Improving Inoculation in Thin Sectioned Ductile Iron Castings

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Introduction:

The Kingsbury Castings Division of Hiler Industries has been producing ductile iron using the shell process for molding since the middle 1970's. Shell molded castings are often intricate designs, requiring great attention to detail when melting, molding and pouring. Castings with thin sections, less than ¼ inch thick, are common due to the ability of the shell mold to remain stable during molding and pouring. Thin knife gates are often used to allow for cast parts to break off easily and cleanly. Chill defects are a major concern when castings less than 1/8 inch thick are poured.

Focusing on improving inoculation in order to reduce chill became the mandate for our foundry. Periodically I would pour and analyze chill wedges from the last iron poured to benchmark a baseline of how well our inoculation practice was working. Once a baseline was established, the effects of changing the inoculation practice could be determined.

The goal was to improve inoculation without altering the final iron chemical composition, particularly the silicon, sulfur and magnesium levels. Various proprietary inoculants were tested over the last 2 years. The results of some tests were positive while others were others were either neutral or negative.

Additional tests combining an oxy-sulfide containing inoculant with both our standard and modified inoculation practices were proposed. The oxy-sulfide containing inoculant is called Sphere-o-Dox S, a patented product (U.S. Patent 6,293,988B1) produced by ASI International, Ltd. This report will briefly summarize the results of those trials.

Purpose of Study:

Improve the current inoculation practice in ferritic grade ductile iron by using ASI's Sphere-O-Dox S either as an addition and/or partial substitution of the current calcium-bearing 75% ferrosilicon inoculant, Calsifer 75. Other modifications in inoculation included a combination of VP216 and Sphere-o-dox S Inoculants.

Description of Test:

The tests were conducted on a ferritic ductile-base iron. The ductile-base iron was melted in two 6000 lb, medium frequency, coreless induction furnaces. The base iron was magnesium treated by the sandwich method, using steel punchings for a cover over the magnesium ferrosilicon, in a 1200 lb batch weight open tundish ladle. Typically 19 lb of 6% 5R2 MgFeSi is used with 8 lb of cover steel for a 1200 lb batch in the treatment vessel.

5R2 Magnesium Ferrosilicon Specifications

%Mg	%Si	%Ce	Total % Rare Earth	%Ca	%Al
5.0 – 6.0	43 - 48	0.45 – 0.60	0.75 – 1.15	0.8 – 1.3	1.2 Max

The treated iron was then split into two 600 lb. open lip pouring ladles, inoculated and transferred to the pouring line. One ladle served a control group using the standard inoculation practice of 5 lb of Calsifer 75 FeSi inoculant per 600 lb ladle. (Thin section work requiring additional chill reduction uses 17 g Germalloy K15 cast inoculant inserts in the mold.) The other one was used for experimental modified practice.

A W3 chill wedge, a nodularity coupon and a chilled iron disk were poured at the end of the ladle to document the results. The chill wedges were cooled in the mold to prevent pearlite formation.

Proprietary Inoculant Compositions:

Calsifer 75: 75% Calcium Bearing Ferrosilicon Inoculant

%Si	%Al	%Ca
74 - 79	0.75 – 1.5	1.0 – 1.5

VP216: High Aluminum Inoculant

%Si	%Al	%Ca
68 -73	3.2 – 4.5	0.3 – 1.5

Sphere-o-dox S: Oxysulfide Inoculant Booster

%Si	%Oxy sulfides (Ca + Al + S + O_{-2} + Mg)
36 – 37	32 - 35

Test Procedure: Standard and Experimental Inoculation Practice

Group	Standard Inoculation	Experimental Inoculation
1	5 lb Calsifer 75	5 lb Calsifer, 0.6 lb Sphere-o-dox S Inoculant
2	5 lb Calsifer 75	5 lb Calsifer, 0.3 lb Sphere-o-dox S Inoculant
3	5 lb Calsifer 75	4 lb Calsifer, 1 lb Sphere-o-dox S Inoculant
4	5 lb Calsifer 75	5 lb VP216, 1 lb Sphere-o-dox S Inoculant
5	5 lb Calsifer 75	5 lb Calsifer, 1 lb Sphere-o-dox S Inoculant

Chemical Analysis:

Chemical Analysis was obtained using the following equipment: Spectro Max CCD Spectrometer and a LECO CS 300 Carbon and Sulfur Analyzer.

Chemical Analysis: *Standard Inoculation Ladles

#	C	Si	S	Mg	Mn	Cu	P	Cr	Mo	Ni	Ti	Al
1	3.65	**2.58**	**.009**	**.038**	.28	.089	.019	.032	.003	.035	.005	.011
2	3.62	**2.63**	**.011**	**.040**	.28	.092	.018	.031	.003	.029	.005	.012
3	3.63	**2.61**	**.009**	**.041**	.27	.090	.018	.032	.003	.030	.005	.011
4	3.65	**2.58**	**.009**	**.037**	.27	.057	.016	.035	.004	.024	.005	.013
5	3.66	**2.57**	**.008**	**.033**	.28	.058	.017	.035	.003	.027	.005	.012

*Standard Inoculation: 5 lb Calsifer75/600lb Ladle

Chemical Analysis: **Experimental Inoculation Ladles

#	C	Si	S	Mg	Mn	Cu	P	Cr	Mo	Ni	Ti	Al
1	3.61	**2.80**	**.013**	**.040**	.25	.12	.018	.033	.003	.034	.005	.013
2	3.65	**2.75**	**.012**	**.037**	.24	.12	.018	.032	.002	.033	.005	.012
3	3.61	**2.64**	**.014**	**.044**	.26	.11	.018	.035	.003	.042	.005	.014
4	3.68	**2.51**	**.012**	**.033**	.28	.06	.017	.036	.003	.026	.005	.015
5	3.67	**2.62**	**.012**	**.039**	.27	.06	.016	.032	.003	.025	.005	.014

**Experimental Inoculation/600 lb. Ladle:

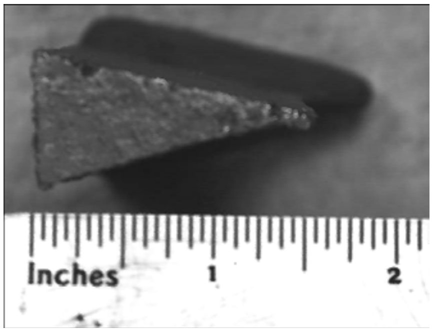
Ladle 1: 5lb Calsifer + 0.6 lb Sphere-o-dox S
Ladle 2: 5lb Calsifer + 0.3 lb Sphere-o-dox S
Ladle 3: 4lb Calsifer + 1 lb Sphere-o-dox S
Ladle 4: 5lb VP216 + 1 lb Sphere-o-dox S
Ladle 5: 5lb of Calsifer + 1 lb Sphere-o-dox S

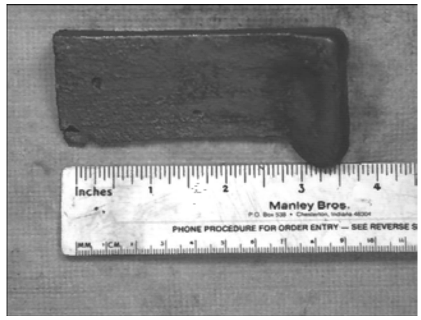
Note: A comparison of the elements most affected by the experiments shows a slight increase in Sulfur levels, but still within our specification. Both Silicon and Magnesium levels were unaffected by the experimental inoculation. No other elements were affected by the experimental practice.

Chill Wedge Analysis :

A W3 chill wedge was poured in each ladle of this study. Chill depth of each experimental sample was compared to a standard poured simultaneously. The wedge samples were broken in half. The chill depths were recorded. The samples were then prepared for metallographic examination. The nodularity and nodule count were taken at both the thicker body, and at the tip, to compare effectiveness in varying section size.

W3 Chill Wedge: ¾ in. wide at top, 1 ½ in. taper height, and 3” Long with a 1 inch riser





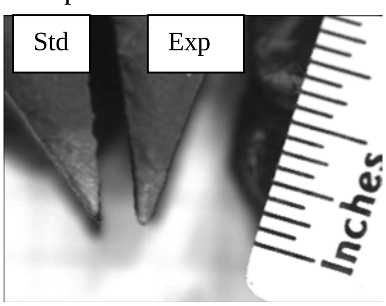
Chill Depth Analysis (Inches):

Ladle #	Standard	Experiment	Difference	% Chill Reduction
1	.35	.20	.15	43
2	.46	.30	.16	35
3	.61	.42	.19	31
4	.38	.10	.28	74
5	.37	.20	.17	46

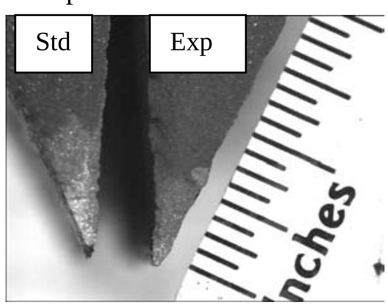
Note: The results of Chill Depth illustrated that Chill was reduced by 31 to 74%. The greatest reduction in chill depth occurred when 1 lb of Sphere-o-dox S was combined with 5 lbs of VP216.

Macro View Comparison of the Broken Wedges:

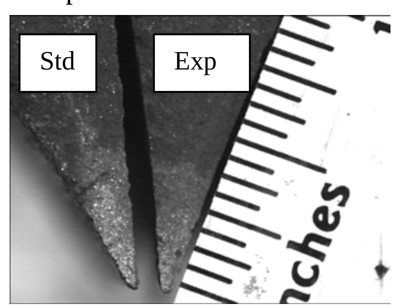
Group 1



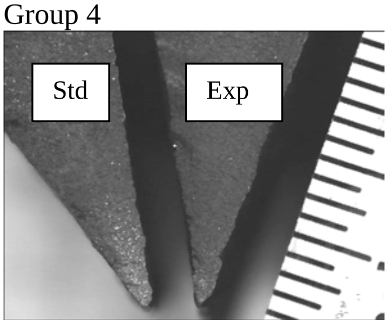
Group 2



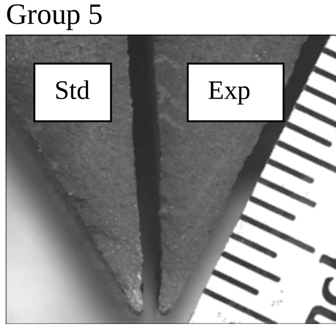
Group 3



Group 4



Group 5



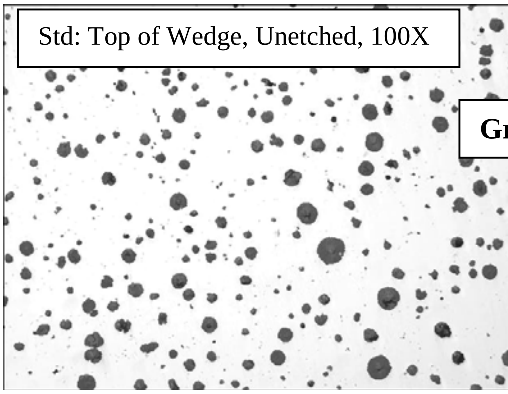
Standard Inoculation: 5 lb Calsifer 75/600lb Ladle

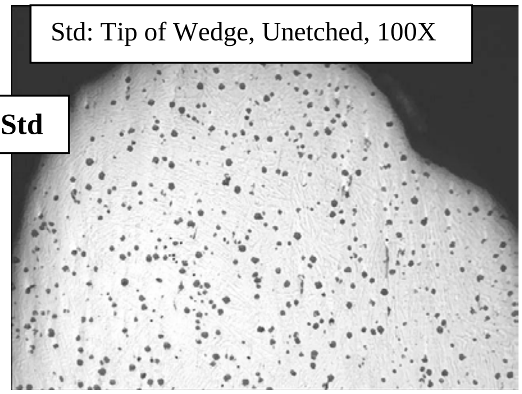
Experimental Inoculation/600 lb. Ladle:
Ladle #1: 5lb Calsifer + 0.6 lb Sphere-o-dox S
Ladle #2: 5lb Calsifer + 0.3 lb Sphere-o-dox S
Ladle #3: 4lb Calsifer + 1 lb Sphere-o-dox S
Ladle #4: 5lb VP216 + 1 lb Sphere-o-dox S
Ladle #5: 5lb of Calsifer + 1 lb Sphere-o-dox S

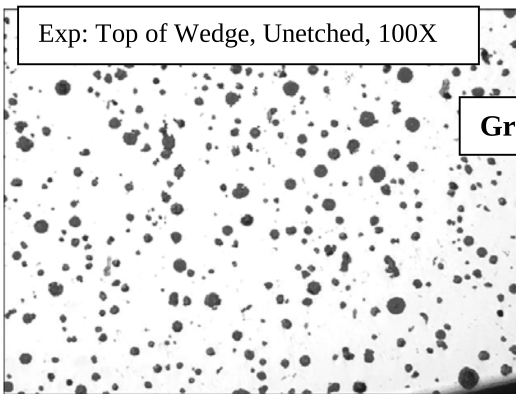
<u>Chill Wedge Microstructure Analysis:</u>

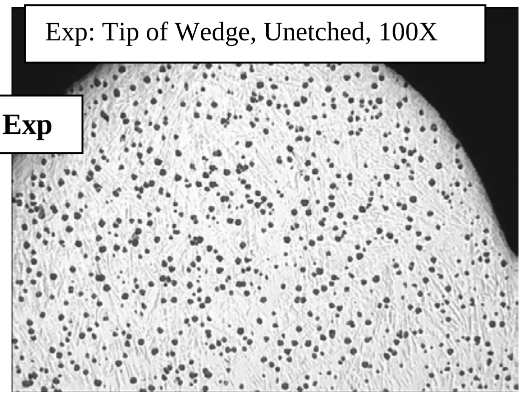
Nodule density is a good indication of inoculation effectiveness. Photomicrographs were taken at both the Tip and the Top of the chill wedge to illustrate inoculation effectiveness throughout the change in section thickness. The inoculation effectiveness can be compared visually between the sample groups.

Group 1 - Std: 5 lb Calsifer / Exp: 5 lb Calsifer + 0.6 lb Sphere-o-dox S

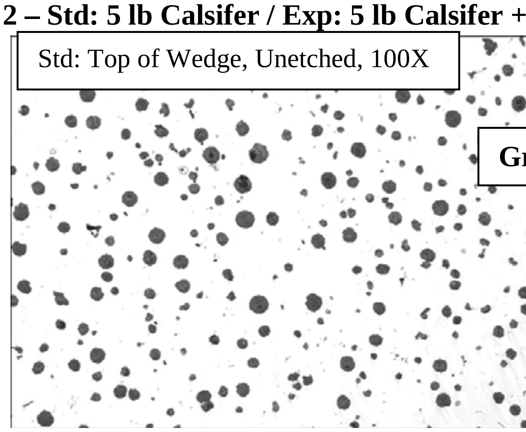


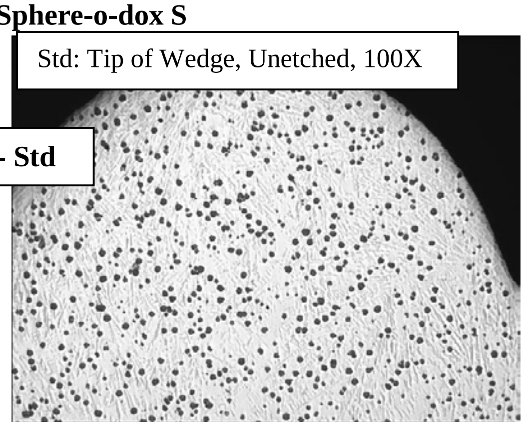


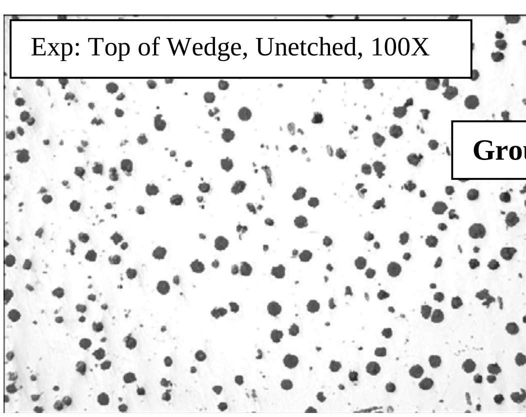


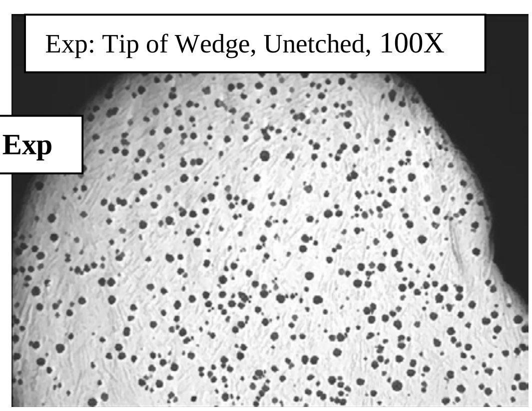


Group 2 – Std: 5 lb Calsifer / Exp: 5 lb Calsifer + 0.3 lb Sphere-o-dox S

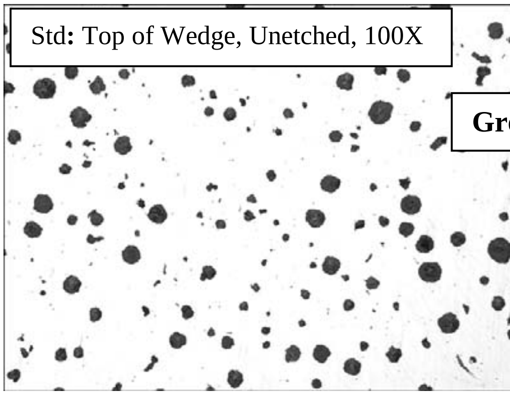




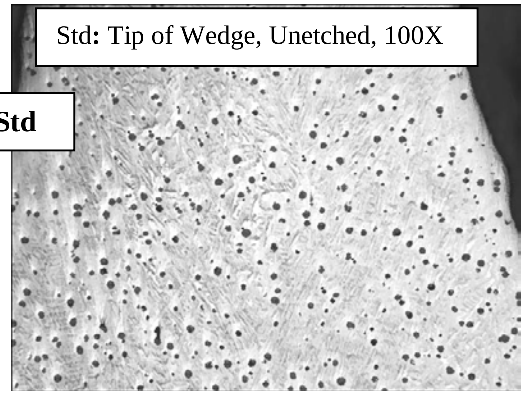


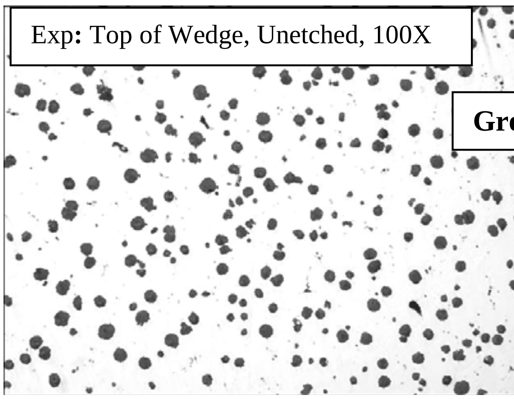


Group 3– Std: 5 lb Calsifer / Exp: 4 lb Calsifer + 1 lb Sphere-o-dox S

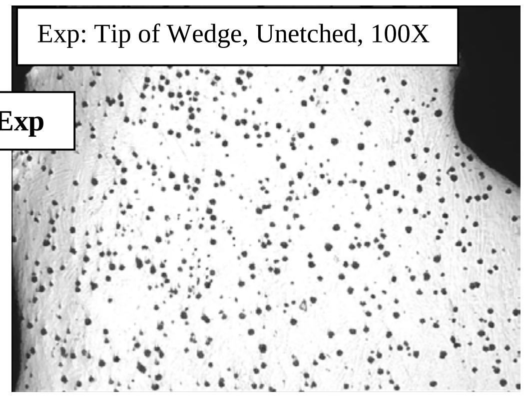


Group 3 - Std

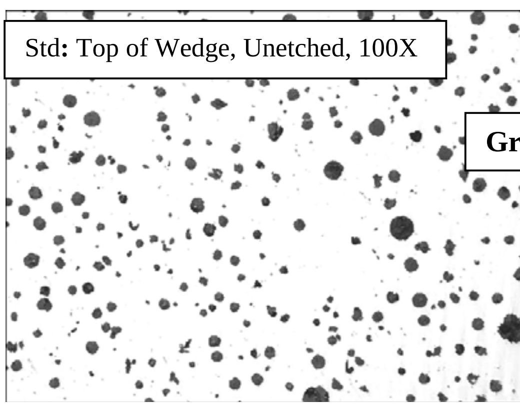




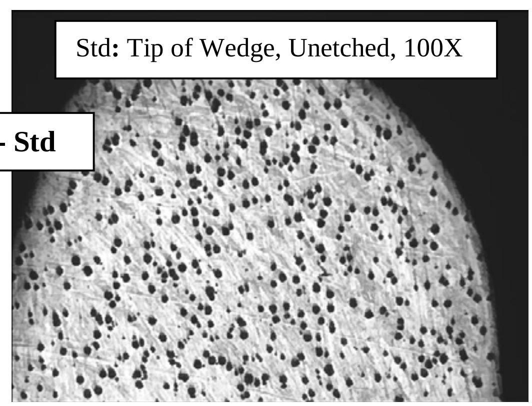
Group 3 - Exp

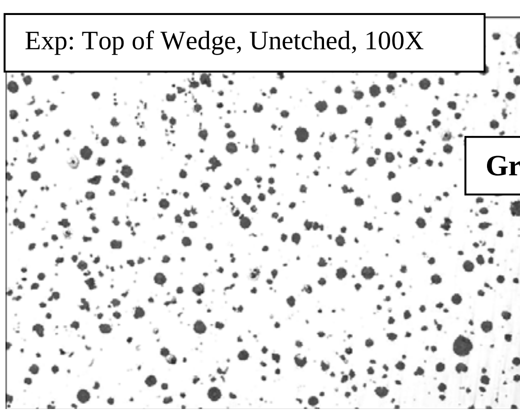


Group 4 – Std: 5 lb Calsifer / Exp: 5lb VP216 + 1 lb Sphere-o-dox S

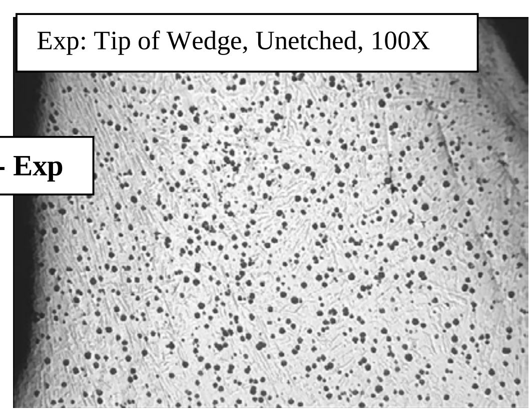


Group 4 - Std

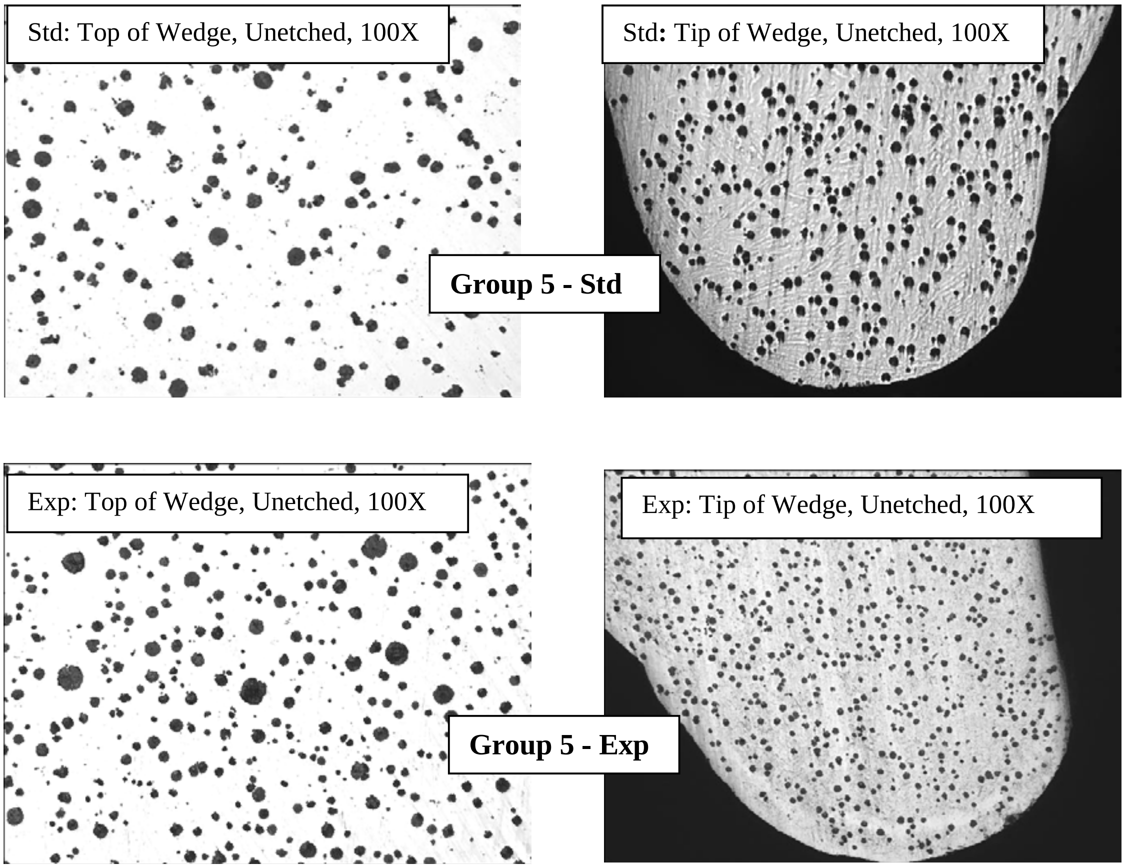




Group 4 - Exp



Group 5 – Std: 5 lb Calsifer / Exp: 5 lb Calsifer + 1 lb Sphere-o-dox S



Metallographic Analysis of Chill Wedges: % Nodularity and Nodule Count (Nodules/mm^2)

Group	Ladle	% Nod.	NC Tip	Dif Tip	NC Middle	Dif Mid	NC Top	Dif Top
1	Std.	95	200		150		125	
1	**Exp.**	**95**	**300**	**50%**	**175**	**17%**	**150**	**20%**
2	Std.	91	250		150		125	
2	**Exp.**	**93**	**300**	**20%**	**175**	**17%**	**150**	**20%**
3	Std.	92	175		150		125	
3	**Exp.**	**94**	**275**	**57%**	**175**	**17%**	**150**	**20%**
4	Std.	95	200		150		125	
4	**Exp.**	**95**	**300**	**50%**	**200**	**33%**	**150**	**20%**
5	Std.	93	200		150		125	
5	**Exp.**	**95**	**250**	**25%**	**175**	**17%**	**150**	**20%**

Note: Nodule counts were increased by 20 to 57% at the tip of the wedge when Sphere-o-dox S was added with either Calsifer 75 or VP216.

Hiler Industries Metallographic Analysis Instruments:

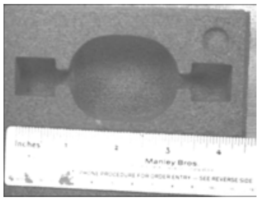
Metallurgical Laboratory: (Used for all metallographic analysis in this report.)
Olympus PME3 with digital camera and IA32 Analysis Software.

Nodularity Coupon Analysis at the pouring floor: (%Nodularity – Every Ladle Poured)
Olympus GX51 with digital camera and IA32 Analysis Software.

<u>Nodularity Coupon Microstructure Analysis:</u>

Nodularity coupons poured along with the chill wedge were used to investigate inoculation effectiveness in a sample with uniform thickness.

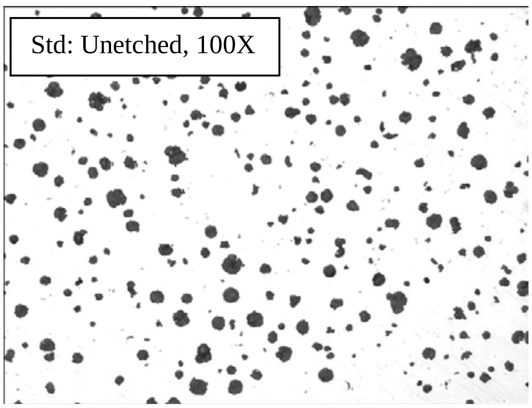
Nodularity Coupon Sample Mold: Shell Sand

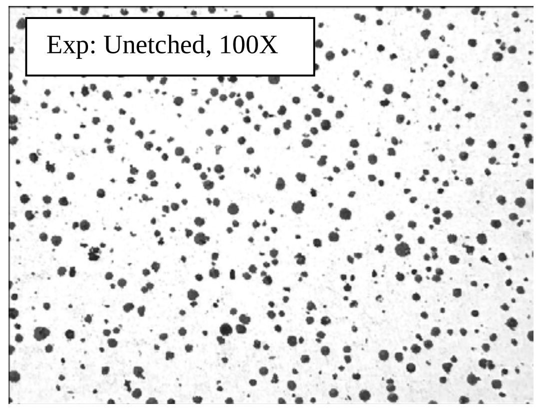


Nodularity Coupons are made from shell sand. The samples are 11/16 inch thick.

<u>Nodularity Coupon Microstructure Analysis:</u>

Group 1 – Std: 5 lb Calsifer / Exp: 5 lb Calsifer + 0.6 lb Sphere-o-dox S


Std: Unetched, 100X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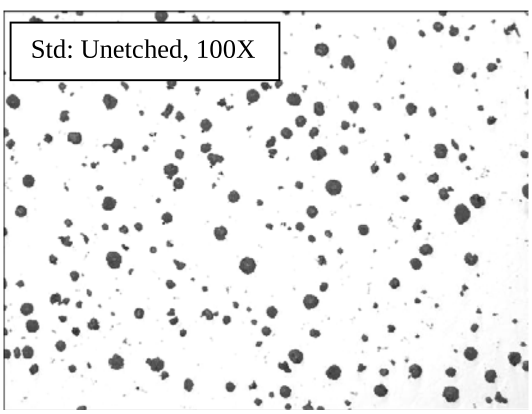
Group 2 – Std: 5 lb Calsifer / Exp: 5lb Calsifer + 0.3 lb Sphere-o-dox S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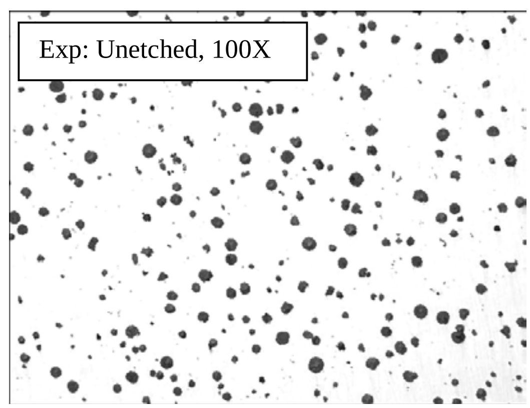
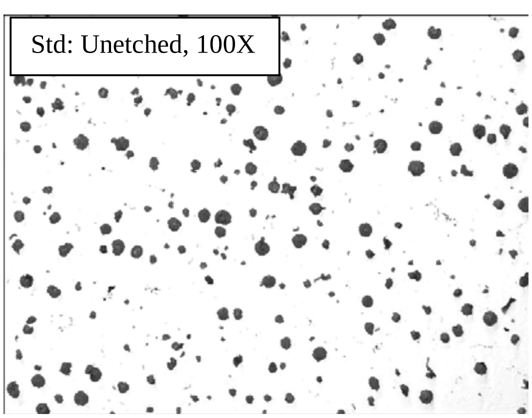
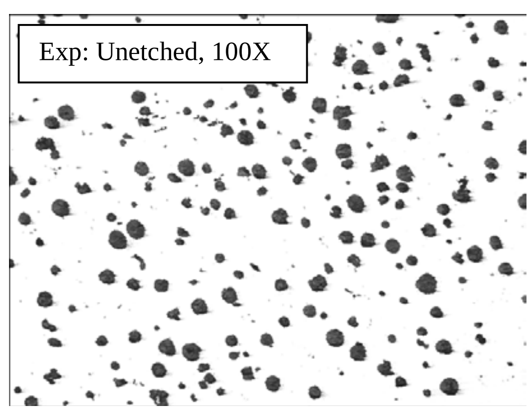

Exp: Unetched, 100X

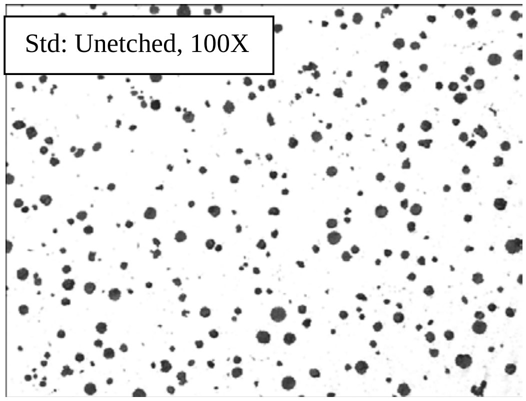
Group 3 – Std: 5 lb Calsifer / Exp: 4 lb Calsifer + 1 lb Sphere-o-dox S

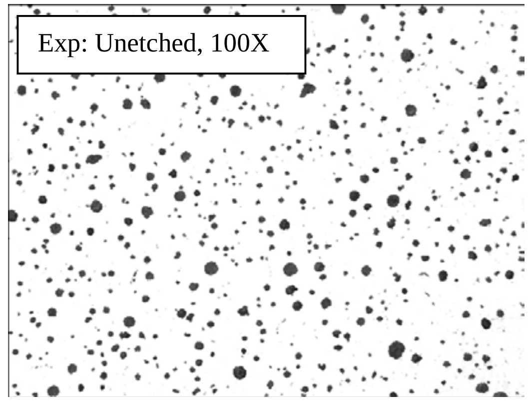

Std: Unetched, 100X


Exp: Unetched, 100X

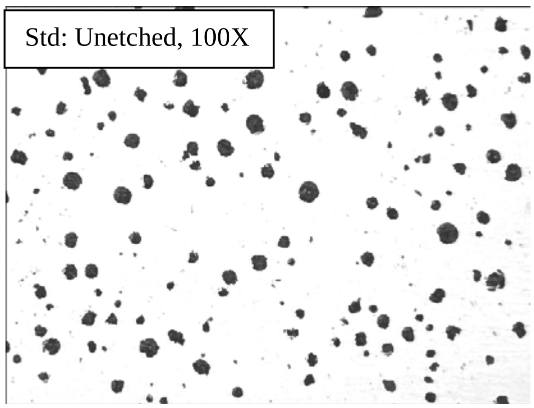
Nodularity Coupon Microstructure Analysis: (Continued)

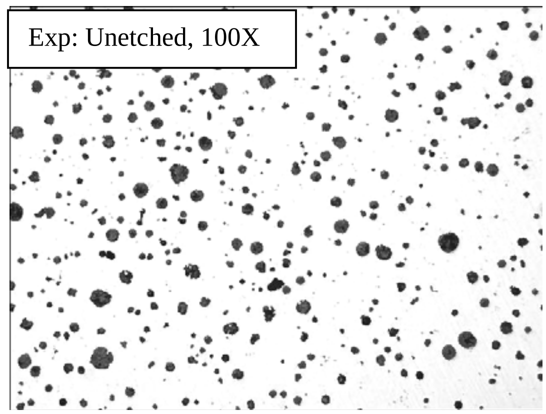
Group 4 – Std: 5 lb Calsifer / Exp: 5lb VP216 + 1 lb Sphere-o-dox S





Group 5 – Std: 5 lb Calsifer / Exp: 5 lbs Calsifer + 1 lb Sphere-o-dox S





Nodularity Coupon Metallographic Analysis

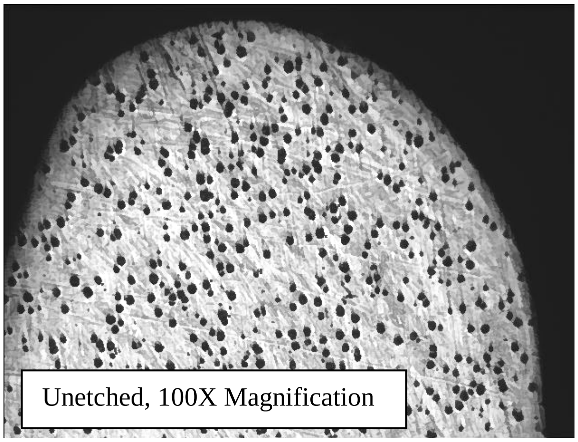
Group	Ladle	% Nod.	NoduleCount	% Difference
1	Std.	95	125	
1	**Exp.**	**97**	**175**	**40**
2	Std.	91	125	
2	**Exp.**	**93**	**150**	**20**
3	Std.	92	125	
3	**Exp.**	**97**	**150**	**20**
4	Std.	93	150	
4	**Exp.**	**95**	**175**	**17**
5	Std.	95	125	
5	**Exp.**	**97**	**150**	**20**

Note: Nodule count was increased in each of the experimental groups.

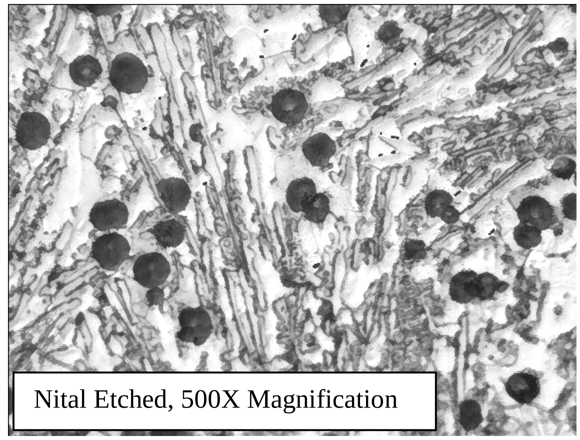
Chill Wedge Tip Matrix Microstructure Analysis

The metal at the tip of the chill wedge represents an experimental thin sectioned casting due to the sensitivity for carbide formation. Investigation of the chill wedge tip region is critical for determining inoculation effectiveness. Increased Nodule Count and decreased Carbide formation at the tip of the chill wedge are indicators of increased inoculation potency. The ability of the enhanced inoculation to increase nodule count at the tip of the chill wedge was illustrated in a previous section of this report by investigating the unetched samples. The polished chill wedge samples were nital etched and the iron carbide formation at the tip was examined at 500X Magnification to investigate carbide formation. The following photomicrographs illustrate the dual benefit of the inoculant enhancer to increase nodule count and decrease carbide formation at the tip of the chill wedge.

Group 4 – Std: 5 lb Calsifer

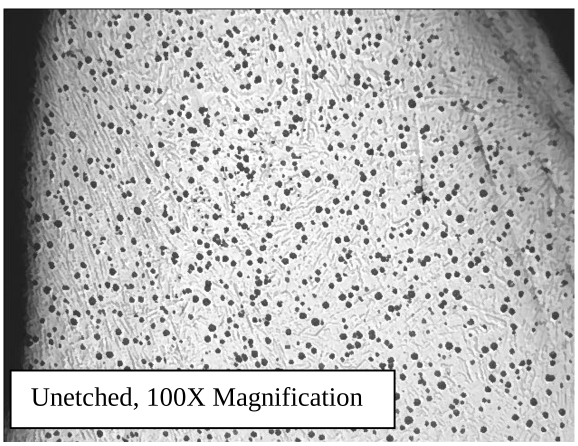


Unetched, 100X Magnification

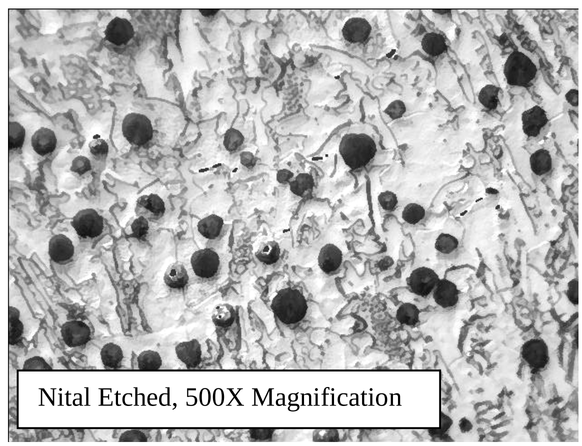


Nital Etched, 500X Magnification

Group 4 –Exp: 5 lb VP216 + 1 lb Sphere-o-dox S



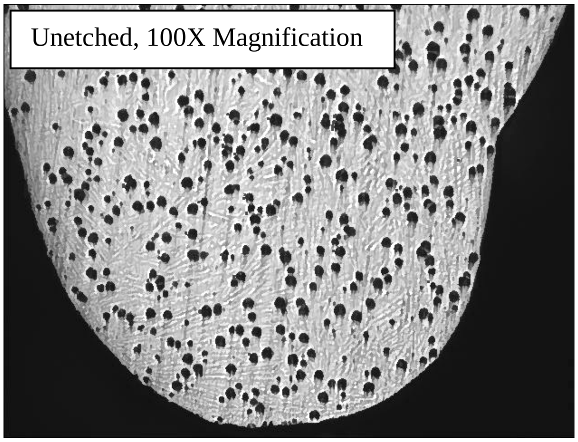
Unetched, 100X Magnification

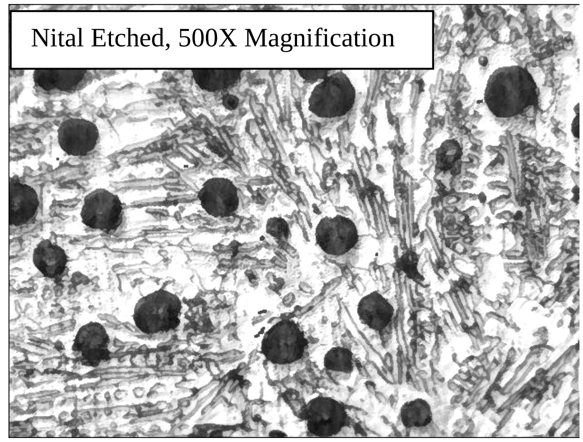


Nital Etched, 500X Magnification

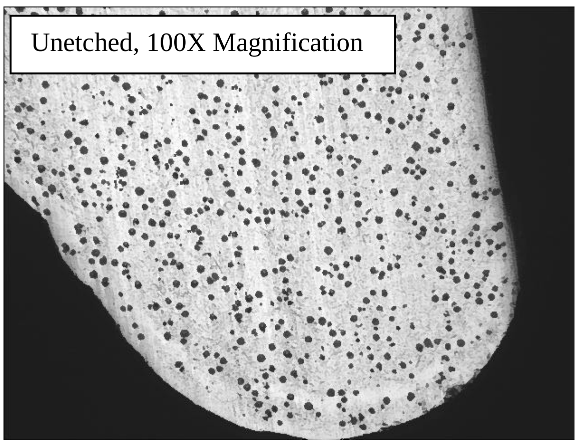
Note: Nodule count is significantly increased and carbide formation is greatly reduced with the use of the high aluminum inoculant VP 216 combined with the inoculant enhancer Sphere-o-dox S in the tip of the chill wedge.

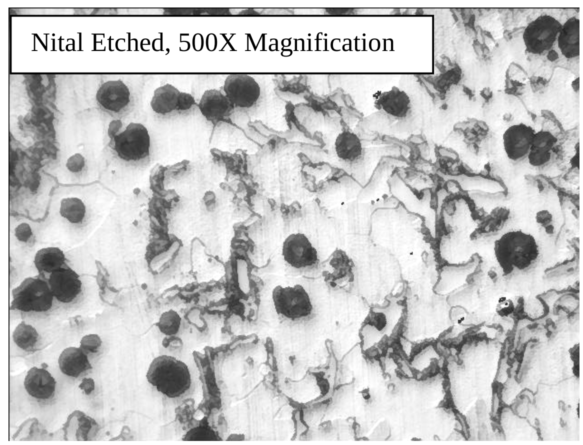
Group 5 – Std: 5 lb Calsifer





Group 5 –Exp: 5 lb Calsifer + 1 lb Sphere-o-dox S





Note: Nodule count is significantly increased and carbide formation is greatly reduced with the use of the calcium containing Calsifer 75 inoculant combined with the inoculant enhancer Sphere-o-dox S in the tip of the chill wedge.

Summary:

The reduced chill depth, increased nodule count, and reduced carbide formation in the chill wedges poured from experimental inoculation ladles, illustrated the ability of oxysulfide inoculants to be powerful inoculation enhancement tools. The addition of oxysulfide based Sphere-o-dox S inoculant booster in each of the experimental ladles reduced the chill depth, increased the nodule count and reduced carbide formation, compared to the standard inoculation method.

Nodule count was increased throughout the thickness of the broken chill wedge sections in the oxysulfide inoculant enhanced experimental samples compared to the standard inoculation sample. This indicates the ability of the oxysulfide inoculant to increase nodule count in 0-0.75 in thick sections.

The nodularity coupon represents a sample of constant thickness with no sections under ¼ inch thick. Nodule count was increased in the nodularity coupons of each of the oxysulfide inoculant enhanced samples.

The etched chill wedges from test Groups 4 and 5 illustrated a reduction in iron carbide formation at the end of the wedge tip in the samples using oxysulfide inoculant additions. The greatest reduction in carbide formation occurred when 1 lb of Sphere-o-dox S oxysulfide inoculant was added to 5 lbs of VP216 high aluminum inoculant proving the inoculation potency of both products.

Comparing the results from test Groups 1, 2, and 5 showed that the inoculation enhancement increased as the percentage of oxysulfide inoculant increased. It is believed that the amount of inoculant enhancer could be trimmed to reduce iron carbide formation in specific castings, creating flexibility in the use of this product combined with the existing foundry inoculation practice.

The results of test Group 3 illustrated that the amount of calcium bearing post inoculant could be lowered by 20% combined with oxysulfide inoculant to increase the inoculation effectiveness over that of the standard practice.

Test Group 4 showed that the combination of calcium bearing/high aluminum inoculant VP216 with the oxysulfide containing Sphere-o-dox S inoculant proved to be very effective with lowering the chill depth, increasing the nodule count and almost eliminating iron carbide formation at the tip of the test chill wedge. This combination will be further tested to determine if it will eliminate carbide formation in thin section work that is currently being heat treated with a carbide annealing cycle.

The oxysulfide inoculation enhancement in the experimental sets occurred without significant changes to the final chemical analysis of the ductile iron. Increasing inoculation potential without significantly altering %C and %Si will improve melt chemistry control if higher CE returns cannot be properly segregated.

Sphere-o-dox S will cause a slight increase in sulfur, and may require a slightly higher magnesium addition to prevent the formation of vermicular graphite.

Conclusions:

This study was performed to benchmark and improve the inoculation of ductile iron for thin-walled castings at Hiler Industries – Kingsbury Castings Division. Calcium bearing 75% ferrosilicon inoculant and high aluminum ferrosilicon inoculant were both combined with oxysulfide inoculant, and the following conclusions can be deduced:

- Chill was reduced by 31 to 74% with the greatest chill reduction occurring when 1 lb of Sphere-o-dox S was added to 5 lb of VP216.
- A significant increase in Nodule count was observed, an increase of 17 to 40%, whether added with the standard 75% ferrosilicon or the VP 216.
- It appears due to the results, i.e. elimination of chill and improved nodule count, that the late in-mold inoculation may not be required.
- Test Group 3 showed that the amount of calcium bearing post inoculant could be lowered by 20% combined with Sphere-o-dox S inoculant to increase the inoculation effectiveness over that of the standard practice. This may prove effective in reducing shrinkage in heavy section castings while still maintaining high nodule count
- Etched chill wedge samples verified that carbide formation was significantly reduced when using the Sphere-o-dox S inoculation booster.
- The inoculation enhancement occurred without major changes to the final chemical analysis of the ductile iron. This fact makes it less disrupting to melt chemistry control than raising carbon or silicon levels.

No physical tests were performed on the enhanced inoculation iron versus the standard practice, but this is something that I wish to investigate in the future. The results of this testing warrant further production analysis to improve the quality of the ductile iron casting process at Kingsbury Castings.

No tests were performed on other iron types, but the results show promise for investigating the use of oxysulfide containing inoculant in thin sectioned gray iron applications produced at our Accurate Castings Division.

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Date Completed: 7-17-09

Presented: DIS Meeting- June 4, 2009; Lancaster, PA