CLEAN CAST STEEL TECHNOLOGY

FINAL REPORT

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**C.E. BATES AND J.A. GRIFFIN
UNIVERSITY OF ALABAMA AT BIRMINGHAM**

JUNE 1998

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CLEAN CAST STEEL TECHNOLOGY

FINAL REPORT

C.E. BATES AND J.A. GRIFFIN

JUNE 1998

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ABSTRACT

This report documents the results obtained from the **CLEAN CAST STEEL TECHNOLOGY PROGRAM** financially supported by the DOE Metal Casting Competitiveness Research Program and industry. The primary objective of this program is to develop technology for delivering steel free of oxide macroinclusions to mold cavities. The overall objective is to improve the quality of cast steel by developing and demonstrating the technology for substantially reducing surface and sub-surface oxide inclusions. Two approaches are discussed here.

A total of twenty-three castings were produced by submerge pouring along with sixty conventionally poured castings. The submerged poured castings contained, on average, 96% fewer observable surface inclusions (11.9 vs 0.4) compared to the conventionally poured cast parts. The variation in the population of surface inclusions also decreased by 88% from 5.5 to 0.7. The machinability of the casting was also improved by submerged pouring. The submerge poured castings required fewer cutting tool changes and less operator intervention during machining. Subsequent to these trials, the foundry has decided to purchase more shrouds for continued experimentation on other problem castings where submerge pouring is possible.

An examination of melting and pouring practices in four foundries has been carried out. Three of the four foundries showed significant improvement in casting quality by manipulating the melting practice. These melting practice variables can be grouped into two separate categories. The first category is the pouring and filling practice. Metallostatic head pressure and tapping rate were found to be important in three of the four foundries with lower head pressure and faster tapping rate improving casting quality. Lower head pressures reduce the velocity of the metal exiting the nozzle and throttling of the ladle. High metal velocities and throttling have been shown to increase air entrainment and reoxidation of the metal ²⁸. Higher tapping rates also reduce the amount of oxygen exposed to the metal.

The second category concerns the concentration of oxidizable elements contained in the steel. Silicon, manganese, and aluminum concentrations were important factors in all four foundries. These elements can be indicators of the oxygen concentration contained in the steel. Carbon is typically used as an indicator of oxygen concentration in the steel bath. However, authors have shown that other oxidizable elements can also influence the oxygen content of the steel and the availability of the oxygen to form reoxidation inclusions in steel castings. ^{28,29} By using the oxidizable elements as indicators and manipulating the melting practice to optimize the concentration of these elements, improvements in casting quality can be observed.

Clean heats can consistently be produced through improved melting practice and reducing exposure of the steel to atmospheric oxygen during pouring and filling.

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CLEAN CAST STEEL TECHNOLOGY

SUMMARY OF RESULTS

This report documents the results from the **CLEAN CAST STEEL TECHNOLOGY PROGRAM** financially supported by the DOE Metal Casting Competitiveness Research Program and industry. The primary objective of this program is to develop technology for delivering steel free of oxide macroinclusions to mold cavities. The overall objective is to improve the quality of cast steel by developing and demonstrating the technology for substantially reducing surface and sub-surface oxide defects and enhance the competitiveness of the U.S. metal casting industry by performing research that leads to production of higher quality castings at a commercially competitive price.

In 1981, the Steel Founders' Society Quality Task Force identified oxide macroinclusions as the number one customer complaint when machining steel castings. In 1991, SFSA technical committees again identified clean steel as a major competitive need for the steel casting industry. In response to customer needs for more machinable castings, the Steel Founders' Society established a program to determine if some practical approaches could be devised to improve metal cleanliness.

Task 1. Shrouding

Fluid flow considerations make some of the benefits of shrouded pouring immediately obvious. If an effective seal can be obtained, air aspiration will be minimized at the juncture between the shroud and the ladle. Eliminating aspiration creates a larger stream diameter which increases the flow rate from the ladle into the cavity. The higher flow rate minimizes the pouring time and helps minimize sand spalling from the cope during pouring. The shroud also minimizes oxidation by eliminating or minimizing contact between the steel and the air during pouring. It is important to have as smooth and nonturbulent filling of the mold cavity as possible.

Trial 1. The lower pouring times for the shrouded castings compared to the conventionally gated castings indicate that the joint between the ladle nozzle and shroud was sealed. The higher pouring times for two of the molds were either throttled or opened and closed repeatedly.

The shroud with the Stelpur filter/riser consistently produced the highest casting quality compared to the shrouded or conventionally poured castings. The combination of the mechanical shroud and the filter provided improved casting quality. Difficulties associated with the lowering the shroud into a relatively small riser and the steel buildup on the shroud make it difficult to draw conclusions. The wide variation within the group indicates the process is not controlled. Defects removed from the shrouded test plates indicate silica sand is the predominate inclusion material. This may have been a result of the shroud contacting the side of the riser and

dislodging sand into the mold during pouring or possibly from erosion of the mold by high velocity metal.

Trial 2. A total of twenty-three castings were produced by submerged pouring along with sixty conventionally poured castings. The submerged poured castings contained on average 96% fewer observable surface inclusions (11.9 vs 0.4) compared to the conventionally cast parts. The variation in surface inclusion also decreased by 88% from 5.5 to 0.7. The machinability of the casting was also improved by submerged pouring. The submerge poured castings required fewer cutting tool changes and less operator intervention during machining. Subsequent to these trials, the foundry has decided to purchase more shrouds for continued experimentation on other problem castings where submerged pouring is possible.

Task 2. Clean Heat/Dirty Heat Trials

Three of the four foundries showed significant improvement in casting quality by manipulating the melting practice. Improvements ranged from 40-50%. The fourth foundry has not yet completed the second phase of the trial.

The important variables in producing clean heats from all of the foundries can be grouped into two separate categories. The first category is the pouring and filling practice. Metallostatic head pressure and tapping rate were found to be important in three of the four foundries with lower head pressure and faster tapping rate improving casting quality. Lower head pressures reduce the velocity of the metal exiting the nozzle and throttling of the ladle. The basic practice did not have head height as a variable since the entire heat was used to pour the selected casting. High metal velocities and throttling have been shown to increase air entrainment and reoxidation of the metal ²⁸. Higher tapping rates also reduce the amount of oxygen exposed to the metal.

The second category concerns the concentration of oxidizable elements contained in the steel. Silicon, manganese, and aluminum concentrations were important factors in all four foundries. These elements can be indicators of the oxygen concentration contained in the steel. Carbon is typically used as an indicator of oxygen concentration in the steel bath. However, authors have shown that other oxidizable elements can also influence the oxygen content of the steel and the availability of the oxygen to form reoxidation inclusions in steel castings. ^{28,29} By using the oxidizable elements as indicators and manipulating the melting practice to optimize the concentration of these elements, improvements in casting quality can be observed.

Clean heats can consistently be produced through improved melting practice and reducing exposure of the steel to atmospheric oxygen during pouring and filling.

Task 3. Castings Produced By Special Pouring Techniques

A series of plant scale experiments has been conducted to evaluate the effect of quadrant ladle design and slanted sprue gating on casting quality. These experiments were conducted to validate the results obtained by water modeling.

Several problems occurred which prevented successful completion of the trial. Metal spillage during pouring fouled the platform rails and made moving the mold extremely difficult in the later stages of the trial. This slowed the pouring rate which produced early freezing of the gating system and incompletely filled molds. The second problem was a misalignment of the sprue with the runner in the slanted sprue molds. The reduced cross-sectional area reduced the pour rate and produced incompletely filled molds or severe cold shuts on the cope surface. There were not enough good castings to produce statistically valid results.

Task 4. Technology Transfer.

A total of 18 papers or talks have been presented to numerous steel casting societies about the technology used in this project and the benefit to the participating foundries. These societies included the Steel Founders' Society of America, the American Foundrymen's Society, and the American Society for Testing and Materials. These presentations were made by either UAB personnel, SFSA personnel, or the participating foundries. Two workshops were also conducted demonstrating techniques developed and used in this project to produce clean steel castings.

ACKNOWLEDGMENTS

We wish to express grateful acknowledgment and deep appreciation to the many companies and individuals who participated in the project by providing advice, technical expertise, and guidance regarding the most fruitful areas for investigation.

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A special word of thanks goes to Mr. Malcolm Blair and Mr. Raymond Monroe from the Steel Founders' Society of America. Their insight and guidance contributed significantly to the success of the project.

CURRENT CLEAN CAST STEEL TECHNOLOGY

Introduction

This report documents the results from the **CLEAN CAST STEEL TECHNOLOGY PROGRAM** financially supported from the DOE Metal Casting Competitiveness Research Program. The primary objective of this program is to develop technology for delivering clean steel free of oxide macroinclusions to mold cavities. The overall objective is to improve the quality of cast steel by developing and demonstrating the technology for substantially reducing surface and sub-surface oxide defects.

Steel castings are crucial basic components used in agriculture, chemical processing, aircraft, road and rail transportation, steam and nuclear power production, and a host of other applications. Oxide macroinclusions in cast steel components represent a technological barrier to economical production, wider usage of castings, and product competitiveness in the U.S. steel casting industry.

Oxide macroinclusions have long been a major cost factor in the production of steel castings. Surface macroinclusion removal, weld repair, and reinspection add 20% to the cost of production. Subsurface inclusions not found and repaired in the foundry can cause costly disruptions in machining operations and result in poor component performance in service. Automated high speed machining lines offer producers the opportunity to economically increase productivity and quality. These lines take rough components and machine them to final form without the variations and delays associated with operator-run stand-alone machining. The productivity and quality of high-speed machining lines make them attractive to the industrial equipment and valve manufacturers to ensure their viability and competitiveness against foreign competition.

High speed machining lines require a rough component with fewer surface and internal discontinuities than acceptable in traditional machining operations. In traditional machining operations, surface and internal discontinuities were handled by an operator who adjusted his machine for each component. Discontinuities found in a component during or after a rough cut may require the component be removed from the machine and weld repaired but did not stop the production process. In high speed transfer machining lines, discontinuities may cause excessive tool wear or even tool breakage which requires halting the line with an attendant productivity and economic loss.

One method of avoiding shutdown problems on machining lines is to oversize the part and use traditional machining techniques to eliminate discontinuities before the parts are put on a transfer line. This minimizes delays using rough components but lowers overall productivity, adds cost, and sacrifices much of the gain made possible by transfer lines.

Surface and internal discontinuities must be reduced or eliminated to realize the full potential of high speed machining lines. Macroinclusions are a major source of steel casting discontinuities. The reduction of macroinclusions in steel castings would therefore be an important step forward for the steel foundry industry. The production of castings suitable for high speed machining lines would help make casting producers competitive while allowing better design and quality for domestic casting users.

Background

Reoxidation. Oxygen can come from several sources including air, water in refractories, molding sand, or oxidizing slag, and react with steel to produce reoxidation products. There is substantial evidence that reoxidation is a major cause of oxide macroinclusions. Reoxidation is considered to be the reaction of elements in steel with oxygen after the steel has been deoxidized. This oxygen may come from the air, reactions with slag or refractories, or the reduction of water in air, refractories, or the mold.

The formation of deoxidation and reoxidation products is schematically illustrated in Figure 1. ⁽¹⁾ Deoxidation products are small, typically 10 μm or smaller in diameter, primarily composed of alumina (Al_2O_3) in aluminum deoxidized carbon and low alloy steels, and dispersed throughout the casting. In reoxidation, oxygen locally depletes the aluminum and reacts with other oxidizable elements in the steel. Reoxidation products are typically macroscopic in size and float to the cope surface of the casting before solidification. Microstructurally, the products contain alumina particles that lie in multi phase globules formed by the oxidation of aluminum followed by silicon, manganese and iron. ^(1,2,3) The oxide matrix in which the alumina particles lie is typically rich in manganese and silicon, but in some cases may contain iron oxide. The presence of iron oxide may cause carbon monoxide gas holes to be formed within the inclusion as the iron oxide is reduced by carbon during solidification.

Typical oxide macroinclusions appear green to white under visible light. The inclusions consist of corundum (alumina) crystals or a mixture of corundum, silica and manganese oxide. The presence of corundum indicates that the inclusion began as a reaction product between oxygen and dissolved aluminum. Most refractories are composed of mullite or lower alumina content materials and are not expected to produce corundum. ^(4,5,6,7,8,9,10)

If reoxidation is a major cause of inclusions, then the deoxidized metal composition should have some effect on the composition of inclusions formed. This has been found to be the case in both carbon steels and high alloy steels. Increasing the manganese-to-silicon ratio increased the manganese oxide and decreased the silicon oxide content of inclusions in low alloy steels, as shown in Figure 2. Aluminum deoxidation increased the amount of aluminum oxide in inclusions and reduced the manganese + iron oxide contents. ^(4,11)

Figure 1. Stylized Formation of Inclusions in Cast Steel Deoxidized with Aluminum ($> 0.01\% \text{ Al}$).

Figure 2. Effect of Manganese/Silicon Ratio in the Melt on the MnO and SiO₂ Content of Cerioxide Samples Taken from Castings Poured from the Melt. (Weights are in percentage)

Not only does reoxidation inclusion composition depend on the composition of the metal, but the volume of inclusions has been related to the amount and composition of deoxidizers added. Increasing the concentration of even a mild deoxidizer, such as manganese, resulted in an increase in the number of inclusions.⁽¹¹⁾ Increasing the amount of strong deoxidizing additions, such as aluminum, zirconium and titanium, also increased the weight of inclusions formed as shown in Figure 3.⁽¹¹⁾ Most reports indicate that subsurface oxide macroinclusions, which are so detrimental to tool life, are much more frequent when aluminum is used compared to when silicon is used. Shallow surface inclusions can be attributed to a higher silica content than the subsurface white powder inclusions composed primarily of alumina.^(4,11,12)

Reoxidation problems increase with the quantity and strength of the deoxidizers added as does the volume of oxide macroinclusions. This trend is shown in Table I which relates the machined cleanliness of "B" turning bars to the deoxidation practice.⁽¹³⁾ As the deoxidizer changed from weaker titanium to stronger aluminum and from less to more deoxidizers added, the cleanliness rating decreased.^(6,11,13)

Radioactive cerium (Ce^{141}) has been added to steel during aluminum deoxidation and to the slag in efforts to determine the source of oxide inclusions. The results are shown in Table II.⁽¹⁴⁾ Almost no trace of radioactive cerium was found in ingots where the slag was activated. The small amount of radioactivity detected in the inclusions was attributed to reduction of the oxides in the slag and not to slag carryover. The trials with the activated deoxidizers showed significant amounts of activity in the slag. High radioactivity also was detected in the large inclusions near the top surface of ingots. These experiments indicate that reoxidation and not slag carryover was the major cause of inclusions.⁽¹⁴⁾

Increasing the carbon content of the steel is known to decrease the incidence of inclusions. This is due both to carbon deoxidation and the beneficial shielding effect of carbon monoxide formed during exposure to air. The carbon monoxide appears to serve as a shroud for the liquid metal.

Reoxidation is implicated by the composition and volume of inclusions which is related to the amount and composition of the deoxidizers. Control of reoxidation can be accomplished by limiting the exposure of the metal to oxygen in all forms since deoxidizer additions are necessary in steel to produce sound castings.

Reoxidation by Exposure to Air. Oxidation of molten steel in air occurs very rapidly as illustrated in Figure 4.⁽¹⁾ The oxygen concentration in steel shot reduced by hydrogen increased from near zero to 0.08% in about 0.25 seconds when exposed to air. The rate of reaction is probably limited only by the ability of oxygen to diffuse through the nitrogen rich layer surrounding the steel to replace oxygen already reacted at the liquid metal surface. In a foundry environment, a major exposure of molten steel to air occurs when pouring the steel into molds through air and when air is entrained in the pouring stream.

611-192

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Figure 3. Effect of the Amount of Deoxidizer Addition to the Melt on Composition of Ceroxide Samples taken from Castings Poured from the Melt.

Table I. Effects of Deoxidation on the Cleanliness of Grade "B" Turning Bar Castings.

DEOXIDANTS	NUMBERS OF CASTINGS	FREQUENCY OF CLEANLINESS					AVERAGE NO.	POUNDS EQUIVALENT OF Al ADDED PER TON
		RATING NUMBERS*						
		1	2	3	4	5		
5 lb titantium per ton	5	—	—	—	—	5	5	0.00
8 lb (Fe-Ti-Si-Mn-Al-Zr alloy) per ton	3	—	—	—	1	2	4.7	1.04
8 lb (Fe-Ti-Si-Mn-Al-Zr alloy) plus 1 lb aluminum per ton	6	1	1	1	2	1	3.2	2.04
2.5 lb aluminum plus 3 lb (Fe-Si-Ti-Ca alloy) per ton	12	3	2	2	4	1	2.9	2.50
4 lb aluminum plus 3 lb (Fe-Si-Ti-Ca alloy) per ton	8	4	2	1	1	—	1.9	4.00

*RATING NUMBER

RATING GRADE

5	Excellent, 0-5 microinclusions (0.0079-0.0158 inches diameter) first cut
4	Very good, 6-15 microinclusions (0.0079-0.0158 inches diameter) first cut
3	Good, 16-30 microinclusions, 0-3 macroinclusions (0.0625 inches diameter) first cut
2	Poor, 31-50 microinclusions, 0-3 macroinclusions (0.125 inches diameter) first cut
1	Very poor, 50+ microinclusions, 3+ macroinclusions larger than 0.125 inches diameter

621-802

5-405

Table II. Specific Radioactivities of the Nonmetallic Materials (c/min/mg).

	HEAT A*	HEAT B*	HEAT C*	HEAT D*
SLAG SAMPLED IN FURNACE		25-25 24-20		
SLAG SAMPLED IN LADLE	55-49 72 61-57	47-26 28 40	228-217 233 130-197	129-117 180-(890) 290
PROTECTIVE POWDER IN TUNDISH	470 745 940	400 490-980	310-570 570	14 4 4
PROTECTIVE POWDER IN INGOT MOLD (CONTINUOUS CASTING)	260 690-670 930	415 385	350	1 2 3
SCUM ON BOTTOM-POURED INGOT	780	300	1,050	12
SCUM ON TOP-POURED INGOT	5,080 3,165 1,000	4,480 5,100 —	— — 1,670	120 18 23
DEPOSIT IN NOZZLE		6,900 10,800 6,280 11,400	22,800 18,700 21,900 (2,960)	

HEAT A - Al-Ce tracer addition during tapping

HEAT B - Al-Ce tracer addition in furnace before tapping

HEAT C - Al-Ce tracer addition during tapping

HEAT D - Cerium oxide tracer addition to ladle slag after tapping

621-800

5-406

5-407

Figure 4. Oxygen Pickup by Falling Droplets. Droplets were Mold-quenched under Nitrogen.

The size distribution of reoxidation products formed during tapping from a furnace are shown in Figure 5. ⁽¹⁵⁾ Reoxidation particles can grow within a minute to macroinclusion size and float out of the liquid in about two minutes. It has been estimated that in each pouring or tapping operation, from three to nine pounds of oxides are produced for each ton of metal transferred. A loss of about 1.6 lb. manganese, 0.3 lb. carbon, 0.9 lb. silicon, and 0.9 lb. aluminum per ton of steel has been reported during metal transfer in some wrought steel operations. ⁽¹⁵⁾ Greater pouring heights result in more reoxidation from stream breakup and from longer exposure to air. Throttling a bottom pour ladle results in a higher surface area of liquid metal exposed, increased air entrainment and longer pouring times. The loss of aluminum, manganese and silicon associated with each metal transfer is an indication of the amount of reoxidation.

Reducing the pouring time is generally recognized to improve cleanliness with all other factors constant. The effect of pouring time on the x-ray rating of SFSA plate castings poured at one foundry is illustrated in Figure 6. The cleanliness was approximately a linear function of the pouring time with long pouring times associated with dirtier castings.

However, when the cleanliness of castings from a variety of foundries using different sized ladles and pouring practices is correlated with pouring time, the trend is much less clear, as illustrated in Figure 7. The lack of correlation is a result of the fact that a variety of other factors influence the exposure of metal to air including pouring height, extent of steam flaring, molding material, runner system design, etc.

In many molten metal transfer operations, the large reoxidation products have time to float from the liquid. However, pouring into a casting cavity forms products that are likely to be trapped at or under the cope surface. In continuous casting, proper shrouding to exclude exposure to air has been found to reduce oxide inclusions by 90%. It has been estimated that in excess of 60% of the inclusions in steel castings are a result of reoxidation during casting. ^(1,2,16)

Many types and sizes of ladles are in use in the steel casting industry. For many years bottom pouring was considered to produce the cleanest castings. Bottom pour ladles certainly have the advantage of requiring minimum foundry floor space, but they suffer from the need to throttle the stream when the ladle is full and when pouring small castings from large ladles. Throttling produces stream flaring, and the flared metal has a high surface area which invites reoxidation. Large bottom pour ladles also have high head pressures which produce high metal velocities that aggravate sprue and runner erosion. Teapot and lip pour ladles require more foundry floor space but permit pouring compact streams with a minimum head pressure and metal velocity.

Pouring must be done with the minimum of exposure to air and without entraining slag or eroding ladle refractories. Minimum air exposure is accomplished by fast pouring, low pouring heights, good nozzle or lip design, and a compact pouring stream.

Figure 5. Particle Size of Deoxidation Products from Tapping to Pouring.

Figure 6. Effect of Pouring Time on Test Plate Casting Cleanliness at One Foundry.

Figure 7. Effect of Pouring Time on Casting Cleanliness. All Data Plotted Where Pouring Times were Reported.

Summary of Prior DOE/SFSA Research. Research sponsored by the Department of Energy and Steel Founders' Society of America has shown that reoxidation of metal during pouring and mold erosion are the principle causes of macroscopic nonmetallic inclusion in steel castings.

Approximately 425 defects from carbon and low alloy steels were removed and examined by optical and scanning electron microscopic techniques to determine the nature and form of oxide nonmetallic materials present. Castings came from a wide variety of practices including acid and basic melting furnaces, large and small pouring ladles, high silica and high alumina refractory ladle linings, and molds prepared from green sand and by resin bonding techniques.⁽¹⁷⁾

The results of the examination of defects removed from carbon and low alloy castings are illustrated in Figure 8. Approximately 80% of the casting defects consisted principally of reoxidation products, and 15% consisted of eroded sand. Slag, refractory and deoxidation products were relatively minor contributors.

The results of an examination of 100 cerioxide defects cut from high alloy and stainless castings are summarized in Figure 9.⁽²³⁾ Approximately 50% of the defects consisted principally of reoxidation products. Approximately 35% were composed principally of eroded molding materials, and 12% consisted of ladle refractories. Slag carry over amounted to less than 5% of the total observed.

The incidence of these inclusions must be reduced to lower the labor and cost involved in producing castings and permit casting use on automated high speed machining lines. Achieving this goal requires that methods be devised to deliver clean metal, free of reoxidation and eroded sand products to the mold cavity. This must be accomplished by pouring with minimal exposure to atmospheric oxygen.

Figure 8. Distribution of Macroinclusion Sources in Carbon and Low Alloy Steel Castings.

Figure 9. Distribution of Macroinclusion Sources in High Alloy and Stainless Steel Castings.

SHROUDING TRIALS

Introduction

Continuously cast wrought steel producers have recognized stream reoxidation as a major source of inclusions for several years and shroud the metal during pouring. The original efforts to eliminate reoxidation products centered around the use of mold fluxes, covers, and powders that could be placed on the molten metal in the mold to "absorb" the reoxidation products. Subsequently, efforts were turned toward minimizing reoxidation product formation by pouring through ceramic shrouds.

In the production of the cleanest and highest quality steel, most metal is now refined in ladle by ladle metallurgy techniques. On completion of ladle refining, which typically takes from 30 to 45 minutes, the ladle is ready for transfer to the pouring station. When the ladle reaches the pouring station, a shroud is attached to deliver metal from the ladle to the tundish without contact with air.

Two arrangements for shroud attachment are schematically illustrated in Figures 10 and 11. In the first arrangement, a collector nozzle is bolted to the bottom of the ladle using a steel ring with bolts or studs. A refractory slurry or mud usually is put between the collector nozzle and the ladle bottom to minimize air leakage at the joint during pouring.

The shroud is then fitted on the end of the collector nozzle with a fork and mechanically held in place with a counterweight or latching device. Since a continuous casting ladle does not have to be moved after it is set in place, latching the shroud is not usually difficult to accomplish.

The second arrangement for attaching a shroud consists of fitting the shroud on a nozzle protruding through the ladle shell, as illustrated in Figure 11. It is common to try to obtain a gas seal between the nozzle and shroud by putting a compression gasket at the joint. Gaskets usually are cut from a refractory cloth or non-woven fiber matt, fitted in place, and the shroud pressed and held in position either hydraulically or mechanically. Since the ladle does not have to be moved, hydraulic manipulators are satisfactory for the purpose.

In continuous casting, metal is poured from the ladle through the shroud and into the tundish. The tundish serves as a large reservoir, typically holding from 30 to 50 tons, and provides a constant metal head pressure above the caster. The tundish also serves to distribute metal to one or more billets or to one or more pouring positions in a slab.

Metal exits the tundish and usually enters the continuous caster mold through a second shroud that also may be mechanically, pneumatically, or hydraulically locked in place. The tundish shrouds are usually shorter than ladle shrouds and serve to deliver steel from the tundish to a location beneath an insulating cover on the liquid metal in the mold. The tundish shroud

Figure 10. Typical Continuous Casting Ceramic Shroud with Collector Nozzle Attachment.

5-485

Figure 11. Typical Shroud Seated on a Nozzle.

usually connects directly to the bottom of the tundish with a compression gasket or gas purge ring in the joint to minimize air aspiration.

A negative pressure is developed in shrouds during pouring that often draws air into the stream. If the shroud has been primed, the negative pressure may be as high as the shroud length multiplied by the density of liquid steel. In a 48 inch long shroud, the total pressure could be as low as 3.7 psi (11 psi vacuum).

A schematic of a shroud with a gas seal ring such as used on a tundish is shown in Figure 12. The gas seal ring consists of a groove on the inside shroud flange into which an inert purge gas is introduced. If a negative pressure develops during pouring, the inert gas in the shroud helps minimize the entrance of air.

A ladle is schematically illustrated in Figure 13 with an inside diameter D and a metal height H . If the nozzle is raised to the fully opened position, the velocity of metal exiting the ladle is described by Equation 1. The flow rate of metal exiting the ladle is given by Equations 2 and 3.

$$V = (2 * g * H_{MTL})^{1/2} \quad (1)$$

$$G = \rho * A * V \quad (2)$$

$$G = \rho * A * (2 * g * H_{MTL})^{1/2} \quad (3)$$

where V = metal velocity (in/sec),
 g = gravitational acceleration = 386 in/sec²,
 H_{MTL} = effective metal head height (inches),
 G = metal flow rate (lbs./sec),
 ρ = metal density (.258 lb/in³),
 A = nozzle area ($\pi * D^2 / 4$),
 D = nozzle diameter (inches).

When the appropriate substitutions are made, the flow rate of metal from a ladle is given by Equation 4.

$$G = 5.63 * D^2 * H_{MTL}^{1/2} \text{ (lbs./sec)} \quad (4)$$

Figure 14 illustrates the flow rate of metal from a bottom pour ladle as a function of the metal head height in the ladle (in inches) with nozzle diameters of from 1 to 2.25 inches. Figure

Figure 12. Schematic of Ceramic Shroud with Inert Gas Seal Ring.

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Figure 13. Schematic of Submerged Shroud, Pouring Ladle and Mold.

5-482

Figure 14. Effect of Metal Head Height and Nozzle Diameter on Metal Flow Rate. Nozzle Diameter Range 1.0 - 2.25 inches.

15 is similar and covers the nozzle diameter range from 2 to 4 inches. These figures can be used to determine the approximate flow from conventional bottom pour ladles as well as shrouded ladles if the following considerations are taken into account.

Two possible situations must be kept in mind when pouring metal through a ladle shroud. First, a sufficiently tight seal must be developed between the shroud and the ladle so the shroud can be filled with metal and be primed to eliminate air. If this is not accomplished, pouring through a shroud may be no more beneficial than conventional bottom pouring. If the joint is not tight, sufficient air may be aspirated between the shroud and the ladle to prevent priming and oxidize the metal during pouring. The pour rate achieved under non-primed conditions is approximately the same as the pour rate achieved when pouring from a conventional bottom pour ladle.

If, however, a good joint is obtained between the shroud and the ladle and the shroud is primed, the stream diameter and the flow rate is increased. If, for example, the height of the metal in the ladle is 40 inches and the length of the shroud is 48 inches, the total effective head pressure during pouring is 88 inches. The flow rate achieved with a 40-inch metal head with metal exiting through a 2-inch nozzle is 142 lbs/sec. The use of a 48-inch extension shroud increases the flow to a value of 211 lbs/sec after priming. The higher flow rate reduces the pouring time compared to the same ladle with the same metal height assuming shroud priming is accomplished. Not only will an effective shroud prevent the metal from being oxidized during pouring, but it increases the pouring rate, minimizes splashing, and minimizes the pouring time, all of which improve metal cleanliness compared to conventional bottom pouring.

The flow rate of metal calculated for a primed shroud is achieved when all of the air is flushed from the shroud. However, as the metal hits the splash cup, fills it, and begins to fill the cavity, the effective metal head is reduced by (1) a drop in metal head in the ladle and (2) the rise of metal above the shroud tip in the mold. As the casting cavity is filled, the height of metal above the shroud tip progressively increases and the pouring rate decreases although never to a value as low as that achieved without a shroud.

An average pouring rate can be calculated by taking the average head of metal in the ladle plus the shroud length minus half of the distance between the bottom of the shroud and top of the riser in the casting. This effective head can be used with the weight of the casting to calculate the approximate pouring time using Equation 5.

$$G = 5.63 * D^2 * (H_{MTL} + H_{SH} - H_{MO/2})^{1/2} \quad (5)$$

where H_{SH} = shroud length (inches),
 $H_{MO/2}$ = half the distance between bottom of shroud and top of riser (inches).

Assuming a casting weight of 1000 lbs and effective metal height in the ladle of 40 inches, a shroud length of 48 inches, a half height of metal in the mold of 20 inches, and a 2 inch

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Figure 15. Effect of Metal Head Height and Nozzle Diameter on Metal Flow Rate. Nozzle Diameter Range 2.0 - 4.0 inches.

diameter nozzle, the pouring time is approximately 5.4 seconds. If the same casting is poured from a conventional bottom pour ladle, the minimum pouring time can be expected to be about 7 seconds plus the time spent minimizing splash out from the pouring basin.

These fluid flow considerations make some of the benefits of shrouded pouring immediately obvious. If an effective seal can be obtained, air aspiration will be minimized at the juncture between the shroud and the ladle. Eliminating aspiration creates a larger stream diameter which increases the flow rate from the ladle into the cavity. The higher flow rate minimizes the pouring time and helps minimize sand spalling from the cope during pouring. The shroud also minimizes oxidation by eliminating or minimizing contact between the steel and the air during pouring. The primary contact of air with the steel during pouring is that produced by the piston effect as the metal forces air from the mold cavity rather than entrainment normally associated with bottom pouring. It is important to have as smooth and nonturbulent rise of metal in the mold cavity as possible. This will require considering some aspects of fluid flow in the mold before the proper designs can be selected.

Conceptual Foundry Shroud Attachment Methods

Several preliminary designs have been considered as methods of attaching ceramic shrouds to bottom pour ladles. Most foundries do not have sufficient pit depth to allow the shroud to be attached to a ladle prior to tapping. This means that the ladle must be filled with molten metal and transferred to a location where the shroud can be attached. For safety reasons it is important that employees not get under the ladle to attach the shroud.

In operation, the filled ladle must first be transported to a stand where it can be positioned and the ceramic shroud attached. The ceramic shroud might be supported on a fork and locked into position, screwed onto the bottom of the ladle, bolted to the bottom of a ladle with air wrenches, pressed into position with a spring load or yoke, or sealed with gasket or a liquid ceramic.

Two potential methods of metal attachment to the shroud are illustrated in Figures 16 and 17. Figure 16 illustrates a ceramic shroud with an Acme thread to match a similar Acme thread on the ladle nozzle. It may be possible to seal the threads with sodium silicate prior to screwing the shroud in place or it may be possible to seal with sodium boro-silicate or other refractory that would melt at moderately elevated temperatures. The molten refractory should serve as a gas seal to prevent aspiration along the joint during pouring. This figure illustrates a shroud with a steel shell having a lower flange to help position the shroud in the mold.

A variation on the same idea is illustrated in Figure 17. In this situation, about half of the ceramic shroud is encased in a metal sheath. The metal sheath has threads on the outside that mate with Acme threads attached to the bottom of the ladle. An argon purge can be provided to eliminate the possibility of air entrainment during pouring.

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Figure 16. Threaded Ceramic Unpurged Shroud.

Figure 17. Purged Ceramic Shroud with Threaded Metal Attachment.

Other simpler devices can be conceived, such as those illustrated in Figures 10 and 11, and may be used provided that the shrouds can be sealed adequately to prevent aspiration and leakage during pouring.

The ladle of steel with the attached shroud may then be transported to the molding area where it can be lowered into the mold cavity. The shroud may be lowered into a side mounted pouring basin, as illustrated in Figure 18, or lowered into a riser in some cases, as illustrated in Figure 19. In either case the shroud must extend to near the bottom of the mold and deliver steel into a ceramic splash basin. The ceramic splash basin is necessary to prevent mold erosion by the high velocity metal exiting the shroud. Some type of positioning device also will be required to locate the shroud in the catch basin such that it does not touch the basin bottom and restrict flow.

When the shroud is properly positioned, the nozzle is ready to be raised and the casting poured. Ideally, the shroud should be extracted during the pouring process such that the tip always remains just under the molten metal surface but not extended too deeply beneath the metal. This might be accomplished by either raising the ladle or lowering the mold away from the ladle during pouring. The purpose of shroud removal is to prevent excessive metal from sticking to the shroud.

Physical Modeling of Bottom and Submerged Pouring

The water modeling experiments were conducted to explore methods for minimizing air entrainment during pouring of steel. Previous water modeling studies at the University of Toronto had pointed out differences in flow and air entrainment characteristics between bottom pouring and submerge pouring ^(17,19), and subsequent bottom pouring trials conducted at Southern Research correlated well with casting results obtained in commercial casting experiments with cruciform and standard nozzles. ⁽²⁰⁾

A careful search and analysis of the water modeling literature was prepared in the current study by Dr. Christoph Beckermann, and presented at the 1992 SFSA T & O Conference. ⁽²¹⁾ The final report by Dr. Beckermann has been issued as SFSA Special Report #26. ⁽²²⁾ This report provided a thorough review of water modeling literature and should be reviewed where details of the literature are desired. The main conclusions from the Beckermann study were:

1. Water is a good liquid for modeling steel flow because of the similarity in kinematic viscosity of the two liquids.
2. For a given fully turbulent fluid flow configuration, the air entrainment rate depends on the square of the Froude number. This implies that the air entrainment is directly proportional to the stream (jet) length and liquid head pressure, and inversely proportional to the stream diameter.

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Figure 18. Schematic of Offset Submerged Pour.

5-490

Figure 19. Schematic of Submerged Pour through a Riser.

3. The critical pouring velocity ($V_{critical}$) for the onset of air entrainment in a particular pouring arrangement depends strongly on fluid properties. Turbulent approach flow conditions can stimulate the onset of entrainment at velocities less than $V_{critical}$.
4. Air entrainment when pouring molten steel is expected to be similar to that observed in a full scale water model since the Reynolds number, Froude number, and the Z parameter of the two fluids and pouring systems are similar.

Water Modeling To Simulate Flow Of Steel. The Beckermann study provided a theoretical foundation for analog modeling and showed that water is a useable fluid because it has approximately the same density to viscosity ratio as steel. This results in a similarity between the kinematic viscosities of the two liquids, and permits Reynolds number matching in a one-to-one scale model of free-surface flow. In simple terms, a full scale water model will have flow conditions similar to those of liquid steel. One-to-one scaling of all geometric dimensions maintains geometric ratios and ensures that Froude Number matching occurs, since fluid velocities are approximately the same. Bernoulli's equation predicts that in unpressurized (i.e., gravity-driven), frictionless free-surface flows, fluid velocity is dependent only on the vertical liquid head height. Since this is a geometric factor, a one-to-one scale model results in similar fluid velocities and matched Froude numbers.

The largest uncertainty in water modeling lies in surface tension effects which are described by the Weber Number. By converting the Weber Number to the "Z" parameter, the inertial effects found in specific velocity and length terms are replaced entirely with fluid properties, independent of flow conditions. Using the best published data available, the Z parameter for room temperature water is approximately equal (within a factor of two) to that of steel, assuming that a thin film of FeO exists at the air-liquid steel interface.

Air entrainment rates are a function of boundary geometries, fluid flow characteristics, fluid properties, and the availability of air. Similitude permits air entrainment rates to be expressed as a function of the Reynolds, Froude, Weber, and Euler numbers when there are constant geometric ratios. Since these ratios can be approximately maintained, the literature indicates that air entrainment rates during steel flow can be modeled with reasonable accuracy using water under similar pouring conditions.

University of Toronto Submerged Pouring Experiments. The model arrangement for the submerged pouring trials consists of a clear acrylic ladle approximately 20 inch diameter with a maximum depth of 20 inches. The ladle is equipped with a 1.0 inch diameter nozzle. A clear acrylic ladle shroud of 1.7 in. in I.D. and an overall length of 21.5 in. is then attached to the ladle shroud collector nozzle to simulate in-plant usage and to determine the effect of a poor seal at the attachment interface. The same simulated casting cavity is used.

Submerged pour trials were conducted by attaching the shroud to the bottom of the pour nozzle and extending it through the riser to within about 2 in. of the bottom of the simulated plate

mold. The fluid exited the bottom pour ladle, traveled down the shroud, and entered the casting cavity directly through the riser without the use of a runner system. The back pressure on the incoming fluid enabled the submerged pouring shroud to prime when the casting cavity was approximately 1/3 to 1/2 full.

The submerged pouring process is shown in Figures 20 and 21. In these photographs, the submerged pouring stream is shown entering an open pool of water, with and without a good ladle collector nozzle to shroud seal. Note that the impact of the unprimed stream upon the open pool has a very rough meniscus and the air entrainment is extensive, while the primed stream has much reduced air entrainment and a much more level meniscus due to the compactness and non erratic nature of the stream.

A photograph at the start of the submerged pouring process is shown in Figure 22. It illustrates the reduced splashing and turbulence that is associated with this process even at the start of cast. However, the impact of the stream directly upon the mold bottom may require an impact pad placed in the cavity's bottom. As shown in Figure 23, when the submerged nozzle primes, the filling of the mold cavity is extremely smooth and free of air entrainment. In addition, filling time is reduced which is associated with the higher flow rates as a result of priming the submerged tube. Pour times for submerged pouring were in the range of 4 to 5 seconds.

These times are dramatically decreased with respect to bottom and lip pouring due to the lack of throttling upon the incoming flow.

SRI Pour Water Modeling Experiments. The objective of the water modeling was to explore techniques for reducing air entrainment during pouring of metal. The principles found in the modeling literature study were used in developing the water model apparatus, designing the experimental matrices, and conducting trials using bottom pour ladles.

The purpose of the water modeling experiments was to investigate a variety of pouring arrangements to quantitatively measure the amount of air entrained under a variety of head pressures, pour rates, pouring basins, and sprue arrangements. Conditions were sought that minimize air entrainment.

Potential Air Entrainment Factors. Most potential factors affecting air entrainment are related to:

- (1) The way metal is delivered to the mold (pouring system), and
- (2) the way metal is received by and fills the mold (the sprue/runner/gating system).

The velocity and flow characteristics of liquid metal influence aspiration of air down the sprue, mixing of air and liquid in the runners, jetting action of metal entering the mold cavity, and

5-623

Figure 20. Air Entrainment and Meniscus Fluctuation Associated with Unprimed Ladle Shroud Pouring into Open Pool

5-624

Figure 21. Air Entrainment and Meniscus Fluctuations Associated with Primed Ladle Shroud Pouring into Open Pool.

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Figure 22. Water Entrance into Mold Cavity at Start of Submerged Pour.

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Figure 23. Water Entrance into Mold Cavity near End of Pour.

mixing as the mold cavity fills. Air entrainment increases the amount of metal exposed to oxygen.

The amount of air entrained during bottom pouring is influenced by the liquid height in the ladle and the distance between the ladle and the mold which affect the liquid velocity and stream impingement velocity in the sprue. The nozzle opening in a bottom pour ladle has a significant effect because it controls the stream surface area and pouring time. Stopper opening affects stream fragmentation. Nozzle and stopper shape affect the surface roughness of the metal stream.

These results from the water modeling experiments tend to support observations made during many years of steel foundry practice. The conclusions drawn from these experiments were as follows:

1. Air entrainment was minimized with low metal hydrostatic heads.
2. Air entrainment was minimized by opening the nozzle as quickly as possible and leaving it open during pouring.
3. Throttling the nozzle to produce a stopper opening less than the diameter of the nozzle increased air entrainment.
4. Taller parallel sprues produce progressively greater amounts of entrained air.

Experimental Foundry Casting Trials

First Submerged Shroud Pouring Trial. The first submerged shroud pouring trial was conducted at a participating foundry. ⁽²³⁾ Two problems have been associated with mechanical shrouding in past experiments. One problem involves making the shroud removable and still obtaining a good seal with the bottom of the ladle. Any leak will aspirate large amounts of air during the pour. A pliable clay graphite gasket to seal the shroud and an inert gas cover around the seal seems to have worked in a previous trial. The second problem involves dealing with the additional metal velocity caused by the shroud. Two different methods were used to reduce the metal velocity as it entered the mold. The first method placed a ceramic filter at the bottom of the riser to absorb the impact of the metal at the start of pour. The second method was to use a filter/riser combination such as the FOSECO Stelpur to reduce the velocity of the metal.

A set of ten molds was poured under three different conditions: standard gating, shrouding with a filter placed in the bottom of the riser to reduce the impact of the metal, and shrouding and pouring the metal into the Stelpur riser/filter. Casting quality was determined by gamma radiography as well as by a visual rating of the surface of the casting.

A difference was observed between the pouring conditions with a 99% statistical confidence. The effect of pouring condition on casting quality as measured by X-ray rating is illustrated in Figure 24. The castings poured with the shroud with the filter/riser combination had the best casting quality with an average x-ray rating of 2. The conventionally poured

Figure 24. Effect of Pouring Condition on Casting Quality Measured by X-Ray Rating.

castings and the shroud with filter splash plate casting were statistically similar. However, the shrouded castings obtained ratings which were as good as the shroud/filter in some cases and in some cases worse than the conventionally poured castings. Figures 25 and 26 illustrate the effect of pouring condition on casting quality as measured by visual rating of the casting surface by two observers. The results were similar to the x-ray results with the shroud/filter combination producing consistently the best castings followed by the shroud and conventionally poured castings. The shrouded castings had several castings almost as clean as the shroud/filter castings but also had several that were very dirty. Wide variation within a group indicates a lack of process control.

A steel buildup was observed to form on the shroud during pouring. This buildup in conjunction with the difficulty in holding the ladle steady when lowering into the riser caused the shroud to contact the side of the riser in several observed instances. It was suspected that sand was dislodged into the mold during pouring by the buildup. Visual examination of the castings did not reveal mold erosion that would account for molding materials defects.

Three conventionally poured castings and three shrouded castings were selected and sample defects were removed from the plates. A mounted and polished defect typical of those removed from the shrouded test plates is illustrated in Figure 27. 99% of the solid inclusion material was silica sand grains. This indicates that molding sand was the source for the inclusions in the shrouded castings. Since there were no indications of mold erosion, the most likely source for the molding material was from sand dislodged by the steel buildup on the shroud.

Conclusions. The lower pouring times for the shrouded castings compared to the conventionally gated castings indicate that the shroud did seal. The higher pouring times for two of the molds were either throttled or opened and closed repeatedly. The calculated pour time for a primed 2 3/4 inch ID shroud with a 42 inch metallostatic head pressure is 276 lbs per second, considerably higher than the rate of 121 lbs per second observed with the shrouded molds. The 1 3/4 inch nozzle would act as a choke for the system. A 42 inch head height with a 1 3/4 nozzle area would produce a pour rate of 112 lbs per second which is comparable to the pour rates observed.

The shroud with the Stelpur filter/riser consistently produced the highest casting quality compared to the shrouded or conventionally poured castings. The combination of the mechanical shroud and the filter which reduced metal velocity and provided filtration improved casting quality. The difficulty in lowering the shroud into a relatively small riser and the steel buildup on the shroud make conclusions on the shrouded castings difficult. The wide variation within the group indicates the process is not controlled. Defects removed from the shrouded test plates indicate silica sand is the predominate inclusion material. This may have been a result of the shroud contacting the side of the riser and dislodging sand into the mold during pouring or possibly from erosion of the mold by high velocity metal.

Figure 25. Effect of Pouring Condition on Casting Quality Measured by Cope Surface Visual Rating. (jg)

Figure 26. Effect of Pouring Condition on Casting Quality Measured by Cope Surface Visual Rating (jag).

Figure 27. Defect removed from a Submerged Poured Test Casting.

Second Submerged Shroud Pouring Trial.

A second submerged shroud pouring trial was conducted. The casting selected had a history of containing macroinclusions on the surfaces especially in the diameter transitions. In this trial, the molds poured were larger in volume and open faced to make lowering the shroud into the mold easier. The ladle was also significantly larger than in previous experiments. A larger ladle increases the likelihood that the ladle will have to be throttled to prevent overfilling the pouring cup.

The shroud was produced by Premier Refractories from fused silica. The shroud length was 27 inches long with a two inch diameter tapered inner diameter. The shroud was attached to the ladle using five mechanical clamps attached to the ladle and a steel collar attached to the shroud. The shroud was typically lowered to within two inches of the drag. The ladle was raised during the pour to keep about four inches of the shroud submerged beneath the steel surface. There was very little splash associated with the submerged pour. The ladle operator was able to fully open the stopper once the shroud was submerged. Once all the molds were filled, the shroud was removed before the ladle was emptied of slag.

A graph illustrating the cleanliness ratings for the castings poured in the first heat is shown in Figure 28. The conventionally poured castings contained an average of 10.8 one-inch diameter circles of macroinclusions with a sample standard deviation of 5.2. The submerge poured casting contained an average of 0.2 one-inch circles of macroinclusions with a standard deviation of 0.6. Figure 29 illustrates the cleanliness ratings for the castings poured in Heat 2. The conventionally poured castings contained an average of 13 one-inch circles with a sample standard deviation of 5.6. The submerge poured casting contained an average of 0.5 one-inch circles of macroinclusions with a standard deviation of 0.7. A graph illustrating the cleanliness rating for all castings poured in both heats is shown in Figure 30. The conventionally poured castings contained an average of 11.9 one-inch circles of macroinclusions with a sample standard deviation of 5.5. The submerge poured casting contained an average of 0.4 one-inch circles with a standard deviation of 0.7.

Casual observation of the cleanliness ratings show that the submerge poured castings were dramatically cleaner than the conventionally poured castings. T-test analysis confirms that there is a 99.99% probability that the submerge poured castings had a lower average and a smaller standard deviation.

The castings from this trial were also followed through the machining process to determine if any defects were uncovered during machining and if any improvements in machinability were detectable.

All of the submerge poured and conventionally poured castings have been followed through the machining process. Surface inclusions can be observed near the machined surfaces. Inclusions like these cause excessive tool wear and breakage. The machine operator will

Standard Vs Shrouded (Heat 1)

Figure 28. Effect of Pouring Method on Surface Cleanliness Rating for Heat #1.

Standard Vs Shrouded (Heat 2)

Figure 29. Effect of Pouring Method on Surface Cleanliness Rating for Heat #2.

Figure 30. Effect of Pouring Method on Surface Cleanliness Rating for Both Heats.

typically reduce the feed rate when encountering an interrupted cut from inclusions. This will cause longer machining times.

A set of ten submerge poured castings were machined without having to change either the rough or final cut tool. The operator also did not have to reduce the feed rate during the machining process. The final cut tool had to be changed twice for the set of ten conventionally poured castings. The operator did have to adjust the feed rate for these castings. Overall, the submerge poured castings were more machinable compared to the conventionally poured castings and required less operator intervention.

Conclusions. A total of twenty-three castings were produced submerge pouring along with sixty conventionally poured castings. The submerged poured castings contained on average 96% fewer observable surface inclusions (11.9 vs 0.4) compared to the conventionally cast parts. The variation in surface inclusion also decreased by 88% from 5.5 to 0.7. The machinability of the casting was also improved by submerged pouring. The submerge poured castings required fewer cutting tool changes and less operator intervention during machining. Subsequent to these trials, the foundry has decided to purchase more shrouds for continued experimentation on other problem castings where submerge pouring is possible.

CLEAN HEAT/DIRTY HEAT TRIALS

Introduction

Many foundries have experienced wide variations in casting quality from heat to heat. Castings from one heat may be almost inclusion free while castings from the next heat require extensive weld repair. The transient nature of the heat quality made casual or indirect observation and analysis of variations difficult. In recent years, two extensive casting trials were conducted to examine the effect of bottom pour nozzle configuration and filtration of steel castings on casting cleanliness.^{24,25,26} A total of 600 castings from 94 heats were poured and evaluated during the course of these trials. Detailed statistical analysis of the data revealed that variation in heat quality was a significant, and in some cases, the largest factor affecting casting quality. However, the analysis did not reveal the source of the variation, only that particular heats were statistically cleaner or dirtier than others. The lack of information on possible sources of variation required a trial where additional information could be collected and analyzed.

Trials have been conducted at four foundries to determine if correlations could be found between one or more variables in the melting or pouring practice and average heat casting quality. Two foundries have begun to collect the necessary information for this trial. The goal is to understand the influence of melting and pouring practice on casting quality, develop engineering principles for controlling and improving metal quality, and learn how to reduce the heat to heat variations.

Background

In 1993, a designed experiment was conducted evaluating the cost effectiveness of filtering the metal using ceramic filters. The primary variable was filtration using two types of commercial filters. Heat-to-heat effects were necessarily a secondary variable. Based on the furnace capacity and production schedule, it was determined that 300 castings could be poured in five consecutive heats over a two-day period. Sixty castings were poured from each heat using 15 molds having four cavities per mold. Five molds with each filter configuration were poured from each heat along with five unfiltered molds.

It was observed in analyzing the data that the castings poured from Heat 2 required more weld repair than most of the other heats. An analysis was made to determine if Heat 2 was statistically different from Heats 1, 3, 4, and 5. It can be said with greater than 99% confidence that castings from Heat 2 were statistically dirtier than the remainder of the heats.

Heats 4 and 5 appeared to be somewhat cleaner than the other heats. Only two castings out of 40 made from each heat required weld repair, for a weld repair rate of only 5%. Analyzed individually, either heat could be said to be cleaner than the rest with about 90% confidence. If, however, the weld repair combined results from Heats 4 and 5 are compared with the combined

results from Heats 1, 2, and 3, it can be concluded with about 98% confidence that these two heats are cleaner than the remaining three heats.

The following conclusions were drawn from the experimental data.

1. The weld repair data indicated that Heat 2 was statistically dirtier than the remainder of the heats. This conclusion can be drawn at a confidence level of at least 99%.
2. Heats 4 and 5 were cleaner than the remainder of the heats. This conclusion can be stated with about 98% confidence.

At this point, the cause of the dirt - whether refractory, eroded molds, reoxidation, etc. - is not known. It can only be concluded that this heat was dirtier.

An analysis of the cruciform nozzle pouring data obtained in 1991 provided indications of heat-to-heat variations in metal cleanliness as well as processing effects on casting cleanliness.^{24,25} The study was conducted to compare the cleanliness of castings poured through cruciform nozzles with those poured through standard nozzles. The resulting data base included the number of surface defects, the accumulated maximum linear dimensions, and notes on factors existing during pouring.

Cleanliness data was collected on 84 castings poured from 35 heats. All castings were bottom-poured through a 2½ inches diameter downsprue.

The statistical test used to evaluate the significance of these observations was the Analysis of Variance (ANOVA). The ANOVA test was used to determine if the differences in variance in two samples was likely to be a result of two different populations being sampled or a result of random sampling of a single population. ANOVA assumes that the population(s) being sampled are normally distributed. An analysis of the data (using ANOVA) indicated with a confidence of 99% or higher that these are significant influences in heat-to-heat cleanliness of the metal poured.

Procedure

There were several requirements that the foundry had to meet in order to participate in the trial. The foundry was requested to provide at least five to ten defects of interest for examination. Figure 31 illustrates a typical cope surface macroinclusion from a production casting produced during these trials. The oxide was a complex mixture of alumina, silica, and manganese oxide produced from a reaction of the oxidizable elements in steel with oxygen. The foundry had to have a casting that has a quality problem and had a reasonable production rate. Documentation from a minimum of thirty heats was needed for a trial. The thirty heat criteria provided enough data for a good statistical analysis. If a large number of castings was poured

(A)

(B)

Figure 31. Typical Cope Surface Inclusion Removed from Production Casting at a Foundry. (A) 3X, (B) 200X

from each heat, a minimum of five castings within each heat was measured to provide a basis for predicting the variation within a heat. If fewer than five castings were poured from a heat, the casting(s) should have represented a significant portion of the heat. The method by which casting quality was to be measured was left up to the foundry.

The participating foundries were asked to supply as much information as possible along with any other documentation, such as the heat sheets, that might be available. There is typically a significant amount of data already being collected at the foundry on each heat. The foundries for the most part did not record any data that was not already available somewhere in the foundry. The largest workload was in collecting the data, keeping track of the castings through the foundry, and rating the castings for quality. Samples of the slag from the furnace and the pouring ladle along with samples of metal were taken to further document each heat.

After the data for the heats were collected, the variables from each heat were keyed into a statistical analysis program. Normality tests were conducted on the casting quality data to ensure statistical analysis techniques could be used. The data was analyzed by two different methods. In the first method, each variable was analyzed individually using simple regression and then ranked according to the highest R^2 and the highest statistical significance. R^2 is the amount of variation in the dependent variable (in this case, metal quality) that can be explained by a variable or a set of variables. In the second method, a t-test was used to detect statistically significant differences of the variables between the cleanest and dirtiest heats. In a t-test, the variables from the cleanest heats are compared to the variables from the dirtiest heats and tested to see if a statistical difference exists. Although the order may change slightly, both methods typically pick the same variables as having a significant influence on heat quality.

The heat quality ratings were expressed in different terms between the foundries due to the different methods in rating heat quality and the different design of the castings. To account for these differences, the quality ratings were standardized using the z-score. The z-score is the heat quality rating minus the average for the population divided by the standard deviation. Basically, the z-score is the number of standard deviations that particular score is from the arithmetic mean of the population.

There were usually 10-12 variables that had at least a moderate correlation with overall heat quality. The list of variables was then reviewed with foundry personnel to evaluate the results. Typically, the list was narrowed down to four or five variables that strongly affected heat quality, were directly affected by the melting or pouring practice, and have a reasonable engineering solution for influencing heat quality. A subsequent trial was conducted at the participating foundries to verify the influence of the variables selected.

Results

One acid practice foundry and three basic practice foundries were involved in the trials. The acid practice foundry melts 1025 carbon steel in a twenty ton, acid electric arc furnace. The foundry poured from a twenty ton silica brick lined bottom-pour ladle. The heat was deoxidized at tap with aluminum and then treated with calcium wire. The molds were formed from clay bonded silica sand. Mold pour weight was about 2250 lbs with a casting weight of 1711 lbs. Pouring temperature was typically 2860 °F. Four to five castings were poured from each heat. Casting quality was determined by measuring the length of weld excavation for dirt inclusions on each casting surface. Data from thirty-five heats were collected for the initial analysis.

The first basic practice foundry melts 1025 carbon steel in a ten ton, basic electric arc furnace. The heat was deoxidized with aluminum, manganese, and silicon during tap. The molds were poured from a ten ton, bottom-pour ladle. The molds were formed from clay bonded silica sand. The casting had a pour weight of about 1650 lbs and a net weight of 1245 lbs. Pouring temperature was typically 2870 °F. Ten to twelve castings were poured from each heat. Casting quality was measured by counting the number of one inch diameter circles needed to cover the dirt on the casting surface after blasting. A total of twenty-five heats were used in the initial analysis.

The second basic practice foundry melts 1025 carbon steel in a twenty-five ton electric arc furnace. The foundry poured from a twenty-five ton 70% alumina brick lined bottom-pour ladle. The heats were deoxidized at tap with aluminum, silicon and manganese. The molds were formed from no-bake bonded silica sand. Mold pour weight was about 7200 lbs with a casting weight of about 4000 lbs. Pouring temperature was typically 2860 °F. Only one mold out of a total of three to six for the heat was included in the trial. However, this single casting represented 14% of the total metal poured. The casting had a large cope surface area so that the likelihood that inclusions would be observed was increased. Casting quality was determined after shotblast and prior to weld repair by measuring the area of cope surface inclusions on each casting surface. Data from thirty heats were collected for the initial analysis.

The third basic foundry melts high manganese carbon steel in a ten ton, basic electric arc furnace. The heat was deoxidized with aluminum, manganese, calcium, and silicon during tap. The molds were poured from a ten ton, bottom-pour ladle. The molds were shell with a pour weight of about 300 lbs and a net weight of 150 lbs. Pouring temperature was typically 3000°F. About thirty-two castings under investigation were poured from each heat with five randomly selected for measurement. Casting quality was measured by counting the number of one inch diameter circles needed to cover the dirt on the casting cope surface after blast. A total of twenty-seven heats were used in the initial analysis.

Acid Practice Foundry. Thirty-five heats were collected over the span of about twelve months. Approximately 150 variables were recorded or calculated for each heat and stored in an analysis spreadsheet. The acid practice foundry selected six variables from a list of thirty-four

that had a reasonable probability of influencing the quality of the heat.²⁷ These variables were metallostatic head pressure, metal pouring temperature, residual silicon after oxygen blow, residual manganese after oxygen blow, number of slag thinner added to the ladle, and furnace tapping rate. An additional twenty-four heats were poured with the six variables set at levels to produce clean heats. The average heat quality rating for the twenty-four heats decreased from about 32.6 inches to an average of 18.1 inches, a decrease of about 44%. Subsequent analysis by the foundry indicated that three variables had the strongest influence on casting quality: metal head height, pouring temperature, and silicon level after the oxygen blow.

First Basic Practice Foundry. Approximately 80 variables were recorded or calculated for each heat and stored in an analysis spreadsheet. Initial t-test analysis of the basic practice foundry data indicated that ten variables influenced heat quality. From this list, six of the variables involved carbon and manganese concentrations in the metal. After discussions with the foundry, the variables of interest were determined to be the percent concentration of carbon and manganese at meltdown. An L4 designed experiment was run to evaluate the effect of meltdown manganese and carbon concentrations on heat quality. A total of eight heats were poured in the L4 with two heats at each condition (low carbon, low manganese | low carbon, high manganese | high carbon, low manganese | high carbon, high manganese).

Subsequent analysis of the L4 revealed that meltdown carbon did not significantly affect heat quality. The manganese concentration at meltdown was, however, important with low meltdown manganese producing cleaner heats compared to high meltdown manganese. The heat quality improved from an average of about 4 to less than 2, an improvement of about 50%. It should be noted that silicon concentration was not measured at meltdown at this foundry.

Analysis of the L4 data also revealed that there was a positive correlation (48%) between the concentration of manganese and carbon at meltdown. In effect, the manganese and carbon concentrations follow each other. There was also a positive correlation (75%) between meltdown carbon concentration and oxygen blow time, as you would expect. In effect, the heats with lower meltdown manganese concentration had less oxygen blown into the metal.

Similar to what was observed in the acid practice foundry, the clean heats had a higher activity compared to the dirty heats. More manganese was available for reaction with oxygen in the clean heats. This is an indication that there is less oxygen available to react with the manganese.

Second Basic Practice Foundry. Thirty-one heats were evaluated over the span of about two months. Approximately 140 variables were recorded or calculated for each heat and stored in a spreadsheet. Initial review of the data showed that one heat had an inclusion surface area count four times higher than the next largest area count. The data also failed all tests for normality. This heat was removed from the analysis. The normality for the remaining heats was adequate to proceed with further analysis.

Initial analysis of the foundry data indicated that four variables influenced heat quality. In both tests, the percent manganese recovered from the slag after tapping had the strongest correlation to casting quality, followed by the angle of the oxygen lance, number of heats on the ladle lining, and tap rate. The initial results were discussed with foundry personnel to determine our next course of action. The high manganese recovery indicated that a reducing slag after tapping improved metal quality. The amount of manganese recovered from the slag is also influenced by the volume of slag tapped on the metal and the concentration of manganese oxide contained in the slag. The higher tap rate for improved metal quality was due to reduced exposure of the metal to atmospheric oxygen. The number of heats on the ladle lining indicates that the lining needs to be baked out to remove any oxygen sources. The effect of lance angle on metal quality was unusual. Quantifying the angle of the lance is subjective since the operator is moving the lance to remove slag as well as boil off carbon. But lance angle was a strong indicator in both analyses.

A second set of castings was poured at the foundry with four variables set at their optimum level. This test was performed to demonstrate that these variables do in fact improve metal and casting quality. Calcium carbide was added to the slag after tapping and more slag was tapped with the metal to increase manganese recovery from the slag. Tap rate was increased as much as possible. Oxygen lance angle was kept to approximately 45 degrees. The number of heats on a ladle lining is not a practical variable to control. Additionally, the silicon and manganese concentrations at meltdown were increased.

Seven additional heats were poured under these conditions and rated identically to the previous heats. The average area of cope surface inclusions decreased by about 51% from 75.4 to 37.2 inches squared. As importantly, the variation in casting quality decreased by 76% from 53.8 to 13 inches squared. As an additional test, the foundry is conducting a designed experiment to determine which variable is the most important and that these variables can be used to increase or decrease metal and casting quality.

Third Basic Practice Foundry. Initial analysis of the foundry data indicated that four variables influenced heat quality. In both tests, the amount of aluminum added to the ladle apparently had a strong effect on metal quality with increased ladle addition improving metal quality. However, the variation in the amount of aluminum added is relatively small so the effect may not be as strong as the analysis indicates. Slag samples were taken from the furnace after block, from the ladle in the pit after deoxidation, and from the ladle at the end of the heat. The color of the slag was rated from 1 to 5 with 1 being light gray and 5 being black. The numbers for the end of heat slag ranged from 1 to 3.5 with only a few ladle slags at the higher end of the number scale. There was a strong correlation between slag color and metal quality. Charge material and final temperature appeared to play a role in metal quality. The final temperature varied about 100 °F over the range of casting poured.

The variables indicated by the analysis provided a starting point for discussions with the foundry to identify factors that are logical in controlling metal quality. Once a reasonable list of

factors has been identified, subsequent trials will be conducted at the foundry to verify the effect of the factors on metal quality.

Summary and Conclusions

Three of the four foundries showed significant improvement in casting quality by manipulating the melting practice. Improvements ranged from 40-50%. The fourth foundry has not yet completed the second phase of the trial.

The variables from these trials can be grouped into two separate categories. The first category is the pouring and filling practice. Metallostatic head pressure and tapping rate were found to be important in three of the four foundries with lower head pressure and faster tapping rate improving casting quality. Lower head pressures reduce the velocity of the metal exiting the nozzle and throttling of the ladle. The basic practice did not have head height as a variable since the entire heat was used to pour the selected casting. The effect of head height on casting quality is illustrated in Figure 32. As the mold number increases, the head height decreases. The first two to three castings poured from the heat are significantly dirtier than the last two or three castings poured. High metal velocities and throttling have been shown to increase air entrainment and reoxidation of the metal ²⁸. Higher tapping rates also reduce the amount of oxygen exposed to the metal.

The second category concerns the concentration of oxidizable elements contained in the steel. Silicon, manganese, and aluminum concentrations were important factors in all four foundries. These elements can be indicators of the oxygen concentration contained in the steel. Carbon is typically used as an indicator of oxygen concentration in the steel bath. However, authors have shown that other oxidizable elements can also influence the oxygen content of the steel and the availability of the oxygen to form reoxidation inclusions in steel castings. ^{28,29} By using the oxidizable elements as indicators and manipulating the melting practice to optimize the concentration of these elements, improvements in casting quality can be observed.

Clean heats can consistently be produced if the oxygen concentration in the steel bath can be minimized through improved melting practice and reducing exposure of the steel to atmospheric oxygen during pouring and filling.

Two additional foundries have completed the initial phase of the trial. One foundry melts CF8M stainless steel in an alumina lined induction furnace. The molds were formed using the shell process and has a pour weight of about 66 pounds. Casting quality was rated by counting the number of surface inclusions discovered during rough machining. The second foundry melts a 1025 mild steel in a three ton acid electric arc furnace. The molds were formed from Alphaset bonded silica sand and had a pour weight of about 30 pounds. Casting quality was rated by scoring the cope surface from 1 to 10.

Figure 32. Effect of Head Height on Casting Quality at Basic Foundry.

SPECIAL LADLE TRIALS

Introduction

Previous water modeling studies at the University of Toronto pointed out differences in flow and air entrainment characteristics between bottom pouring and lip pouring ladles, and subsequent bottom pouring trials conducted at Southern Research correlated well with casting results obtained in commercial casting experiments with cruciform and standard nozzles. In general, pouring with low metal head pressures, pouring through unflared bottom pour nozzles, and pouring compact, smooth-flowing streams with minimum impingement velocities minimize air entrainment and the reoxidation which results from entrainment. A series of modeling experiments were conducted with a quadrant pour ladle and slanted sprues and the results compared with those obtained using commercial teapot and lip pour ladles.

The potential benefits of a quadrant pour ladle are that a constant rate of ladle tilt can be used to produce a constant metal pouring rate, and the ladle lip can be maintained at a constant height above the mold. The iron pipe industry has used quadrant pour ladles for many years because the quadrant ladle can be consistently controlled to pour the same weight of metal regardless of the amount of metal in the ladle. Quadrant pour ladles usually rotate around a point near the lip, and if the tilt point can be located over the sprue, the drop height of metal into the sprue can be minimized. A slanted sprue was shown to reduce air entrainment if used in combination with a quadrant pour ladle compared to a vertical sprue.

A series of plant scale experiments has been conducted to evaluate the effect of quadrant ladle design and slanted sprue gating on casting quality. These experiments were conducted to validate the results obtained by water modeling. The quadrant ladle and stand were fabricated and delivered to the foundry. The ladle with refractory will hold about 1500 lbs of steel. The ladle was lined with disposable refractory board to reduce the heat loss through the refractory.

Water Model Studies

A quadrant pour ladle was fabricated from 3/16 inch steel sheet with a ladle that had a back radius of 36 inches and covering a 60° arc. The ladle had a capacity of approximately 4 cf, equivalent to a capacity of 2000 lbs of steel. The ladle pivoted around a steel rod under the lip that was supported on two stands. The ladle was poured using a hoist which raised a chain wrapped around the curved end of the ladle. The conditions considered in the quadrant ladle pouring experiments were schematically illustrated in Figure 33.

A number of experiments have been conducted with a quadrant pour ladle and the results compared with those obtained using a teapot ladle. The quadrant pour ladle has the potential advantage that it tilts around the ladle spout and the spout can be kept close to the mold if the sprue can be kept near the edge of the mold. All of the experiments in this series were conducted using a 2 inch diameter sprue, a 5 inch sprue length with a sprue tilted from the vertical. The

Figure 33. Conditions Considered in the Quadrant Ladle Experiments.

variable factors were the quadrant pour ladle vs. the teapot ladle and the angle of rotation of the ladle.

The teapot ladle experiments with a full ladle and with a half full ladle at the start of the pour resulted in about 0.2 cf of mean air entrainment. The quadrant pour ladle resulted in less air entrainment, with a mean of about 0.07 cf, or about one third of that produced under similar conditions with a teapot ladle.

Ladle type had the largest effect on the amount of air entrained. The type of ladle accounted for about 84% of the variation about the mean value. The average air entrained in these experiments was about 0.14 cf. Pouring from the teapot ladle produced an average air entrainment of 0.21 cf compared to an average of 0.07 cf from the quadrant pour ladle. Pouring from a full ladle produced an average air entrainment of about 0.15 cf compared to 0.12 cf when pouring from a half full ladle.

In theory, the quadrant-pour ladle should yield the same results performance regardless of angle of rotation. However, in practice, the entrainment may vary because of variations in the ladle spout shape as the ladle rotates from the full position to one containing less liquid.

Mean entrainment when pouring from a full quadrant ladle was lower (0.03 cf) than during the pours down with a partially empty ladle (0.10 cf). This suggests that either the shape of the pouring lip or the type of approach flow to the lip has an effect which has not been identified.

Quadrant Ladle Casting Trials

A series of plant scale experiments has been conducted to evaluate the effect of quadrant ladle design and slanted sprue gating on casting quality. These experiments were conducted to validate the results obtained by water modeling. The quadrant ladle and stand were fabricated under the direction of the participating and delivered to the foundry. The ladle with refractory will hold about 1500 lbs of steel. The ladle was lined with disposable refractory board to reduce the heat loss through the refractory.

The first trial was conducted at a participating foundry that casting parts of a size that could be poured by the quadrant ladle. The casting selected for the trial was a WCB valve body. The mold was produced with PepSet bonded silica sand coated with zircon mold wash. The casting had a pour weight of 626 lbs and a casting weight of 305 lbs. The WCB carbon steel was melted in a 9 1/2 ton acid electric arc furnace and deoxidized with Calsibar and aluminum upon tapping in the ladle. The molds were poured from either a board lined 700 lb teapot ladle or a 1500 lb quadrant pour ladle. Pouring temperature was about 2850 °F. A designed experiment comparing the quadrant ladle to a conventional teapot ladle and a slanted sprue to a conventional vertical sprue was agreed upon with the participating foundry.

Casting cleanliness was rated by measuring the surface area of the macroinclusions on the casting surface after shakeout and cleaning.

The location of the downsprue and pouring cup was not optimized for pouring from the quadrant pour ladle. The inability of the quadrant pour ladle to be moved hindered the pouring of the molds. These factors increased the pouring time of the quadrant ladle molds from about 30 seconds to 80 seconds compared to the teapot poured molds. The slower pouring times produced cold metal related defects on the casting surface. This made reliable appraisal of the quadrant ladle impossible.

Another foundry agreed to conduct a pouring trial using the quadrant ladle and slanted sprue design. The foundry initially video taped water pouring from the ladle to examine the trajectory of the flow as the water exits the spout. A number of water modeling trials were made to verify the trajectory of the water so the location of the sprue could be established. The mold used for the trial was a discontinued pattern that had a history of surface inclusion problems. The arrangement of the gating system allowed for the attachment of a slanted sprue with the correct geometry. The mold was formed from clay bonded silica and the cores formed from sodium silicate bonded silica sand.

The original gating system was used for the conventional vertical sprue molds. A sodium silicate bonded core was used to extend the runner to allow the slanted sprue to be connected to the runner. In both cases, a shell sprue was used. Initial tests with the slanted sprue molds produced acceptable castings with some modifications to increase the strength of the sprue.

The quadrant ladle was fixed on the foundry floor for safety. However, the molds were placed on a platform that allowed the molds to be moved in both the X and Y planes. This would allow the ladle operator to adjust the mold so the metal stream entered the sprue properly. The molds were placed on pallets and were moved with a fork lift to the quadrant ladle before and after pouring.

An L4 designed experimental matrix was agreed upon with the foundry with four replicates for each condition. The four variables were slanted sprue, conventional straight sprue, quadrant ladle, and conventional teapot ladle. Each mold was stamped with a unique number to allow identification after pouring. The metal used in the trial was a WCB carbon steel tapped from the furnace at a temperature of 3244 °F. The heat was initially tapped into a five ton bull ladle from an acid electric arc furnace. After the bull ladle was moved to the pouring floor, the quadrant ladle was lifted to the bull ladle, filled, and returned to the stand.

The castings were shaken out and shot blasted after pouring. Casting quality was rated by counting the number of one inch diameter circles needed to cover cope surface inclusions and by wet magnetic particle inspection using the number of indications as a measure of quality.

Several problems occurred which prevented successful completion of the trial. Metal spillage during pouring fouled the platform rails and made moving the mold extremely difficult in the later stages of the trial. This slowed the pouring rate which produced early freezing of the gating system and incompletely filled molds. The second problem was a misalignment of the sprue with the runner in the slanted sprue molds. The reduced cross-sectional area reduced the pour rate and produced incompletely filled molds or severe cold shuts on the cope surface. There were not enough good castings to produce statistically valid results.

The foundry has agreed to rerun the trial after we have sat down and discussed the problems with the first trial and implemented remedies.

TECHNOLOGY TRANSFER

A total of 18 papers or talks have been presented to numerous steel casting societies about the technology used in this project and the benefit to the participating foundries. These societies included the Steel Founders' Society of America, the American Foundrymen's Society, and the American Society for Testing and Materials. These presentations were made by either UAB personnel, SFSA personnel, or the participating foundries. Two workshops were also conducted demonstrating techniques developed and used in this project to produce clean steel castings.

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