Ultrapremium™ and Endurance Steels

Daniel Gynther
TimkenSteel Corporation
Outline

• TimkenSteel at a glance
• Ultra premium™ certified air-melt clean steel technology
  – What is clean steel? / Why is clean steel important?
  – Measuring and characterizing clean steel
  – Link between steel cleanness and component fatigue performance
• Endurance Steels
  – Three new, patent-pending steels combining ultra high-strength with high toughness
  – Power densification analysis
Overview

- Headquartered in Canton, Ohio
- Annual melt capacity of ~2 million tons
- Only focused North American SBQ producer
- Supplies more than 30% of seamless mechanical tube demand in North America

Alloy steel bars (SBQ)

TimkenSteel Applications

- Bearings
- Fuel injectors
- Gun barrels
- Crankshafts
- Tri-cone bits
- Percussion bits
- Energy CRA production
- CV joints
- Gears

Value-added solutions

Supply chain

Semi-heavy duty vehicle

Machining, honing and drilling

Components

Seamless mechanical tubing
What is Clean Steel?

- Various definitions of steel cleanness
  - Non-metallic inclusions
    - Type: oxides, sulfides, nitrides
    - Size range: critical size, macro vs. micro
  - Residual Solutes (Cu, Sn, Sb, As)

- All steels contain some concentration of non-metallic impurities
- Inclusions are of various types (compositions), sizes and shapes

Clean steel contains a minimal number of harmful inclusions
Why is Clean Steel Important?

- Inclusions can increase local stresses and initiate fatigue failure

![Stress Riser](image1)

**Stress Riser**

![Crack Initiation](image2)

**Crack Initiation**

![Crack Propagation](image3)

**Crack Propagation**
Why is Clean Steel Important?

- Inclusion-initiated fatigue failures

**Micro-inclusion**

**Macro-inclusion**

Rolling/Sliding  
Bending  
Axial
Why is Clean Steel Important?

- Effect of non-metallic inclusions on fatigue performance
  - Strong correlation between fatigue limit and hardness
    - Hardness is a proxy for strength (YS & UTS)
  - Fatigue limit data more scattered with high strength steels
  - Scatter in data attributed to variation in non-metallic inclusion populations

Why is Clean Steel Important?

- Improving fatigue life and power density

Steel cleanness affects component performance

Clean steels provide power density opportunities
What Size Inclusion can cause a Fatigue Failure?

It depends…

Diameter of typical human hair
What Size Inclusion can cause a Fatigue Failure?

- Highly dependent on loading of the component
  - Estimation based on fracture mechanics:
    
    \[ \sigma_{Fat} = \frac{2\Delta K_{th}}{\sqrt{\pi \text{area}}} \]

- Actual data from fatigue studies
  - General observation: fatigue failures can initiate at micro-oxides as small as 10 µm

\[ \Delta K_{th} = 4 \text{ MPa m}^{0.5} \]

\[ \geq 10 \mu m \]

\[ \geq 20 \mu m \]
Stressed Volume Concept

Determining the Probability of an Inclusion Initiated Fatigue Failure

- Largest oxide is seldom the one that initiates the failure

- Proportional to probability of having a critical size inclusion in the stressed volume of a loaded component

- Dependent on the population of critical size inclusions in steel

**Clean steel** has smaller and fewer critical sized oxide inclusions

Lower probability of having a critical oxide in the stressed volume
High-cycle axial fatigue study*

- Melt process/steel cleanness
  - Clean
  - Dirty

- Specimen size (stressed volume)
  - Small specimen: 33 mm$^3$
  - Large specimen: 781 mm$^3$

- Study results
  - Small specimen $\Delta$FS: ~ 5%
  - Large specimen $\Delta$FS: ~ 25%

What Size Inclusion can cause a Fatigue Failure?

- Oxide sizes observed at initiation sites of axial fatigue failures*

Small Specimen (33 mm$^3$)  
Large Specimen (781 mm$^3$)

Increased probability of finding a larger oxide inclusion in the larger stress volume

Steel Cleanness Measurement

• Proper measurement of steel cleanness is important
  - The manufacture of clean steel begins with the ability to accurately measure/characterize the inclusion population

• Two of the key steel cleanness measurement tools employed at TimkenSteel are:
  - Scanning electron microscope (SEM) image analyzers
  - High-resolution ultrasonic scanner
Steel Cleanness Measurement

Deficiencies of Traditional Methods

- Most of the industry steel cleanness standards developed many years ago (outdated)
- Insufficient inspection volume to detect statistically significant number of critically sized inclusions
- Focus on qualitative (or semi-quantitative) metrics with little correlation to application performance

Total oxygen content versus component life

No correlation
Steel Cleanness Measurement

Meeting industry standards does not provide entire picture

<table>
<thead>
<tr>
<th>ASTM Specification / Sample</th>
<th># Samples Insp Area (mm²)</th>
<th>B Thin</th>
<th>B Heavy</th>
<th>D Thin</th>
<th>D Heavy</th>
</tr>
</thead>
<tbody>
<tr>
<td>A534 (Carburizing Bearing Steels)</td>
<td>6 / 960</td>
<td>2.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>A1089 (Highly Loaded Bearing Steels)</td>
<td>6 / 960</td>
<td>1.5</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>SBQ A Sample</td>
<td>6 / 1200</td>
<td>0.5</td>
<td>0.0</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>TimkenSteel Sample</td>
<td>6 / 1200</td>
<td>1.0</td>
<td>0.0</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>VAR Sample</td>
<td>6 / 1200</td>
<td>0.5</td>
<td>0.0</td>
<td>0.5</td>
<td>0.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SEM Image Analysis</th>
<th>Conc of Oxides &gt; 10 μm (#/10³ mm²)</th>
<th>Conc of Oxides &gt; 20 μm (#/10³ mm²)</th>
<th>Oxide Area Total (μm²/mm²)</th>
<th>Oxide Area &gt; 100 μm² (μm²/mm²)</th>
<th>Maximum Inclusion (Area¹/²)max (μm)</th>
<th>SEV Least Squares Max Likelihood (Area¹/²)max (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SBQ A 32 / 7324</td>
<td>47.65</td>
<td>3.41</td>
<td>47.94</td>
<td>8.90</td>
<td>31.563</td>
<td>35.13 / 33.54</td>
</tr>
<tr>
<td>TMST 32 / 7079</td>
<td>3.15</td>
<td>0.0</td>
<td>11.72</td>
<td>0.43</td>
<td>14.106</td>
<td>19.89 / 19.34</td>
</tr>
<tr>
<td>VAR 32 / 6682</td>
<td>1.20</td>
<td>0.0</td>
<td>2.34</td>
<td>0.21</td>
<td>18.06</td>
<td>20.60 / 14.98</td>
</tr>
</tbody>
</table>

Conclusion: Very different cleanness levels with materials rated for the same spec!
Fatigue Performance vs. Steel Cleanness

Rotating Bending Fatigue (RBF) of High Strength 4140 Steel

<table>
<thead>
<tr>
<th>Sample</th>
<th>B Thin</th>
<th>B Heavy</th>
<th>D Thin</th>
<th>D Heavy</th>
<th>Combined Non-Met Rating*</th>
<th>O Total</th>
<th>Conc. of Critical Oxides (&gt; 10 µm)</th>
<th>RBF Fatigue Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A866</td>
<td>2.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>6.0</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Group A</td>
<td>1.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>3.5</td>
<td>7</td>
<td>21.7</td>
<td>877</td>
</tr>
<tr>
<td>Group B</td>
<td>1.0</td>
<td>1.0</td>
<td>0.5</td>
<td>0.5</td>
<td>3.8</td>
<td>7</td>
<td>8.1</td>
<td>955</td>
</tr>
<tr>
<td>Group C</td>
<td>1.5</td>
<td>1.0</td>
<td>1.0</td>
<td>0.5</td>
<td>4.8</td>
<td>15</td>
<td>74.5</td>
<td>804</td>
</tr>
</tbody>
</table>

*Combined Non-Met Rating = \(B_T + D_T + 1.5(B_H + D_H)\)

Selection of proper cleanness metrics is critical
Fatigue Performance vs. Steel Cleanness

Rotating Bending Fatigue (RBF) of High Strength 4140 Steel

Which metric is better for predicting fatigue performance of cleaner steels?
Can you Reduce the #/Size of Critical Inclusions?

• Yes! There are multiple ways to achieve this
  • TimkenSteel Ultrapremium™ certified air-melt technology reduces the size and concentration of harmful oxide inclusions
• Our most advanced clean steel technology is defined by:
  – A carefully designed steelmaking practice
  – Advanced steel cleanness characterization metrics (SEM Image Analysis)
  – Applicable to most steel grades
• It is our highest quality level
  – A level of cleanness approaching VAR
  – Complements our suite of other clean steels including Parapremium, VacTec, MicroTec and more
# Ultrapremium Technology Certification

## 2.3. Steel Certificate of Test Limits Values

### 2.3.1. For Micro Inclusions:

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Provisional Limits*</th>
</tr>
</thead>
<tbody>
<tr>
<td>The average concentration of inclusions ≥ 10 μm in √Area per unit inspected area</td>
<td>≤ 0.02 #/mm²</td>
</tr>
<tr>
<td>The average concentration of inclusions ≥ 20 μm in √Area per unit inspected area</td>
<td>≤ 0.003 #/mm²</td>
</tr>
</tbody>
</table>

### 2.3.2. For Macro Inclusions (Stringers):

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Provisional Limits*</th>
</tr>
</thead>
<tbody>
<tr>
<td>The average concentration of stringers ≥ 100 μm in length in the order or heat.</td>
<td>≤ 0.02 #/mm²</td>
</tr>
<tr>
<td>The average concentration of stringers ≥ 200 μm in length in the order or heat.</td>
<td>≤ 0.005 #/mm²</td>
</tr>
</tbody>
</table>

### 2.3.3. For Statistics of Extreme Values:

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Provisional Limits*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum sized inclusion likely (√Area) – Max Likelihood</td>
<td>≤ 35 μm</td>
</tr>
</tbody>
</table>

*Provisional limits are conservative

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**Micro inclusion:** oxide

**Macro inclusion:** oxide stringer
Case Study: Gear Performance Improvement

- Gear set transmitting up to 400 horsepower in a volume about the size of your fist
- Manufacturing / heat treat optimizations improved performance, but still needed more
- Multiple steel suppliers were being used
- **Ultra premium** steel was offered as a solution to test for improved fatigue life
  - 10 gear sets reached 100 hours with no signs of fatigue under harshest test conditions (historically multiple failures occurred prior to 100 hours)
- Gear customer now uses **Ultra premium** steel in multiple applications
  - Has reported increase in power throughput and decrease in gear-related claims
Summary – Clean Steel

- **What is clean steel?**
  - Clean steel has the least probability of having a critical inclusion in the stressed volume

- **Why is clean steel important?**
  - Non-metallic inclusions (especially oxides) have a detrimental impact on fatigue performance

- **Steel cleanness measurement**
  - Industry standards do not provide entire picture

- **Fatigue performance vs. steel cleanness metrics**
  - Good correlation between concentration of critical size oxide inclusions and fatigue performance

- **TimkenSteel Ultra premium™ certified air-melt technology reduces the size and concentration of harmful oxide inclusions**
TimkenSteel Endurance Steels

- Improvements in component performance and power density can also be achieved by using higher strength, higher toughness steels

- TimkenSteel endurance steels are three new, patent pending steels with ultra-high strength and high toughness
  - High strength provides greater load bearing capacity and fatigue strength
    - Requires clean steel to take full advantage
  - High toughness provides greater resistance to fracture

- Affordable solution for power densification

- Broad range of applications
  - Shafts, gears
Patent pending endurance steels fill the green NEW oval (UHS230-47, UHS230-44 and UHS250-35)
High Fatigue Strength

- Rotating bending fatigue (RBF) results
- Limited number of samples from small scale laboratory heats
- Recently produced 120 tons of UHS250-35 and UHS230-47 and will complete a full test schedule
- Plan to produce and test UHS230-44 as well
High Fracture and Fatigue Resistance

- Fatigue limits shown are calculated as 0.5 x UTS
- Measured fatigue limits
  - UHS230-44: 150 ksi
  - UHS230-47: 135 ksi
  - UHS250-35: 160 ksi
Power Densification Analysis

• Analysis framework: ANSI/AGMA 2001-D04
  – “Fundamental Rating Factors and Calculation Methods for Involute Spur and Helical Gear Teeth”
  – Calculation of bending and contact stresses based on gear set and operating parameters
  – Comparison to AGMA grade 3 allowable values and to values for TimkenSteel Endurance steels

• Gear set
  – Gear 1: 2” pitch diameter, 35 tooth gear, 2” face width
  – Gear 2: 4” pitch diameter, 55 tooth gear, 2” face width

• Baseline calculations
  – @ 330 hp, reached bending stress limit of 75 ksi (AGMA grade 3)
    – Contact stress below allowable limit

• Power densification calculations based on Endurance Steel bending stress limit of 110 ksi
  – Increase horsepower or decrease gear face width until 110 ksi limit is reached
Contact stress increases from 195 to 230 ksi (Below the 275 ksi limit)
Summary – Endurance Steels

• Three new, patent pending steels with ultra high-strength and high toughness

• Affordable solution for power densification
  – Potential to reduce gear set mass by as much as 30% or increase power throughput by as much as 45%

• Clean steel technology enables full achievement of performance improvements
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