{mm} \) at ID, \( N_{y\text{min}} = 0.69 \) at OD
• These low Niyama values (\( N_{y\text{min}} < 1 \)) correspond well with shrinkage porosity observed in metallographic sections.
Additional Examination Areas

- After examining the leaking area, additional areas were selected for metallographic examination (all regions on valve mid-plane):
Comparison: Region #1
Comparison: Region #2
Comparison: Region #3
Comparison: Region #4
Comparison: Region #6
Additional Region Summary

• In general, areas with $Ny < 1$ show a significant amount of porosity (macroporosity)
• In general, areas with $1 < Ny < 2$ show a noticeable amount of microporosity
  – Region #4 was a slight exception, with no substantial microporosity in a region with $1.5 < Ny < 1.8$
• In general, areas with $Ny > 2$ were free from shrinkage porosity
Leaker Case Study #2

• 150# CN7M Valve Sand Casting:
Leaker Case Study #2

cross-section of leaking area

shrinkage, possibly segregation
Case Study #2 Simulations

• Original rigging:

  $N_{y_{\text{min}}} = 1.6$ at OD, $N_{y_{\text{min}}} = 0.5$ at ID

  • visible macro-porosity for $N_{y_{\text{min}}} < 1.0$
Conclusions

• In general, areas with Ny < 1 show a significant amount of porosity (macroporosity)
• In general, areas with 1 < Ny < 2 show a noticeable amount of microporosity
• In general, areas with Ny > 2 were free from shrinkage porosity
• It appears that the Niyama criterion can be used for quality assurance, especially if shrinkage porosity is so small that it cannot be detected by radiography.
• Note for MAGMAsoft users: the valves had only minimal feeding indications (porosity %); the shrink seen in the valves was only predicted using Niyama criterion.