Thin-Wall Ductile Iron Castings: Technology Status 2008

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Rio Tinto Iron & Titanium
&
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Outline

• Introduction
• Production Methods
• Properties
  – Microstructures
  – Mechanical Properties
• Austempered TWDIC or TWADI
• Application Examples
• Concluding Remarks
Introduction

• Carbide-free Thin-wall ductile iron casting (TWDIC) industrial production is a reality.
• A wide spectrum of properties is achievable.
• Various processing techniques can be used.
• Detailed production methods are not readily available.

Objective: Summarize published data in order to ease launching new TWDIC applications.
Production Method
Ex 1: Patented Ferritic TWDIC

- Mg treatment
- Wire Cored Mg or NiMg\textsubscript{15} or FeSiMg

1\textsuperscript{st} step inoculation
- 0,3\%wt*

Casting stream inoc.
- Up to 0,8\%wt*

4\%C
2,5\%Si
0,02\%Mg

2 mm thick
6000 Nod/mm\textsuperscript{2}
Max size
Casting
300 x 300 x 400 mm

* Inoculant: FeSi70\%; 0,4\%Ce, 0,7\%Ca, 1\%Al , 0,8\%Bi

Ref [6]
Production Method
Ex 2: Low Thermal Conductivity Mould

35% Pig Iron
40% ferritic DI returns
25% Steel Scrap
Graphite FeSi

Induction Furnace

Mg treatment
FeSiMg6%
Tundish
Ladle 1510°C

1st step inoc
0,75%wt FeSi

Pouring Ladle 1415°C

2nd step 0,2% inoc*

Bassin & Plug

Mould 50% LDASC

* Inoculant: Fe;62-66%Si;0,8%Al;1,8-2,4%Ca;0,8-1,2%RE;0,8-1,3%Bi

Ref [18]

3,6%C
2,6%Si
0,035%Mg
3 mm thick
700 Nod/mm²
Production Method
Ex 3: Combined Mg Treatment & Inoc

Induction Furnace → Preheated Ladle (~1525°C) → Mg + Inoc* → ~1466°C In-stream inoc** → Sand Mould Pepset Resin

37% Pig Iron
49% DI returns
12% Steel Scrap
0.6% Carbon Raiser
1.1% FeSi

3.9%C
2.7%Si
0.04%Mg
2 mm thick
~2000 Nod/mm²
3 mm thick
~1500 Nod/mm²

* 0.4%FeSiMg3,5+ 0.26%FeSiM6%+ 0.3%FeSi75 Foundry grade (1%Al-0.6%Ca)
**Inoculant: Fe-75%Si 30 x 80 mesh

Ref [11]
<table>
<thead>
<tr>
<th>Ref.</th>
<th>Year</th>
<th>Wall mm</th>
<th>Mould Process</th>
<th>Casting mm</th>
<th>Pre-inoc / Pre-condition / Mg treatment</th>
<th>Inoculation Post-inoc.</th>
<th>Pour. Temp. °C</th>
<th>Nod/mm²</th>
<th>%Mg</th>
<th>%C</th>
<th>%Si</th>
<th>Yield MPa</th>
<th>UTS MPa</th>
<th>El. %</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0</td>
<td>na</td>
<td>Investment casting</td>
<td>Stator 203 x 60</td>
<td>FeSi75 0,3% Zirconoc 0,2% Germalloy 0,15%</td>
<td>na</td>
<td>1550</td>
<td>na</td>
<td>0,055</td>
<td>3,5</td>
<td>2,6</td>
<td>444-480</td>
<td>630-670</td>
<td>6-8</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>2</td>
<td>na</td>
<td>300x300x400</td>
<td>Up to 0,8% wt SphériX transfer furnace to pouring ladle</td>
<td>na</td>
<td>6000</td>
<td>0,02</td>
<td>4</td>
<td>2,5</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>na</td>
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<tr>
<td>7</td>
<td>0</td>
<td>2</td>
<td>LDASC+ Phenolic Urethan</td>
<td>Manifold 380 L x ID 50</td>
<td>FeSi75 during Mg treatment</td>
<td>Before pouring</td>
<td>2550</td>
<td>na</td>
<td>3,5</td>
<td>2,4</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>na</td>
</tr>
<tr>
<td>8,9</td>
<td>0</td>
<td>3</td>
<td>CO₂ silica AFS GFN55</td>
<td>Step block 1 to 12</td>
<td>0,1%FeSi+0,1%SiC before tapping</td>
<td>1% in-stream+ 0,1% on filter FeSi75-BiRE</td>
<td>na</td>
<td>1000</td>
<td>3,77</td>
<td>2,73</td>
<td>345</td>
<td>517</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0</td>
<td>1,5</td>
<td>Alkydic resin silica sand 60-62 mesh</td>
<td>Horizontal plates</td>
<td>Sandwich 2%FeSiMg9Ce 0,6%FeSi75</td>
<td>late inoculation</td>
<td>1400</td>
<td>Up to 2400</td>
<td>0,034-0,08</td>
<td>2,98</td>
<td>-3,38</td>
<td>2,94</td>
<td>4,84</td>
<td></td>
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<tr>
<td>11</td>
<td>0</td>
<td>1,5</td>
<td>Pepset resin</td>
<td>Horizontal step and stripes</td>
<td>FeSiMg3,5 FeSiMg6 Minoc + FeSi75%</td>
<td>In stream with FeSi75 20 x80 mesh</td>
<td>1466-1438</td>
<td>2100 Ave in 1,5</td>
<td>0,04</td>
<td>3,9</td>
<td>2,7</td>
<td>na</td>
<td>na</td>
<td>na</td>
</tr>
<tr>
<td>12</td>
<td>0</td>
<td>2</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
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<td>&quot;</td>
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<td>&quot;</td>
<td>&quot;</td>
<td>~450</td>
<td>~650</td>
<td>~4</td>
</tr>
<tr>
<td>13</td>
<td>0</td>
<td>2</td>
<td>&quot;</td>
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<td>~450</td>
<td>~650</td>
<td>~4</td>
</tr>
<tr>
<td>14</td>
<td>0</td>
<td>2,5</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>296-317</td>
<td>413-482</td>
<td>18-25</td>
</tr>
<tr>
<td>18</td>
<td>0</td>
<td>3</td>
<td>50%LDASC 50%Silica</td>
<td>Fig. 1</td>
<td>FeSiMg6 tundish 0,2%Bi bearing Inoc. basin</td>
<td>1415-1380</td>
<td>490</td>
<td>0,035</td>
<td>3,6</td>
<td>2,35</td>
<td>340</td>
<td>550</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>0</td>
<td>3</td>
<td>Ref [18]</td>
<td>Fig. 1</td>
<td>Ref [18]</td>
<td>Ref [18]</td>
<td>1450-1410</td>
<td>718</td>
<td>0,032</td>
<td>3,65</td>
<td>2,39</td>
<td>na</td>
<td>&gt;600</td>
<td>&gt;2</td>
</tr>
</tbody>
</table>
Properties: Microstructures

• **High** nodule count (NC) is required in order to avoid eutectic carbide and achieve good properties.

• The minimum NC varies accordingly to composition, inoculation, sand properties, mould design...

• Empirical models were described.
Properties: Microstructures

Empirical models: Example 1

• Min. NC vs step block thickness in order to avoid carbides [8]
  – 3 mm plate => 1000 Nod/mm²
  – 1 mm plate => 3550 Nod/mm²

Nod/mm² = 310 (section size, mm)²-2675(section size, mm) + 6177

Production method:
Charge: 93% Pig iron, 3% low Mn Steel Scrap, ferroalloys. Mg treatment tundish with FeSiMg5,5% RE free. RE added as mischmetal. CO₂ bonded silica moulds. %C (3,65-3,95); %Si (2,4-3,4); %Mg (0,03-0,045); %Ce(0,005-0,009); %Mn<0,10. Pre-conditionning immediately before tapping and various in-stream inoculation procedures.
Properties: Microstructures

Empirical models: Example 2

• NC vs solidification time [10]
  – 1,5 mm plate => 2400 Nod/mm²

  $\text{Nod/mm}^2 = 5600 \ (\text{solidification time in s})^{-0.57}$

Production method:
Charge: Pig iron, steel scrap, returns, ferroalloys. Mg treatment with 2%FeSi9%MgCe (sandwich). Late inoculation 0,6%Fe75%Si (5-15 mesh). Alkidic resin bonded silica sand moulds. Pouring 1400°C. %C (2,98-3,38); %Si (2,9-4,8); %Mg (0,03-0,08);
Properties: Microstructures
Empirical models: Example 3

• NC vs as-cast thickness (t) [11]
  – 1.5 mm plate => 2100 Nod/mm$^2$

  \[ \text{Nod/mm}^2 = 1394 + 3000/t^2 \]

Production method:
See slide #6.
Production Method
Ex 3: Combined Mg Treatment & Inoc

- **Induction Furnace**
  - 37% Pig Iron
  - 49% DI returns
  - 12% Steel Scrap
  - 0.6% Carbon Raiser
  - 1.1% FeSi

- **Preheated Ladle ~1525°C**
  - Mg + Inoc*

- **Sand Mould**
  - Pepset Resin

- **In-stream inoc**
  - ~1466°C

- **3 mm thick**
  - ~2000 Nod/mm²

- **3 mm thick**
  - ~1500 Nod/mm²

**Ref [11]**

* 0.4%FeSiMg3.5+ 0.26%FeSiM6%+ 0.3%FeSi75 Foundry grade (1%Al-0.6%Ca)
**Inoculant: Fe-75%Si 30 x 80 mesh**
Properties: Microstructures
Lower NC with Thermal Insulating Sand

3 mm Vertical Plates,
50%LDASC, 2.34%Si, 3.6%C,
491 Nod/mm² [18]
Mechanical Properties
Ex 1: Ferritic DI [13]

- As-cast carbide free vertical plates 2.5 to 6 mm thick
- 200 to 900 Nod/mm²
- Meet ASTM A536
- Composition range
  - C = 3.3 to 3.8%
  - Si = 2.4 to 2.8%
  - Mn = 0.2%
  - Mg = 0.03 to 0.056%

<table>
<thead>
<tr>
<th>UTS [MPa]</th>
<th>YS [MPa]</th>
<th>EI%</th>
</tr>
</thead>
<tbody>
<tr>
<td>413</td>
<td>296</td>
<td>18</td>
</tr>
<tr>
<td>482</td>
<td>317</td>
<td>25</td>
</tr>
</tbody>
</table>

Sand blasted samples

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Co-Sponsored by DIS and AFS
Mechanical Properties

Ex 2: Cu Alloyed Pearlitic DI [14]

- Same procedure as previous example
- Vertical plates 2,5 to 6 mm thick
- NC up to 600 Nod/mm²
- Meet or exceed ASTM A536
- Composition range
  - C= 3,3 to 3,8%
  - Si= 2,4 to 2,8%
  - Mn= 0,2%
  - Mg=0,03 to 0,056%
  - Cu= 0,5%

<table>
<thead>
<tr>
<th>UTS [MPa]</th>
<th>YS [MPa]</th>
<th>EI %</th>
</tr>
</thead>
<tbody>
<tr>
<td>413</td>
<td>296</td>
<td>18</td>
</tr>
<tr>
<td>482</td>
<td>317</td>
<td>25</td>
</tr>
<tr>
<td>620</td>
<td>413</td>
<td>10</td>
</tr>
<tr>
<td>758</td>
<td>482</td>
<td>5</td>
</tr>
</tbody>
</table>

Fully machined samples
## Mechanical Properties

**Ex 3: Low %Si Pearlitic DI & 50% lined LDASC Mould [18]**

- Vertical plates 3 mm thick at parting line
- 491 Nod/mm²
- Composition
  - C = 3.6%
  - Si = 2.35 %
  - Mn = 0.24%
- Meet ASTM 65-45-12

### Table: Mechanical Properties

<table>
<thead>
<tr>
<th>UTS [MPa]</th>
<th>YS [MPa]</th>
<th>El%</th>
</tr>
</thead>
<tbody>
<tr>
<td>550</td>
<td>340</td>
<td>12</td>
</tr>
</tbody>
</table>

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2008 Keith Millis Symposium on Ductile Cast Iron
Co-Sponsored by DIS and AFS
Ex 4: Cu Alloyed DI & lined LDASC Mould [19]
Mechanical Properties

Ex 4: Cu Alloyed Pearlitic DI & 50% lined LDASC Mould [19]

3 mm Vertical Plates
3.6%C, 2.4%Si, \textbf{0.49}\%Cu
718 Nod/mm\(^2\)

3 mm Vertical Plates
3.6%C, 2.20%Si, \textbf{0.04}\%Cu
884 Nod/mm\(^2\)
Mechanical Properties

Avenues to control mechanical properties
- Nodule Count (by late and strong inoculation)
- %Si
- %Cu
- Thermal insulating sand

Potential detrimental effects on the mechanical properties
- Too high %Si reduces low temperature impact strength and ductility
Mechanical Properties
Fatigue Endurance Limit [20]

- Tests according to ASTM E 466-96
- 4 million cycles R = 0.1
- Machined and rounded edge sample
- Samples:
  - 2 mm – 6000 Nod/mm² (± 4 & 7 mm)
  - 3.8%C-2.9%Si-0.04%Mn-0.6% Ni
  - UTS = 574MPa; YS = 458 MPa
- Results
  => 183 MPa FEL
  => FEL decreases with increasing thickness!
    ⇒ size of Nodule = size of defect!!
### Mechanical Properties

Impact [21]

<table>
<thead>
<tr>
<th>Nod/mm²</th>
<th>Upper Shelf Energy J/cm²</th>
<th>Ductile to Brittle Transition Temperature °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>220</td>
<td>18</td>
<td>-26</td>
</tr>
<tr>
<td>1770</td>
<td>16</td>
<td>-80</td>
</tr>
</tbody>
</table>

Ferritized samples
Austempered TWDIC

• Advantages of TWDIC to produce ADI
  – High NC => low diffusionnal distance for alloying elements
    • No segregation
    • Rapid austenitization
  – Very effective heat transfer during quench => min. alloying addition

=> Total treatment time was reduced to 50 min for 1.9 mm & 2000 Nod/mm² [22]
Austempered TWDIC

- Example of TWADI [23]
  - 3 mm
  - 3.6% C, 2.48% Si, 0.24% Mn
  - 400-600 Nod/mm²

<table>
<thead>
<tr>
<th></th>
<th>UTS MPa</th>
<th>YS MPa</th>
<th>El %</th>
</tr>
</thead>
<tbody>
<tr>
<td>TWDADI*</td>
<td>1160</td>
<td>900</td>
<td>7-10</td>
</tr>
<tr>
<td>TWDIC 0.5%Cu</td>
<td>758</td>
<td>482</td>
<td>5</td>
</tr>
</tbody>
</table>

*Grade ASTM A897-06M 1050-750-07
Application Examples

Suspension Arm
PSA Peugeot-Citroen (France)

Exhaust Manifold
WESCAST (Canada)
Suspension Arm

Expected Difficulties

- Cold shuts/laps in the thinnest sections; such defects are difficult to detect when producing long series of parts.

- Obtain the desired microstructure (no carbide & <25% pearlite).

- Have good sphericity in thick section (40 mm) & meet the specified chemistry i.e. % Si < 3.1% and CE < 4.60.

- Achieve dimensional tolerances and soundness.
Suspension Arm

Problem Solving – Cold shuts/laps
Increase pouring temperature?
Augment the risk of sand defects and microshrinkage

Optimise the gating/risering system!
Cast a prototype **without** riser.
Redesign the gating knowing the real location of the shrinkage cavities.

No computer filling simulation but could accelerate the gating design process.
Suspension Arm: Fabrication

- Melting in Arc Furnace
- Transfer in Holding Furnace (16 t)
- Transfer in 3t Converter
- Pre-Inoculation
- **Mg Treatment**
  - Base Metal: %S ≤ 0.010%
  - Pure Mg and Minimum Mg Content
Suspension Arm: Fabrication

- Transfer in 8t Chanel Furnace with Neutral Atmosphere
- *Inoculation*
  - 1st step: in the automatic pouring vessel with 0,15% FeSi(Bi)
  - 2nd step: in-mould with 0,15% FeSi(Bi)
## Suspension Arm

<table>
<thead>
<tr>
<th>Element</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>3.46</td>
</tr>
<tr>
<td>S</td>
<td>0.003</td>
</tr>
<tr>
<td>Si</td>
<td>2.94</td>
</tr>
<tr>
<td>Mg</td>
<td>0.040</td>
</tr>
<tr>
<td>P</td>
<td>0.017</td>
</tr>
<tr>
<td>Mn</td>
<td>0.16</td>
</tr>
<tr>
<td>Cu</td>
<td>0.003</td>
</tr>
<tr>
<td>Al</td>
<td>0.014</td>
</tr>
<tr>
<td>C.E. *</td>
<td>4.45</td>
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</tbody>
</table>
Suspension Arm Microstructure

<table>
<thead>
<tr>
<th>Nod. / mm² ± σ</th>
<th>% Graphite</th>
<th>% Nodularity</th>
<th>% Pearlite</th>
</tr>
</thead>
<tbody>
<tr>
<td>455 ± 45</td>
<td>12</td>
<td>94</td>
<td>5</td>
</tr>
</tbody>
</table>
### Suspension Arm Mechanical Properties

**4 mm thick**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>UTS* [MPa]</td>
<td>448 ± 4</td>
</tr>
<tr>
<td>YS* [MPa]</td>
<td>310 ± 22</td>
</tr>
<tr>
<td>% El * [%]</td>
<td>18 ± 4</td>
</tr>
<tr>
<td>VHN (100 gf)</td>
<td>183</td>
</tr>
</tbody>
</table>
Suspension Arm

Comparative study of three point bending fatigue of 6 and 4 mm suspension arms

Samples Dimensions 31.7 mm x 12.7 mm x 3.5 mm
Stress Ratio R ($\sigma_{\text{min}}/\sigma_{\text{max}}$)=0.1
Loading Frequency = 30 Hz (sinusoidal Wave)
Fatigue Limit Calculated for $2 \times 10^6$ Cycles for max. stress.
Validation Test at $10 \times 10^6$ Cycles

<table>
<thead>
<tr>
<th></th>
<th>50 % Survival Rate (MPa)</th>
<th>90 % Survival Rate (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 mm</td>
<td>472</td>
<td>459</td>
</tr>
<tr>
<td>4 mm</td>
<td>466</td>
<td>441</td>
</tr>
</tbody>
</table>
Suspension Arm

- The manufacture of 4 mm thick DI suspension arms is feasible when high metallurgical quality iron and carefully control processes are utilized.

- The tensile properties of the parts exceeded the minimum values specified for the GS 420-12 grade. UTS was 448 MPa and elongation was 18 %.

- The three points bending fatigue of as-cast 4 mm thick DI is comparable to that of 6 mm when the property is measured on samples machined to a thickness of 3,5 mm.
Exhaust Manifold
Turbo-Manifold

• An exhaust manifold is a component mounted to a cylinder head.
• It is used to collect exhaust gases from each cylinder and direct them to a common system whereby gases are treated to remove harmful emissions before being released from the vehicle.
• An integrated turbo-manifold is a manifold and a turbine housing designed as one single component/module.
• This integrated approach yields benefits where tight packaging constraints exist, eliminates an assembly operation as well as reduces the potential for leakage between exhaust components.
## Composition wt% of Alloyed TWDIC

<table>
<thead>
<tr>
<th>Alloy</th>
<th>C</th>
<th>Si</th>
<th>Mo</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Mg</th>
<th>Ni</th>
<th>Cr</th>
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</thead>
<tbody>
<tr>
<td>SiMo</td>
<td>3.4</td>
<td>4.0</td>
<td>0.6</td>
<td>0.45</td>
<td>0.016</td>
<td>0.01</td>
<td>0.03</td>
<td></td>
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<tr>
<td>D5-S</td>
<td>2.0</td>
<td>5.1</td>
<td></td>
<td>0.72</td>
<td>0.009</td>
<td>0.013</td>
<td>0.089</td>
<td>34.5</td>
<td>1.83</td>
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</table>
SiMo Microstructures

4 mm thick SiMo Manifold

Fine Moly-rich Precipitates
D5S Microstructures

Chromium Carbides
## Mechanical Properties of Alloyed TWDIC

<table>
<thead>
<tr>
<th>Materials</th>
<th>Room Temperature</th>
<th>at 800°C</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>UTS MPa</td>
<td>YS MPa</td>
</tr>
<tr>
<td>SiMo</td>
<td>592</td>
<td>451</td>
</tr>
<tr>
<td>D5S</td>
<td>489</td>
<td>224</td>
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</tbody>
</table>
## Microstructural Analysis of Manifolds

<table>
<thead>
<tr>
<th>Materials</th>
<th>Thick.</th>
<th>Nod %</th>
<th>Nod/mm²</th>
<th>Precipitates %</th>
<th>Primary carbides %</th>
<th>G %</th>
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</thead>
<tbody>
<tr>
<td>SiMo</td>
<td>4 mm</td>
<td>98</td>
<td>573</td>
<td>16</td>
<td>1</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>12 mm</td>
<td>95</td>
<td>486</td>
<td>20</td>
<td>1</td>
<td>11</td>
</tr>
<tr>
<td>D5S</td>
<td>4 mm</td>
<td>90</td>
<td>909</td>
<td>5.3</td>
<td>4.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>12 mm</td>
<td>93</td>
<td>522</td>
<td>5.5</td>
<td>4.6</td>
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</tbody>
</table>
SiMo & D5S Durability Test

- Durability tests of a truck manifold were performed on the EES (Engine Exhaust Simulator) for the different materials.

- The test was cyclic heating and cooling with 1030°C EGT (Exhaust gas Temperature) and 860-870°C PMT (Peak Metal Temperature).
SiMo & D5S Durability Test

It is found that D5S (NiResist) has much higher cycles to failure than ferritic Ductile Iron (SiMo). Austenitic stainless steel has the longest life in this test condition.
Concluding Remarks

• The manufacture of TWDIC is technically feasible when state-of-the-art foundry practices are utilized.

• Many production routes and chemical compositions can be employed to achieve as-cast carbide free TWDIC.

• The as-cast mechanical properties meet or exceed the ASTM A536 specifications, either for the high ductility grade (60-40-18) or the high strength one (80-55-06).

• The impact and the fatigue properties of the TWDIC are equivalent to the properties of the DI cast in thicker section size.

• ADI, SiMo and D5-S alloyed Ductile Irons can also be produced successfully.

• NC can be controlled by the inoculation technique and/or the type of inoculant and/or the use of insulating sand.
Concluding Remarks

• The minimum NC necessary to ensure a carbide free structure is difficult to clearly establish since it depends on the solidification rate which is controlled by the geometry of the casting and the type of mould (sand type, mould coating, etc.)

• Hence, carbide free structures were reported for nodule counts in the range of 500 Nod/mm$^2$ in 2,5 mm plate. It was also possible to get 6000 Nod/mm$^2$ in 2,5 mm.
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