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**

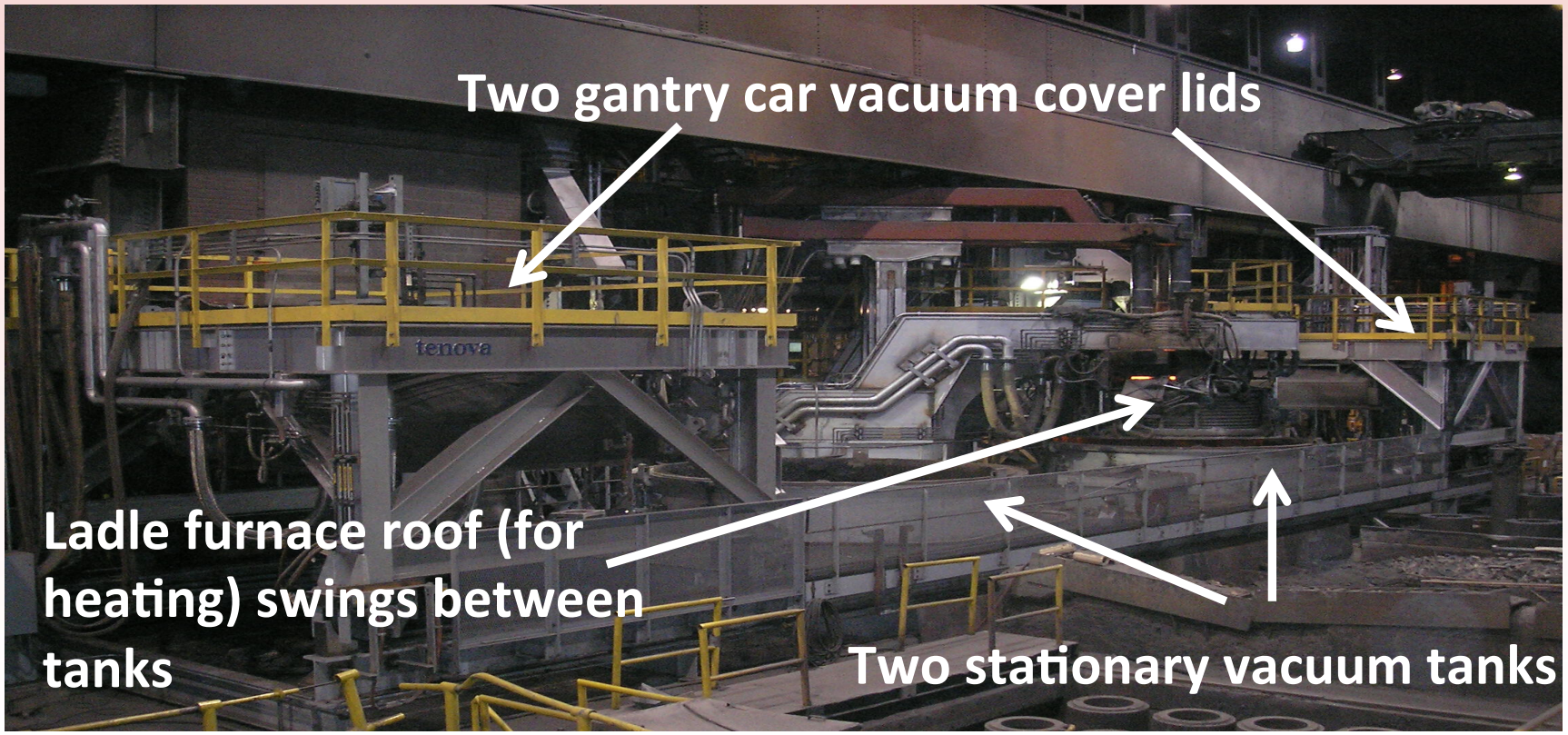
Electric Arc Furnace Revamp

Ladle Tilt Stand/Slag Rake System For Removing EAF Slag

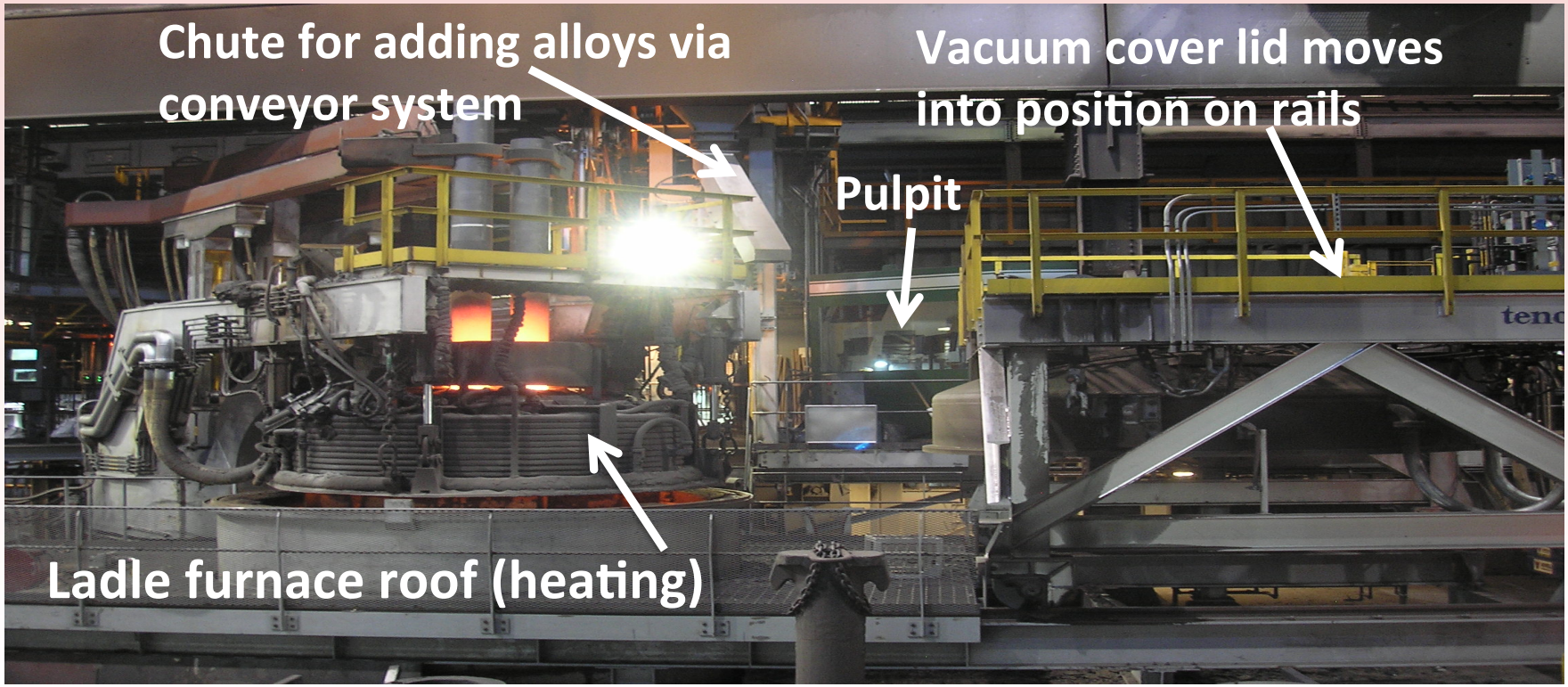
New Twin-Tank, Ladle Refining / Vacuum Degassing (LFVD) Station

Overview of Ladle Refining & Vacuum Degassing Station

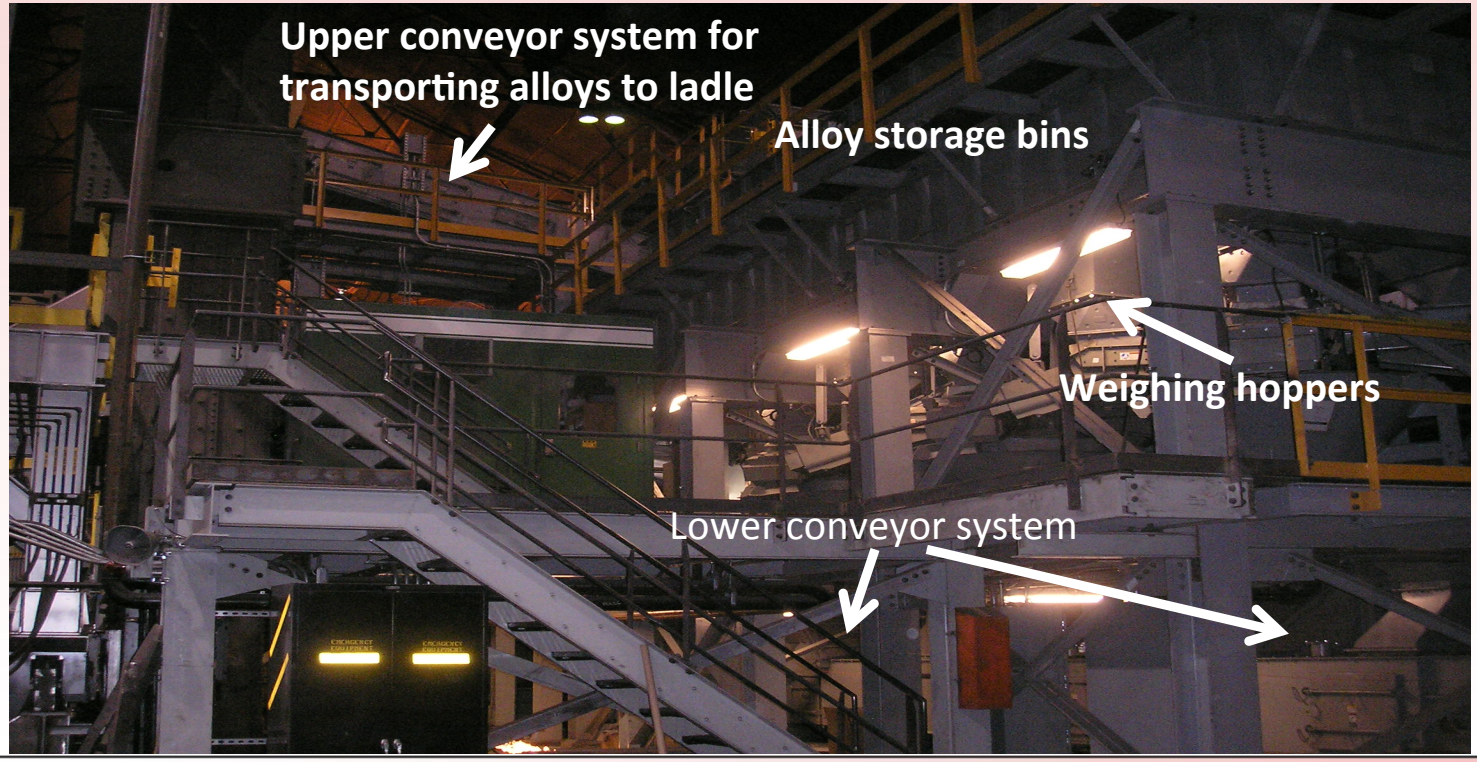
Twin-Tank LFVD Station



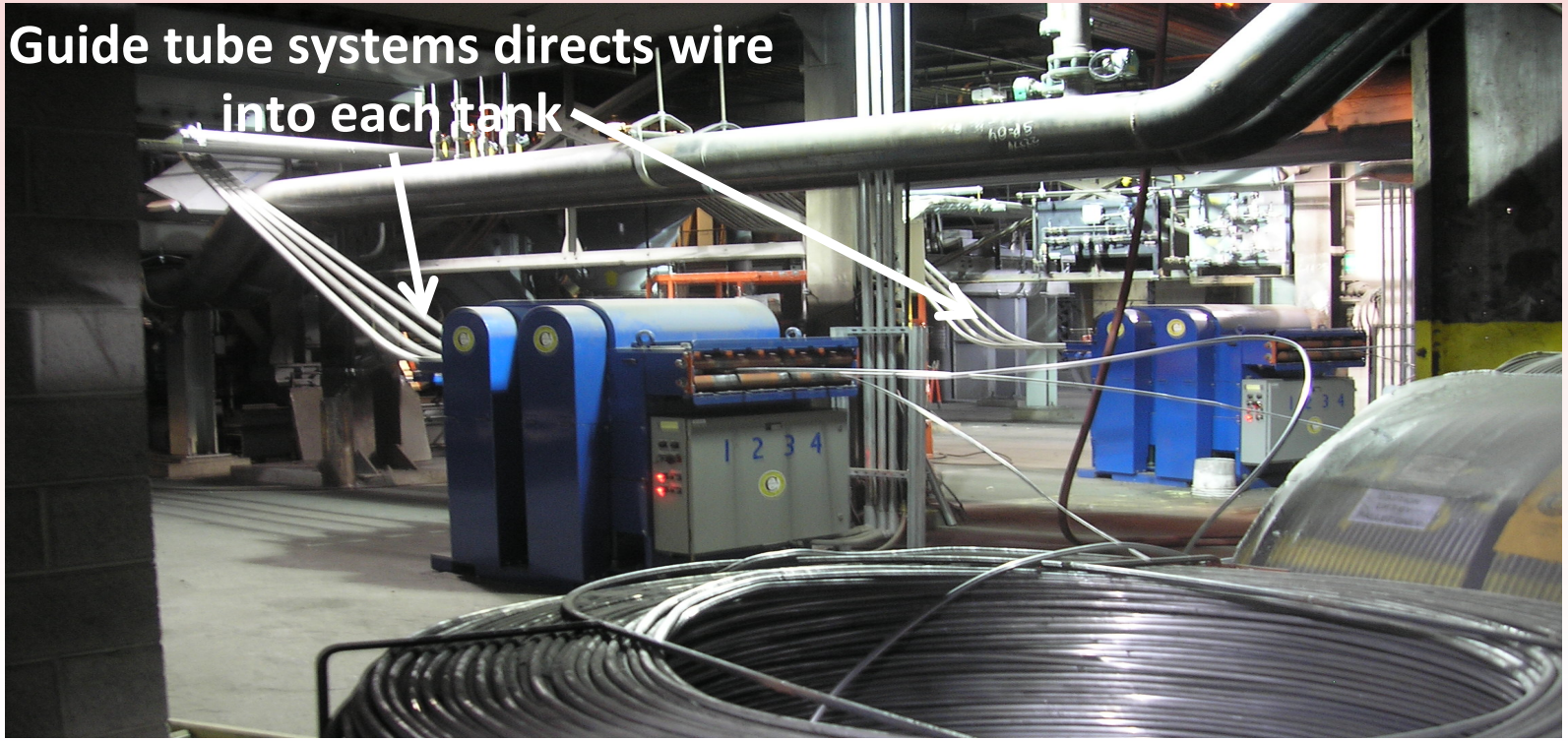
LFVD Stations with ladle being heated



Material Handling System-Precise Alloy Additions



Wire Feeding Systems – Precise Alloy Additions



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.**

	Mean Volume % Voids + Oxides	Maximum Volume % Voids + Oxides	Mean Volume % Sulfides	Maximum Volume % Sulfides
Old Steelmaking Process	0.0095%	0.150%	0.137%	0.365%
New Steelmaking Process	0.0073%	0.045%	0.120%	0.224%
% Improvement with New Process	23%	70%	12%	39%

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**

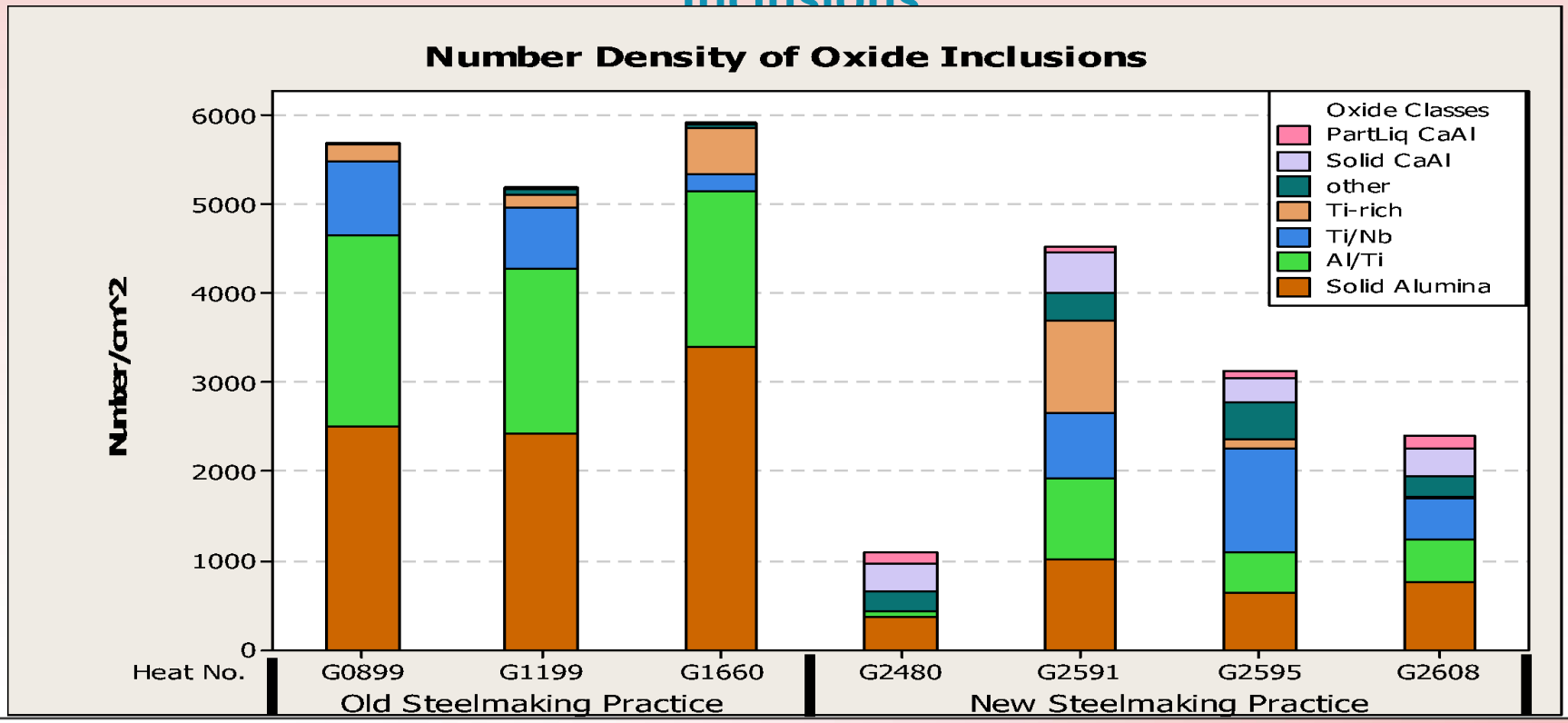
ASCAT

- 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



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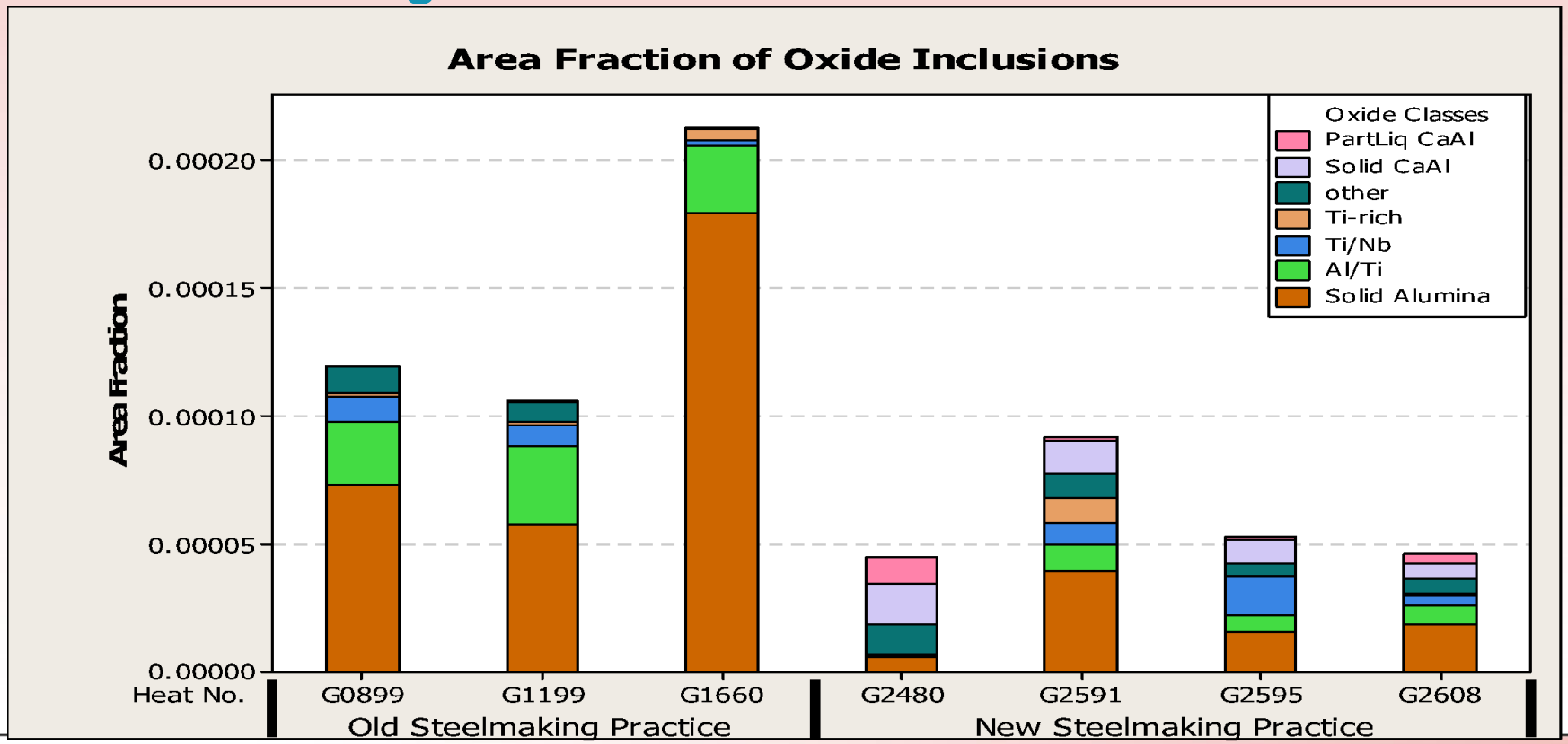
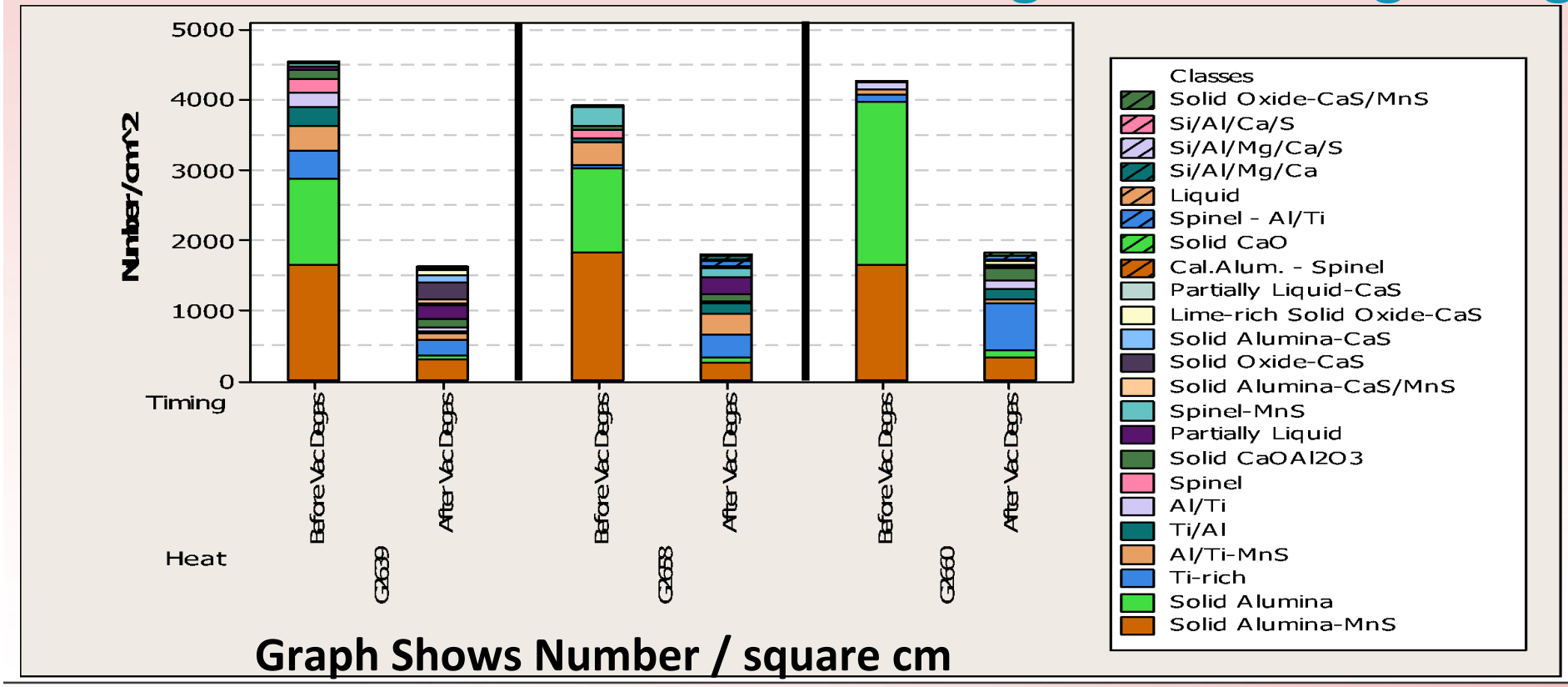
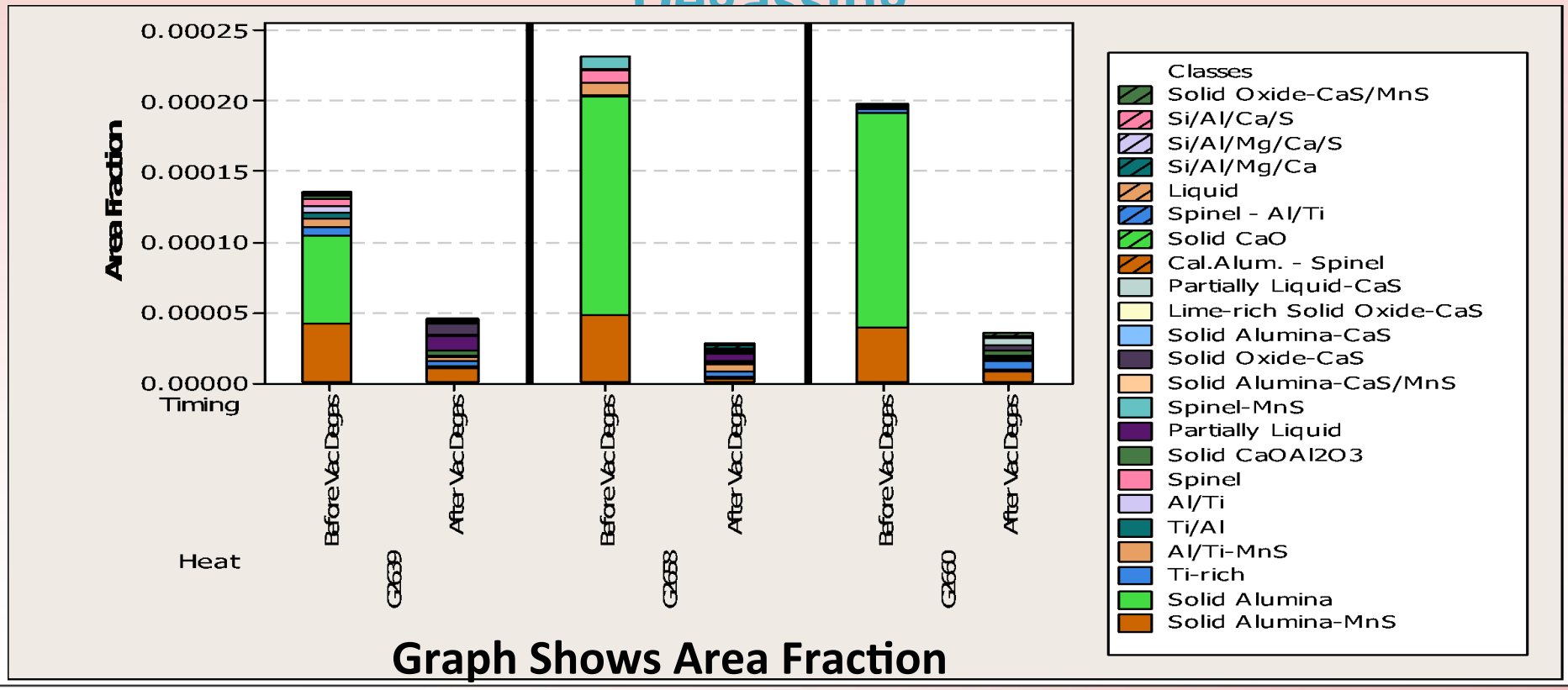


Removal of Oxide Inclusions During Vacuum Degassing



Graph Shows Number / square cm

Removal of Oxide Inclusions During Vacuum Degassing

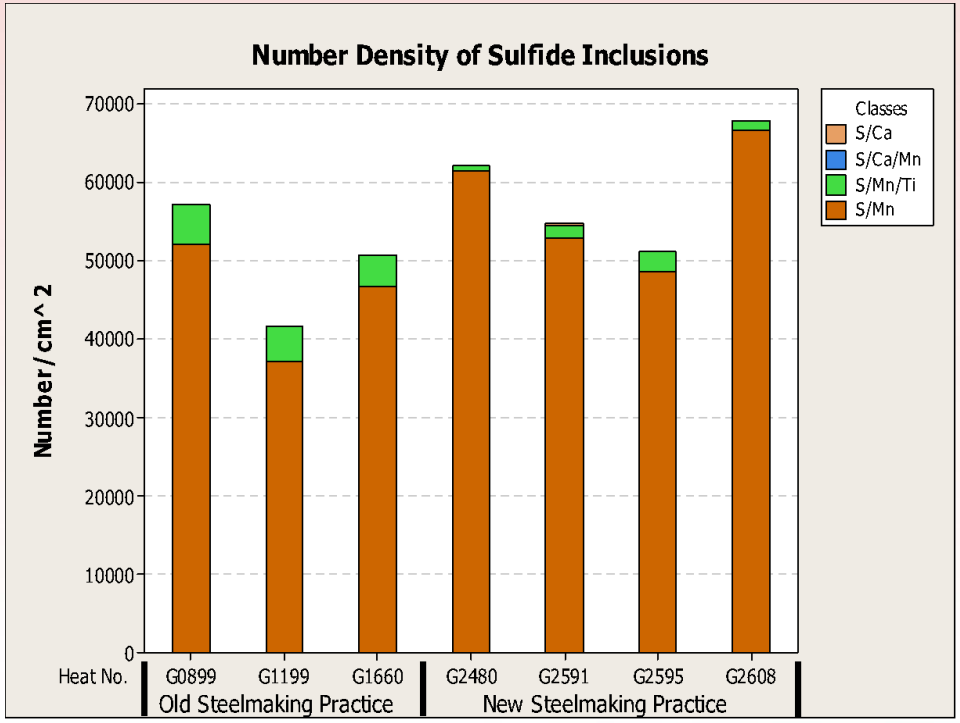


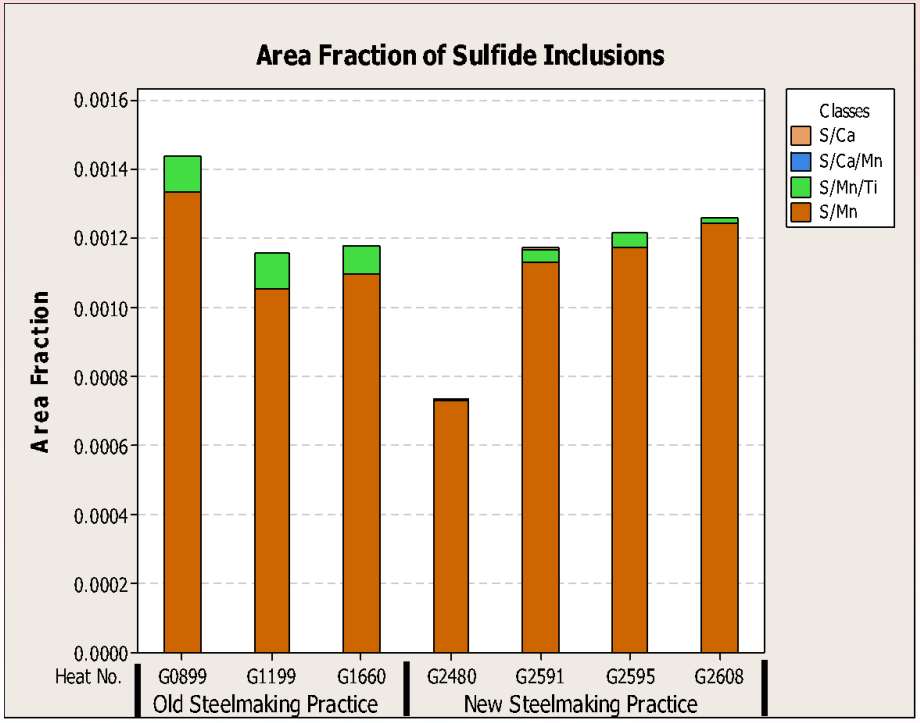
Graph Shows Area Fraction

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

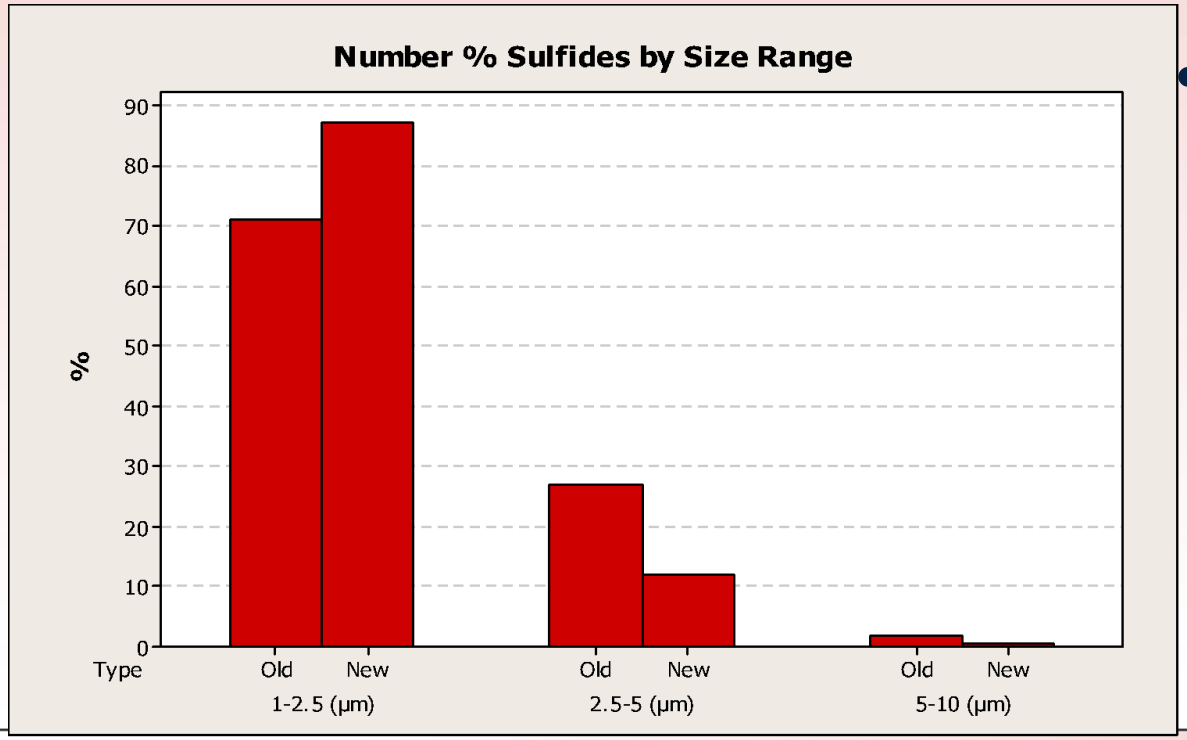




New Steelmaking Practice Results: Impact on Sulfide Inclusions

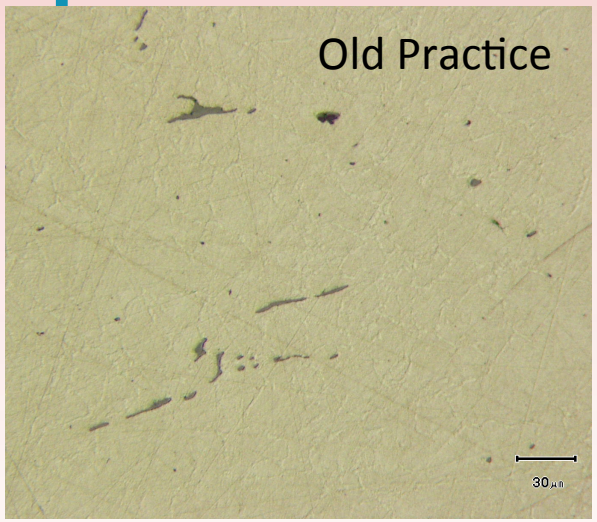
- **Similar area fraction of sulfides, but higher number density → sulfides are smaller.**
- **We are now re-sulfurizing to help insure machinability – Sulfur assists machining**
- **Finish boring & tread turning downstream**
- **Sulfide content could be made much lower**

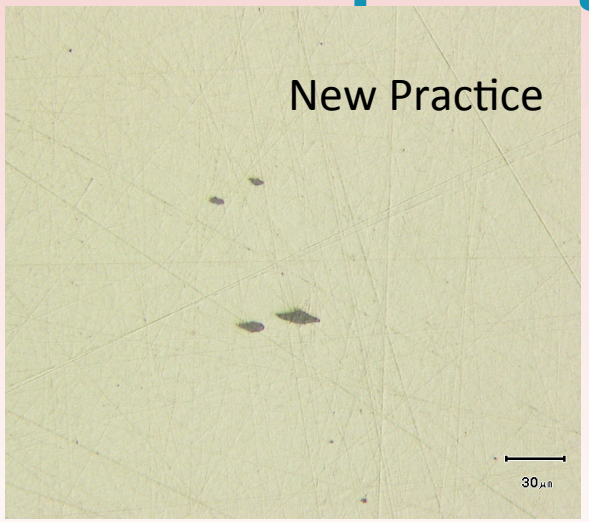
New Steelmaking Practice Results: Impact on Sulfide Inclusions



- **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

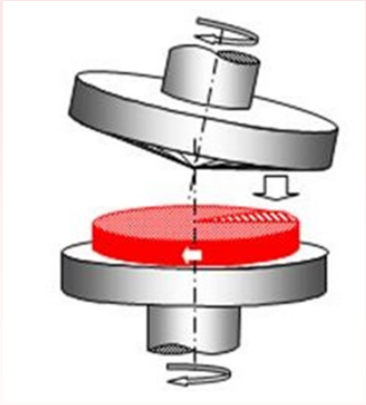
	Tensile Strength (ksi)	Yield Strength (ksi)	% Elongation	% Reduction in Area	ASTM Grain Size #
Old Steelmaking Process	98.1	56.9	22.9	44.9	7.0
New Steelmaking Process	98.7	57.9	24.8	48.8	7.8
Improvement:	1%	2%	8%	9%	12%

- 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

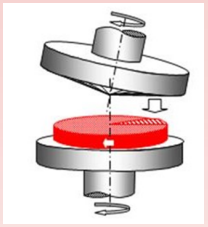
Upcoming Technical Paper at WCRR, Milan, Italy

- 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

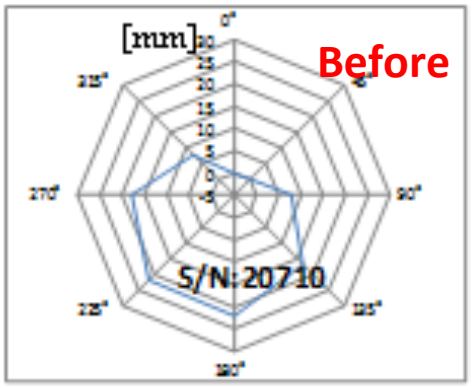


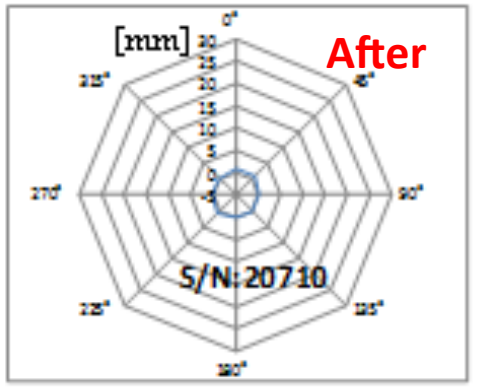
- **Principle: Incremental deformation using an inclined top forging die that maintains constant contact while both the top & bottom dies rotate to maintain work piece stability**
- **Advantages:**
  - **Closer to net-shape prior to machining**
  - **Tighter overall dimensional tolerances**
  - **Rotundity 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?