Role of Ladle Refining and Vacuum Degassing in Railroad Wheel Steel Cleanliness

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Recent Capital Projects

- Projects totaling more than $60M USD
- Steelmaking
  - New basic electric arc furnace
  - Twin-tank ladle refining and vacuum degassing station
- Synchronized Inclined Rotary Dishing Press (SIRD) Installation
- Goals: Produce ultra-clean, low-stress, high-precision wheels
Melt Shop Installation Update

Phase 1 of project completed at the end of Dec 2013:

• Revamped Electric Arc Furnace (continued acid practice)
• Replaced 30 MVA transformer with a 50 MVA
• Installed new water cooling system & bag house was upgraded
• Installed new 110-ton crane

Phase 2 completed Jan 2014 - 2015:

• Twin tank ladle refining/vacuum degassing facility
• Slag rake system
• Change-over to basic steelmaking practice – January 2015
Electric Arc Furnace Revamp

Before

During

After
Ladle Tilt Stand/Slag Rake System
For Removing EAF Slag
New Twin-Tank, Ladle Refining / Vacuum Degassing (LFVD) Station
Overview of Ladle Refining & Vacuum Degassing Station
Twin-Tank LFVD Station

Two stationary vacuum tanks

Ladle furnace roof (for heating) swings between tanks

Two gantry car vacuum cover lids
LFVD Stations with ladle being heated

- Chute for adding alloys via conveyor system
- Vacuum cover lid moves into position on rails
- Pulpit
- Ladle furnace roof (heating)
Material Handling System-Precise Alloy Additions

Upper conveyor system for transporting alloys to ladle

Alloy storage bins

Weighing hoppers

Lower conveyor system
Wire Feeding Systems – Precise Alloy Additions

Guide tube systems directs wire into each tank
Steel Cleanliness Improvements: Implications for Heavy Haul Wheels

• Wheels are subject to a dynamic loading environment - impacts

• For steels with similar strength (i.e., hardness), dynamic fracture toughness is a strong function of the steel’s cleanliness, micro-porosity, and microstructure

• Under heavy axle loads, rim fatigue cracks can initiate internally at stress concentrations (i.e., voids and inclusions)
  – Hard oxide inclusions, primarily alumina, are likely sources of initiation
  – Interdendritic sulfides reduce ductility and toughness

• Evidence suggests that steels with a high degree of cleanliness are less susceptible to shattered rims & rolling contact fatigue (i.e., shelling)
Steel Cleanliness Improvements

- Verification by two methods:
  - ASTM Standard Practice E1245 (average & worst field area %’s of oxides, voids, & sulfides) Basis for AAR specification.

<table>
<thead>
<tr>
<th></th>
<th>Mean Volume % Voids + Oxides</th>
<th>Maximum Volume % Voids + Oxides</th>
<th>Mean Volume % Sulfides</th>
<th>Maximum Volume % Sulfides</th>
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</thead>
<tbody>
<tr>
<td>Old Steelmaking</td>
<td>0.0095%</td>
<td>0.150%</td>
<td>0.137%</td>
<td>0.365%</td>
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<td>Process</td>
<td></td>
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<td>0.045%</td>
<td>0.120%</td>
<td>0.224%</td>
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<td>% Improvement with</td>
<td>23%</td>
<td>70%</td>
<td>12%</td>
<td>39%</td>
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<tr>
<td>New Process</td>
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</table>
Steel Cleanliness Improvements

– **Automated Steel Cleanliness Analysis Tool (ASCAT)**
  
  • Based on computer-controlled scanning electron microscopy
  • Provides detailed size distribution and chemistry information of inclusions in steel
  • Has been shown to provide good correlation with ultrasonic test data
  • Developed by US Steel, Carnegie Mellon University & RJ Lee Group
ASCAT

• Samples are taken from the ladle
• Gives information on number of inclusions & area fraction of inclusions in the samples
• Provides information on specific inclusion types and chemistry
• Not just – “Oxide” but *specific type of oxide*
ASCAT

• Number Density – The count (number) of inclusions seen by the computer on a polished steel sample surface in the area scanned.

• Area Fraction – The area percentage of the polished steel sample surface that is inclusions, and not steel
New Steelmaking Practice Results: Reduction in Oxide Inclusions
New Steelmaking Practice Results: Reduction in Oxide Inclusions
Removal of Oxide Inclusions During Vacuum Degassing

Graph Shows Number / square cm
Removal of Oxide Inclusions During Vacuum Degassing

Graph Shows Area Fraction

Classes
- Solid Oxide-CaS/MnS
- Si/Al/Ca/S
- Si/Al/Mg/Ca/S
- Si/Al/Mg/Ca
- Liquid
- Spinel - Al/Ti
- Solid CaO
- Cal.Alum. - Spinel
- Partially Liquid-CaS
- Lime-rich Solid Oxide-CaS
- Solid Alumina-CaS
- Solid Oxide-CaS
- Solid Alumina-CaS/MnS
- Spinel-MnS
- Partially Liquid
- Solid CaAl2O3
- Spinel
- Al/Ti
- Ti/Al
- Al/Ti-MnS
- Ti-rich
- Solid Alumina
- Solid Alumina-MnS
Steel Cleanliness

- Removal of oxides that are deleterious to dynamic fracture toughness and rolling contact fatigue require the right combination of slag chemistry and slag/metal interaction
- Most notable is the presence of smaller and fewer alumina inclusions which results in greater resistance to fatigue & fracture
- Reduced area fraction and number density of inclusions
- Hydrogen is measured, and controlled with degassing
New Steelmaking Practice Results: Impact on Sulfide Inclusions

Number Density of Sulfide Inclusions

Area Fraction of Sulfide Inclusions
New Steelmaking Practice Results: Impact on Sulfide Inclusions

• Similar area fraction of sulfides, but higher number density → sulfides are smaller.
• We are now re-sulfurizing to help insure machinability – Sulfur assists machining
• Finish boring & tread turning downstream
• Sulfide content could be made much lower
New Steelmaking Practice Results: Impact on Sulfide Inclusions

- 17% more sulfide inclusions in the 1 to 2.5 micron (SMALL) range for steel produced using the new practice.
Improvement in Sulfide Morphology

• Even at the same sulfur levels (to maintain acceptable machinability), the new steelmaking practice results in small, globular sulfides with a complete lack of large, eutectic sulfides. Eutectic sulfides tend to reduce tensile ductility and toughness.
New Steelmaking Practice Results: Improvement in Mechanical Properties

<table>
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<tr>
<th></th>
<th>Tensile Strength (ksi)</th>
<th>Yield Strength (ksi)</th>
<th>% Elongation</th>
<th>% Reduction in Area</th>
<th>ASTM Grain Size #</th>
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<tr>
<td>Old Steelmaking Process</td>
<td>98.1</td>
<td>56.9</td>
<td>22.9</td>
<td>44.9</td>
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<td>57.9</td>
<td>24.8</td>
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<td>7.8</td>
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<td>Improvement</td>
<td>1%</td>
<td>2%</td>
<td>8%</td>
<td>9%</td>
<td>12%</td>
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- Room temperature tensile test data of AAR Grade F axles
- Clean steelmaking practices with improved deoxidation practices results in:
  - Finer-grained
  - Slightly higher strength
  - Higher ductility
Upcoming Technical Paper at WCRR, Milan, Italy

• Kato, et al., to be presented May 30 – June 2
• Failure data (broken rim, AAR Why Made Code 68) of “clean steel” Class C vs conventional wheels examined
• “Higher fracture toughness wheels were predicted to have much lower VSR rates than conventional wheels.”
• “Higher fracture toughness wheel steels make it possible to reduce the rate of VSR failures in wheels.”
Synchronized Inclined Rotary Dishing Press (SIRD) Installation: Higher Precision-Forged Wheels

- **Principle:** Incremental deformation using an inclined top forging die that maintains constant contact while both the top & bottom dies rotate to maintain work piece stability.

- **Advantages:**
  - Closer to net-shape prior to machining
  - Tighter overall dimensional tolerances
  - Rotundity and eccentricity between rough bore and tread significantly improved → **Reduction in overall stress state of the railroad**
  - Expected to result in consistently larger tape sizes with more useable wear metal in the rim
Synchronized Inclined Rotary Dishing Press (SIRD) Preliminary Results

• Radial run-out contour plots show improvement in the concentricity of the hub and rim with SIRD process

• Rim thickness is more consistent around the circumference

• Tape size is more uniform

• Minimal variation in front face/back face rim thickness & hub wall thickness
Questions?