CLEAN CAST STEEL TECHNOLOGY – MACINABILITY AND TECHNOLOGY TRANSFER

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CLEAN CAST STEEL TECHNOLOGY-
MACHINABILITY AND TECHNOLOGY TRANSFER


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EXECUTIVE SUMMARY

There were two main tasks in this project. These were (1) determine the processing factors that control the machinability of cast steel and (2) determine the ability of ladle stirring to homogenize ladle temperature, reduce the tap and pouring temperatures, and reduce casting scrap. Summaries of both tasks are presented in the following paragraphs and details are given in subsequent sections of this report.

Task 1. Machinability of Cast Steel

The purpose of the machinability study was determine the reasons for poor machinability sometimes encountered in cast steel. It was theorized that changes in deoxidation practice might influence the volume and character of the oxides formed and hence machinability. All of the castings evaluated were produced in commercial foundries using acid and basic melting practices, two heat treatments, and a variety of deoxidation practices. Machinability was evaluated using a drill wear procedure. The hardness, micro inclusion number density, and other microstructural features were measured on each material and correlated with the tool failure rate. The following conclusions were drawn from this study:

1. Casting hardness had a significant effect on both the number of holes to squeal and flank wear rate. The number of holes to squeal followed an exponential relationship with higher hardness associated with higher tool wear rates.

2. Higher oxide and nitride inclusion contents reduced the tool life. The tool life was reduced as either the number or the size of inclusions increased.

3. Within the range of deoxidants studied, the type of deoxidant was not found to significantly affect tool wear rates or life. A better correlation was found with the volume of deoxidation products rather than by whether the deoxidizing additions contained aluminum, calcium, titanium, or zirconium.

Task 2. Accelerated Transfer of Clean Cast Steel Technology

The goal of this task was to provide the steel foundry industry with the technical resources to implement clean cast steel technologies being developed. This goal was accomplished by providing foundries with experienced technical personnel to aid in applying (1) ladle shrouding technology, (2) Determine causes for some heats being clean and others being
relatively dirty, and (3) develop a video to teach employees the fundamentals of producing cleaner cast steel.

Ladle Shrouding Technology

In a previous phase of this project, a ceramic shroud was used to pour commercial castings using techniques similar to those used in wrought steel mills. The improvement in casting quality produced by shrouding the stream was dramatic. Conventionally poured castings exhibited an average of 11.9 one-inch circles of macro-inclusions with a sample standard deviation of 5.5. The shroud poured castings contained an average of 0.4 one-inch circles with a standard deviation of 0.7. Details of this program were presented at the 1998 SFSA Technical and Operating Conference held in Chicago, IL.

Since the initial work, the use of shrouds has been extended to other product lines with additional improvements in casting quality and lower product cost. Other foundries have begun evaluating shrouding technology UAB and SFSA are assisting in transferring the technology to their operations.

One foundry has conducted trials for nine months on a variety of castings. A 60% reduction in macro-inclusions on the casting surface is the minimum improvement seen on parts. In some cases, casting rework caused by reoxidation products was eliminated. This foundry is continuing to develop the technology.

A second foundry pours large castings used in pumping and dredging operations. Three trials have been conducted, but additional trials are necessary before the issues associated with mechanically attaching the shroud to the ladle are resolved. Developments in this foundry are continuing.

Two more foundries are implementing procedures for attaching the shroud to large foundry ladles.

Clean Heat/Dirty Heat Studies

Experiments have been conducted in five foundries to define the variables in the melting and pouring practices that affect heat-to-heat casting cleanliness. Metal composition at the end of refining significantly affects cleanliness, and a thermo-chemical explanation has been developed for the acid melted steels. It has been found that steels with a higher silicon and manganese and carbon concentrations after boil produces lower oxygen residuals, and this is associated with cleaner steel castings. Higher finishing temperatures increase the residual silicon and manganese concentrations, which act to buffer the heat and reduce oxygen concentration as the metal cools in subsequent processing.
Miscellaneous Technical Services To the Steel Foundry Industry

Over the past year, UAB has provided technical assistance to twenty foundries ranging from casting inclusion analysis for problem castings to technical assistance in reviewing melting process data for improving metal quality.

Clean Steel Training Video

The video illustrates good practices associated with producing clean steel castings and was designed for use by foundry floor personnel. The video considers all steps in producing steel castings including pattern design, melting, molding, and pouring. The areas where cope surface macroinclusions can be produced and techniques for reducing the incidence of macroinclusions were considered. The material was reviewed by steel foundry personnel to ensure that it properly addressed the important issues.

The procedures covered the following areas:

1. **What is an Inclusion and Why They are Important.**
2. **Where do Inclusions come from.**
3. **Entrapment of Molding and Melting Oxides.**
   A. Molding/Core System
   B. Slag Control
   C. Refractory Practice
   D. Summary
4. **Reaction of Oxygen and Steel.**
   A. Pouring
   B. Gating Design
   C. Summary
CLEAN CAST STEEL TECHNOLOGY

MACHINABILITY OF CAST STEEL AND ACCELERATED TECHNOLOGY TRANSFER

Introduction and Objectives

The objective of the Clean Cast Steel Program at the University of Alabama at Birmingham (UAB) is to improve casting quality by minimizing oxide defects and allowing castings to be consistently machined at high speeds. In past years, the research was concentrated on macro-inclusions that break, chip, or crack machine tool cutters and cause immediate shut down of the machining lines. Work to eliminate macro-inclusions has focused on metal stream shrouding, ladle design, metal filtration, filter-flow control devices, and gating systems. Recently, some research has focused on determining the sources of heat-to-heat variations in metal cleanliness. Foundry trials have demonstrated that modifications of the furnace practice can improve the quality of steel castings produced from 30 to 40%.

However, foundry experience has shown that castings identical in composition, shape and heat treatment cast at different foundries can have widely different machining characteristics. This demonstrates the fact that variables not currently measured in the foundry have a substantial effect on the machinability of the steel.

The goal of the Machinability task was to identify the metallurgical factors influencing machinability of steel and to gain an engineering understanding of the mechanisms that cause rapid tool wear. A series of experiments using castings produced in participating foundries were be evaluated for machinability. Factors of interest included the furnace practice, deoxidation practice, calcium wire injection, and heat treatment.

A second objective of the program was to provide the steel foundry industry with the technical resources needed to implement some of the technologies being developed.

EFFECTS OF FOUNDRY PROCESSING ON THE MACHINABILITY OF CAST STEEL

Machinability is an important issue for steel foundries. A significant part of the total manufacturing cost of most parts is associated with the machining operation. Wrought steel producers, using large furnaces and ladle refining units, are producing steel with very low levels of impurities, and steel foundries have joined in an effort to make cast products more machinable. If foundries are to compete with wrought product producers, they must understand the effects of process and metallurgical variables on machinability.

Oxide and nitride inclusions in cast steel are known to degrade machinability, but
quantitative data in castings are not available. These inclusions are introduced into the steel during refining, deoxidation, and pouring processes. The specific metallurgical conditions that degrade machinability and process changes that might be made to improve machinability were of particular interest.

All of the experimental castings used in this study were produced in commercial steel foundries using well developed melting, deoxidation and pouring practices. Machinability was evaluated using a standardized drilling procedure. Micro-inclusions that degrade machinability were identified and quantitative measurements of various inclusions present in each steel were made.

Tool life was compared to the number density of abrasive micro-inclusions and to the hardness of the workpiece. The number of holes to squeal reduced when steels having a higher hardness or a larger number of abrasive inclusions were machined.

Background

Toward the end of the nineteenth century, the Bessemer and the open-hearth steel-making processes rapidly replaced wrought iron as the major construction material. Steel, however, with its higher strength and reduced silicate stringer content, was more difficult to machine than wrought iron. The cost of machining increased because of the increased power and capital requirements. Cost reduction became the main incentive to cut metal faster while minimizing tool wear and automating the cutting process (1). Much research has taken place in the last 50 years to improve cutting tools and increase machining speeds.

Generally, machinability research on steel has concentrated on wrought steels because it is produced and used in such large quantities. The annual consumption of wrought steel in North America is about 100,000,000 tons each year. Total steel casting produced is about 1,000,000 tons, only 1% of the wrought steel production.

Wrought steel can be ladle refined after melting to produce a product with exceptional cleanliness and compositional consistency. However, a limitation associated with wrought steel is that it is only cast as bars, billets, and slabs. Production of complex parts from these simple shapes can be cumbersome and may require extensive machining and forging.

The advantage of the casting process is that parts can be made near the desired shape and then finish machined to produce the desired dimensions. Casting saves metal-working time and reduces the number of joints needed by combining different sections in an assembly. The major incentives for producing cast parts are production efficiency, weight reduction, and conservation of energy.

Cleanliness of cast steel is an important issue from both strength and machining viewpoints, just as it is in wrought products. However, very little work has been done to
determine the effects of process variables and cleanliness on the machinability of cast steel. Cast steel differs from wrought steel in the way it is melted, refined, and poured. The weight of a heat of steel in a foundry is rarely over 10% of the weight of a wrought steel heat, and it is often less than 1%. Steel mills producing large heats can use extended refining periods after deoxidation. The molten metal is usually poured through a protective shroud to minimize exposure to the atmosphere. These processes minimize the number of micro-inclusions in the matrix, and macro-inclusions on the surface of cast billets and slabs.

Macro-inclusions, usually visible to the naked eye, include deoxidation by-products, eroded sand from mold walls, ladle refractory, and entrapped slag. Catastrophic tool failure occurs as the machining tool hits macro-inclusions, and the chipped tool leaves a rough surface on the work-piece.

Micro-inclusions are found at higher magnifications under optical or scanning electron microscopes. Micro-oxides and -nitrides are introduced during deoxidization, pouring, and cooling. While the oxides may be small, the surface area of the workpiece traversed by a tool face is extremely large, and the probability of hitting abrasive materials is high. The area of metal traversed is equal to the product of the width of cut, cutting speed, and cutting time. Therefore, a substantial fraction of the inclusions contained in the steel contact the tool surface and cause abrasive tool wear (2).

As the tool wear progresses, more tool flank area comes in contact with the workpiece which produces more heat at the tool tip. The end result is heating of the workpiece, softening of the tool material, and sometimes catastrophic failure when the tool welds to the work-piece. The influence of hardness, grain structure, and composition of the workpiece on machinability of wrought steel has been extensively studied (13), but such information is not available on cast products.

There have been reports of substantial differences in tool life when machining cast steels from different sources having the same composition, hardness, and strength. An understanding of foundry process effects on machinability is crucial. This understanding will allow foundries to consistently produce more machinable castings.

Acid-melted steels are generally thought to be more machinable than basic-melted steel because it contains more manganese sulfides, but no data is available to substantiate this claim. The principle difference between the two melting practices is the type of slag used during melting and refining. The basic slag contains high calcium oxide and can be used to reduce the sulfur and phosphorous in the metal. The basicity of the slag is calculated from the V ratio, where

\[ V = \frac{\%\text{CaO} + \%\text{MgO}}{\%\text{SiO}_2} \]
If the ratio is less than one, the slag is considered acidic, and if the ratio is more than one, it is basic. Acid slags are more viscous than basic slags due to the high silica concentration. The high viscosity of the slag makes it difficult for inclusions in the molten steel to be entrapped in the surface (3).

The deoxidizers used in the steel-making process play an important role in determining the inclusions formed. The inclusion hardness is a strong function of the composition of the inclusion and an important machinability consideration. Generally, strong deoxidizers tend to form hard inclusions. Some studies have indicated that the hardness of certain inclusions may be lowered by deoxidizing the steel with a combination of strong and weak deoxidizers (2).

Pouring practices also have a significant effect on steel cleanliness. Molten steel has a high affinity for oxygen, and the metal is exposed to air from the time it leaves the ladle until it fills the mold. Oxygen enters the steel from air and reacts with dissolved deoxidizing elements to form secondary oxide inclusions. Pouring shrouds, used primarily in wrought steel production, reduce the contact between air and the molten metal during pouring. Such technologies may also be adapted for use in steel foundries when pouring from bottom pour ladles.

Literature Review

Sources of Micro-inclusions in Steel-making Process All steels contain micro-inclusions. Faulting categorized the inclusions in three groups based on their origin (2). They arise from 1) precipitates formed during solidification, 2) oxidation of the liquid metal during handling and pouring, and 3) mechanical and chemical erosion of the refractories and molds. Precipitation from the molten steel during cooling and solidification is believed to produce the greatest number of inclusions (2). Larger inclusions arise from erosion and oxidation during pouring.

Deoxidation inclusions in steel are an inherent part of the steel-making process and may be grouped based on when they form: 1) in the ladle during deoxidation (primary inclusions), and 2) in the mold during freezing of the metal (secondary inclusions). Some primary inclusions may be removed by stirring the liquid metal with an inert gas. The secondary inclusions form as the metal freezes. They are locked between the dendrite arms and have no path to escape to the metal surface.

Effect of Micro-inclusions on Machinability Micro-inclusions can also be described in terms of their hardness and deformability. During machining, the workpiece undergoes high plastic deformation, and inclusions present in the chips are subjected to high strains. It is therefore important to consider the deformation behavior of inclusions with respect to the matrix. Ramalingam reported a relation between the high temperature hardness, inclusion deformability and machinability. Westbrook tabulated common oxide inclusions found in steel and their hardness at elevated temperatures. The data is reproduced in Table I (4). Inclusions
## Table 1

**High Temperature Hardness of Oxide Inclusions Found in Steel (4)**

<table>
<thead>
<tr>
<th>Phase</th>
<th>Hardness (H) in Kg/mm at 400 C</th>
<th>Hardness (H) in Kg/mm at 600 C</th>
<th>Hardness (H) in Kg/mm at 800 C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron</td>
<td>45</td>
<td>27</td>
<td>10</td>
</tr>
<tr>
<td>Iron and Interstitials</td>
<td>90</td>
<td>27</td>
<td>10</td>
</tr>
<tr>
<td>TiO</td>
<td>1300</td>
<td>1000</td>
<td>650</td>
</tr>
<tr>
<td>FeO</td>
<td>350</td>
<td>210</td>
<td>50</td>
</tr>
<tr>
<td>MgO</td>
<td>320</td>
<td>220</td>
<td>130</td>
</tr>
<tr>
<td>NiO</td>
<td>200</td>
<td>140</td>
<td>100</td>
</tr>
<tr>
<td>MnO</td>
<td>120</td>
<td>60</td>
<td>45</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>1300</td>
<td>1000</td>
<td>650</td>
</tr>
<tr>
<td>SiO</td>
<td>700</td>
<td>2100</td>
<td>300</td>
</tr>
<tr>
<td>ZrO</td>
<td>650</td>
<td>400</td>
<td>350</td>
</tr>
<tr>
<td>TiO</td>
<td>380</td>
<td>250</td>
<td>160</td>
</tr>
<tr>
<td>MgAl₂O₄</td>
<td>1250</td>
<td>1200</td>
<td>1050</td>
</tr>
<tr>
<td>ZrSiO</td>
<td>400</td>
<td>290</td>
<td>140</td>
</tr>
<tr>
<td>TiN*</td>
<td>1500 (at 200 C)</td>
<td>1000</td>
<td>500 (at 1000 C)</td>
</tr>
<tr>
<td>Cementite**</td>
<td>420 (at 500 C)</td>
<td>280</td>
<td>98 (at 700 C)</td>
</tr>
<tr>
<td>Pearlite**</td>
<td>180 (at 500 C)</td>
<td>80</td>
<td>30 (at 700 C)</td>
</tr>
</tbody>
</table>

*Obtained from a commercial tool coating company. **Obtained from Faulring's analysis

(2) TiN at room temp 2500 - 3000 Hv, ZrN at room temp 2800 +/- 200 Hv
have a range of hardmesses, and some deoxidizers might be preferentially used to produce the softer oxides.

Malkiwicz and Rudnik defined deformability index “v” for several non-metallic inclusions.

\[ V = \frac{\varepsilon_{\text{inclusion}}}{\varepsilon_{\text{steel}}} \]

Where \( \varepsilon \) is the induced strain.

The authors showed that aluminum silicates \((v=0)\) do not deform. Iron silicates had deformability index values ranging from 0.04 to 0.23, and iron-manganese-silicates had values of 0.51 to 1.07.

The low deformability index of aluminum-silicate and alumina inclusions was low, and this implies that the inclusions are brittle. They break into smaller pieces as they are subjected to stress and may produce an abrasive powder. However, the particles are more difficult to fracture as their size decreases. Correlations were also made between melting points and hardness with the higher melting point inclusions having higher hardness (5).

Soft inclusions  Soft inclusions are sometimes put in steel to serve as chip breakers and provide some lubrication at the tool chip interface. These inclusions are known as free machining additives and include manganese-sulfide, selenium-manganese, and tellurium-manganese. Additions of lead, bismuth, and boron also have similar effects (6). Field and Zlatin reported that manganese sulfide inclusions reduce the friction at the tool chip interface by providing lubrication (7).

Hard inclusions  Small abrasive particles in steel have very little effect on the tensile or yield strengths but they are believed to accelerate tool wear during machining. The effect of hard inclusions on tool wear was studied by Ramalingram and Wright who prepared using powder metal compacts containing varying amounts of \( \text{Al}_2\text{O}_3 \) and \( \text{SiO}_2 \). Machinability experiments conducted on 4620 P/M, and 4620 + 2% \( \text{Al}_2\text{O}_3 \) compacts showed that higher tool wear rates were caused by the \( \text{Al}_2\text{O}_3 \) and that increasing the particle size from 1 \( \mu \text{m} \) to 25 \( \mu \text{m} \) increased the tool wear rate.

At high metal cutting speeds, thermal softening of the tool tip and higher wear rates were observed. This "micro-machining" process, illustrated in Figure 1, was blamed for both tool flank and crater wear.

Paliwoda studied the effect of oxygen on machinability (9). Oxygen can be either beneficial or detrimental to machinability, depending on its form. Active or residual oxygen, can be present in small amounts as FeO. FeO aids in the nucleation and growth of manganese sulfide inclusions, giving them globular shape. The presence of silicon and aluminum, however, can significantly alter the morphology by pulling the oxygen out of the manganese sulfide inclusions.
Figure 1. Micro Machining Due to Abrasive Inclusions in Steel (7).
and forming alumina and silica rich inclusions.

**Machinability Evaluation Procedures**

Machinability tests are generally grouped in two categories. These are generally referred to as "short tests" based on the force required to remove metal and "long tests" based on measurements of tool life or wear rates. Short tests are often preferred because of the reduced amount of time, effort, and material required. However, some short tests do not correlate with tool wear rates, and have less credibility. The choice of machinability test in this study was based on the ability of the procedure to provide tool wear and tool wear rate data.

**Short-Term Machinability Tests** Measuring the cutting forces during machining is a useful short-term machinability test. The forces involved in orthogonal machining are illustrated in Figure 1. The friction at the tool chip interface can be calculated from the measured forces, and equations have been developed to resolve the cutting forces and friction.

Albechert determined the cutting friction by taking into consideration the radius of the cutting edge of the tool introduced the concept of ploughing force. The ploughing component of the force can be experimentally determined by plotting cutting force, $F_c$, and thrust force $F_t$ verses the uncut chip thickness, $t$.

Cutting forces have been related to the hardness of the workpiece by many researchers. Black used flow stress, $\tau_s$, as the machinability criteria. The flow stress is given by

$$\tau_s = \frac{F_s}{A_s}$$

where $F_s$ is the force component parallel to the shear plane, and $A_s$ is the area of the shear plane. They are given by:

$$F_s = F_c \times \cos \phi - F_t \times \sin \phi$$

$$A_s = \frac{t \times w}{\sin \phi}$$

where $\phi$ is the shear angle, $t$ is the depth of cut, and $w$ is the width of cut.

Extensive short-term machinability studies have been conducted by Eyada. Some experiments were conducted with a power hacksaw. Various grades of free-machining steels were cut with the hacksaw at constant feed force. The machinability rating was obtained by counting the number of saw passes required to cut a fixed cross section. The experiment was repeated with various feed forces. A linear correlation coefficient of 86% was obtained when the
results were compared to results obtained during machining on an automatic screw machine. (13)

Another short-term machinability procedure developed by Eyada involved end milling and slotting on a horizontal CNC milling machine. Slots 3/8-inch deep were cut in 1-inch diameter by 6 inch long test bars using high speed steel (M7) end mills. The width of the slot decreased as the wear on the end mill increased. A tool wear profile was obtained from successive measurements of the slot width starting from the initial cutting position. While wear occurred and could be measured, the correlation with the automatic screw machine data was not as good as obtained with the power hacksaw test \( r^2 = 0.59 \).(14)

Heritier et. al. developed a procedure that involved gradually increasing the cutting speed on a turning operation and measuring the cutting forces with a dynamometer.(16) The cutting speed was kept constant until the cutting force reached a plateau, then the speed was increased at a constant rate. The procedure was stopped when the cutting force reached twice the initial value.

The machinability rating was obtained from one of the following: 1) the amount of material removed, 2) cutting speed at the end of the cutting cycle, or 3) cutting speed at the angular failure speed. Cutting speed at tool failure resulted in the least amount of scatter in the data.

**Long-Term Machinability Procedures** A machining procedure was developed by the Homer Research Laboratory at Bethlehem Steel Corporation and later standardized by the American Society of Testing and Materials (ASTM).(15) A standard specimen was machined from 1-inch diameter bar stock and the machinability evaluated using drills of various diameters. The cutting speed and feed rate were varied with each material, and the surface roughness and diameter of the hole in each workpiece was periodically measured. The machinability rating was obtained from the amount of material removed prior to reaching a specified surface roughness or dimensional limit.

Tool wear experiments are reliable and are widely accepted measurements of machinability. Results are usually evaluated in terms of tool flank wear, but some investigators have used the cutting thrust force as a wear indicator. A typical flank wear curve on a drill operated at a constant chip load is illustrated in Figure 2.(17)

DelSorbo and Pears developed this linear model from this type of curve to describe tool wear.(17) The wear curve was divided into three regions, including: 1) break-in, 2) linear steady state, and 3) failure wear regions. The break-in wear region, characterized by a high initial wear rate, initiates as the tool penetrates the workpiece for the first time. The break-in wear results from high stresses concentrated on the initially sharp cutting edge. The stress becomes more distributed as a radius develops on the cutting edge.

The tool failure region is characterized by very fast wear. As tool wear increases beyond the linear steady state region, more tool surface is exposed to the workpiece. This results in more frictional heat and heat transfer to the tool. As the temperature rises, the tool is thermally softened and catastrophic wear begins.(17)
Figure 2. Illustration of Linear Model for Data From Tool Wear Experiment (17).
Several aspects of this curve can be used to describe machinability, including: 1) the slope of the linear portion of the wear curve, 2) the amount of metal removed prior to tool failure, 3) the amount of wear at the onset of catastrophic wear, and 4) amount of material removed at a user-defined wear level.\(^{(17)}\)

**Materials and Procedures**

The steels examined in this study was WCB, a nominal 1025 steel. The metal was poured in phenolic urethane bonded molds to produce well-risered two inch thick plates. A schematic of the mold and gating arrangement is shown in Figure 3. The materials matrix is presented in Figure 4.

Steels were melted using both acid and basic practices. Slag basicity of basic-melted steels usually varies between v-ratio of 0.6 and 1.0. The v ratio for the acid-melted steel was 0.078.

Variations in the deoxidizing additions were made in the acid melted steels. The first variations involved the use of calcium. The calcium addition was the same in the first two series of heats, but the calcium was added as wire in one series and as a CaSi addition to the ladle in the next series. The calcium recovery was higher using the wire process.

Supplemental deoxidizers were used with the calcium wire treated steels. The first steel in this subgroup was deoxidized to produce a low aluminum concentration, was blocked with 1.44% Si-Mn and 0.54% Fe-Si in the furnace. The ladle additions consisted of 0.25% Fe-Si, 0.10% Al, and 0.03% calcium in the form of wire.

The high aluminum steel was blocked with 1.31% Si-Mn and 0.84% Fe-Si in the furnace and the ladle deoxidation consisted of 0.15% Al and 0.03% calcium in the form of wire. The zirconium deoxidized steel was blocked with 1.37% Si-Mn and 0.58% Fe-Si in the furnace and deoxidized in the ladle with 0.10% Al, 0.14% Zr, and 0.03% calcium as wire. Finally, the titanium deoxidized steel was blocked with 1.33% Si-Mn and 0.83% Fe-Si in the furnace and deoxidized in the ladle with 0.10% Al, 0.04% Ti, and 0.03% calcium in the form of wire.

After cleaning, the plate castings were normalized from 1700°F after holding for two hours at that temperature. The quenched and tempered steels were put through the same normalization cycle and then solution treated at 1650°F for 45 minutes, quenched in water, and tempered at 800°F.

**Machinability Evaluation**

Machinability, in this study, was evaluated using a drilling procedure. Drilling represents a common machining operation, and a drilling problem was the initial motivating force behind
Figure 3. Schematic of the Mold for the Experimental Plate Casting.
Fig. 4 Materials matrix.
this study. The experimental castings were ground flat to produce a final plate thickness of 1.75 inches. The holes were drilled on ½ inch centers to minimize strain hardening effects between adjacent holes.

All experiments were conducted with ¼ inch diameter, M7 high-speed steel drills in a 30 horsepower Cincinnati Milacron milling machine, model Cintimatic 7VC-750. The CNC mill was programmed to drill 720 through holes through the 1.75 inch thick test plates. All experiments were conducted with Zep Lubeze 28 plus x-4294 coolant.

The drilling procedure used a one "peck" drilling cycle. This consisted of drilling a hole one inch deep, backing the drill out to remove chips and allow coolant into the hole, and then drilling the remainder of the way through the plate. The "pecking" cycle is common practice when drilling steel castings because it allows coolant to enter the hole, aids in removing chips, and aids in breaking the chips.

The drill was periodically removed from the CNC mill to measure the amount of flank wear. Drilling experiments were conducted at four speeds on each material and triplicate experiments were performed at each speed.

Experiments were terminated when drill squeal occurred. Machining beyond squeal resulted in the drill welding to the casting which usually caused catastrophic drill failure. When this occurred, all wear data obtained since the last measurement was lost, and it was no longer possible to examine the wear pattern.

Initial drilling experiments were conducted with the as-cast surface in place; but after a considerable number of drill failures, the as-cast surface was removed to eliminate heat treat scale, ferrite skin, and surface roughness associated with the casting process. This procedure eliminated surface effects and provided a measure of the base metal machinability.

Premature drill breakage sometimes occurred and appeared to be a result of a low feed rate. The recommended feed rate in the Machinists Handbook for cast steel is about 0.004 inches per revolution with a surface speed of about 80 sfm, and these were the conditions initially used. However, drill after drill broke at these rates when drilling straight through or when using a "pecking" cycle. The initial pecking cycle consisted four one-half inch pecks. After many failed drills, an experienced machinist recommended an increase in the feed rate. After some experimentation, a drill cycle was developed that allowed drilling through the 1.75 inch thick plate using one "peck" at a feed rate of 0.008 inches per revolution.

The drill wear evaluation procedure included the following steps:

1. The drill was examined under an optical comparator at 30X to ensure there were no chipped edges.
2. The drill was mounted in a fixture so a common angle and reference point could be maintained during a series of wear measurements on the drill.
3. The drill was positioned in a tool holder so the cutting edge was parallel to the horizontal axis of the optical comparator.
4. These coordinates were recorded so that the same position could be found in successive measurements. The coordinates established a standard reference point so factors such as built-up material on the cutting edge would not affect the wear measurements.

5. Holes were drilled in the test plates and the tool wear was measured as a function of the number of holes drilled. Tool wear measurements were made after drilling the first and second holes and then at various intervals depending on the rate of tool wear.

6. The drills from the experiment were collected and coded for future examination.

The tool wear was measured by digitizing the wear pattern from the chisel edge to the lip of the drill using an optical comparator. The wear profile was recorded on a computer connected to the optical comparator, and the wear area was calculated from the stored data. A schematic wear profile is illustrated in Figure 5. The area under each curve divided by the cutting edge length provided a measure of the "average wear".

**Microstructural Analysis**

All specimens for microstructural examination were mounted in Bakelite and ground dry using silicon carbide papers with grits size of 120, 240, 320, 400, 600, 800, and 1200. A water-free grinding was necessary to avoid inclusion pull-out. A constant spray of methanol kept the specimens from overheating.

Each specimen was ground from one to three minutes at each stage on a wheel turning at 400 rpm. Specimens were then polished using 1 micron diamond on napped polishing cloths composed of synthetic rayon fibers bonded to a woven cotton cloth. A constant spray of methanol was again used with the 1 um diamond polish.

**Base Microstructure** The specimens were etched with 4% Nital. The amount of ferrite was measured by overlaying a 5 X 5 grid (25 intersection points) on the microstructure at magnification of 500X. Thirty fields were examined using this process. The ferrite content was calculated by dividing the number of intersection points on ferrite by the total number of intersection points on the grid as illustrated in the following equation.

\[
\text{Percent ferrite} = \frac{\text{Intersection points on ferrite}}{\text{Total number of intersection points}} \times 100\%
\]

The amount of pearlite was calculated by subtracting the percent ferrite from 100%.

Pearlite and ferrite micro-hardness was measured using a Vicker’s diamond indenter with a 10 gram load. Fifteen to twenty hardness measurements were made at different locations, and the pearlite hardness was calculated from the ten highest values. This reduced the error due to punching through some thinner pearlite colonies. The ferrite average hardness was calculated from the lowest ten measurements.
Figure 5. Schematic of Drill Tip Illustrating Flank Fear and Data Used in Calculation of Average Wear.
Micro Inclusion Analysis The volume fraction of inclusions was usually much less than one percent, and inclusion sizes ranging from as low as 1 \( \mu m \) to 10 \( \mu m \). Such small inclusions required the use of a scanning electron microscope (SEM) fitted with an energy dispersive x-ray spectrograph (EDXS) for qualitative composition determinations. Samples were scanned for different types of inclusions at a magnification of 500X, and the number of inclusions found in 50 random fields was determined. Representative inclusions were photographed using both optical and SEM techniques.

A metallographic technique based on ASTM E45-99 was used to determine the number density of the inclusion. This technique consisted of examining the polished surface at 500X in an optical microscope and recording the number of inclusions in each field. This technique was possible because the different inclusions were distinguishable at 500X from their color and texture.

The total number of fields inspected for each material varied from material to material, depending on the inclusion content and distribution, but the number of fields was never less than 200. Inclusions were classified into three groups according to size: small (less than 2 \( \mu m \)), medium (between 3 to 5 \( \mu m \)), and large (larger than 6 \( \mu m \)). The inclusion size rating chart illustrated in Figure 6 was used to classify the inclusions.

Results

Tool life curves from the drilling experiments are summarized in Figure 7. Tool life decreased, as expected, as the cutting speed increased. Differences in tool life were most distinct at a cutting speed of about 105 sfm which is within the normal operating for high speed steel drills.

The greatest number of holes could be drilled before tool failure in the basic-melted steel. Machinability decreased in the acid-melted, low aluminum deoxidized heats, E0660 and E0649, and the addition of calcium in the form of wire did not significantly affect machinability.

An average of 155 and 147 holes were drilled through the acid-melted, high aluminum heat G19, and the titanium deoxidized heat X36, respectively. These were slightly lower values than observed when drilling the acid-melted, low-aluminum heats. This was followed by the zirconium deoxidized heat, G37, with an average of 108 holes. Acid-melted heats G19, G37, and X36 exhibited unusually low wear at the onset of catastrophic wear.

The acid-melted, quenched and tempered heats, E0669 and V0680 with a hardness of 195 BHN, exhibited significantly lower number of holes-to-squeal and higher wear rate than the normalized steels at a hardness of about 150 BHN. The calcium wire heat exhibited slightly lower machinability than the heat without calcium wire treatment.

Microstructural Analysis The acid-melted and normalized heats G19, G37, X36, and the basic-melted and normalized heat had slightly lower pearlite content than the acid-melted heats.
Figure 6. Inclusion Size Rating Chart.

Small: <2 microns

Medium: 3-5 microns

Large: >6 microns
Figure 7. Number of Holes to Squeal Versus Cutting Speed.
E0649 and E0660. The pearlite contents in quenched and tempered steels were toward the higher end of the normalized group. The pearlite micro hardness in the acid-melted heat X36 was the highest among the normalized steels. This was followed by the acid-melted heat G19. The rest of the normalized steels exhibited similar pearlite micro hardness.

The ferrite hardness of the acid-melted heat G37 was slightly higher than the rest of the normalized steels. The ferrite colonies in the quenched and tempered steels were too small to measure hardness.

The acid-melted heats G19, G37, and X36 exhibited finer pearlite than heats E0649 and E0660 and the basic-melted steel. The pearlite colony spacing in the quenched and tempered steel was significantly lower than the normalized steels. The overall hardness of the steels was dependent on the pearlite colony spacing. A linear regression analysis between pearlite colony spacing and Brinell hardness yielded r^2 value of 0.87.

**Inclusion Identification**  Micro-inclusions in the cast steels were identified in a scanning electron microscope, and qualitative compositions were obtained using an energy dispersive x-ray spectrometer. A semi-quantitative inclusion count was obtained at 500X from 50 random fields.

The acid-melted heats E0649 (calcium wire treated) and E0660 (ladle treated with calcium silicon) had similar inclusions consisting primarily of manganese sulfides and alumina with traces of calcium. The quenched and tempered versions of these heats, V0680 and E0669, exhibited similar inclusions. Typical alumina rich inclusions in heat E0669 are illustrated in Figure 8.

The energy dispersive x-ray spectra show manganese and the sulfur peak associated with a MnS surrounding the alumina. The acid-melted heat, G0019, deoxidized with aluminum to produce a high aluminum residual, exhibited similar inclusions.

The acid-melted heat G0037, deoxidized with zirconium and aluminum, exhibited primarily oxide inclusions. Approximately 55% were zirconia, 30% zirconia-alumina, and 15% alumina. All of the oxides contained traces of calcium.

The acid-melted heat X0036, deoxidized with titanium and aluminum, contained primarily oxide and nitride inclusions. Approximately 75% were aluminum oxides and 25% were titanium-nitride. Approximately 86% of the oxide inclusions were alumina and 14% were a duplex aluminum-titanium oxide.

The basic-melted steel contained primarily alumina inclusions, some containing some silicon, but not containing calcium.

**Micro Inclusion Volume**  Micro-inclusion volumes were measured using an optical microscope at a magnification of 500X. The predominant inclusions were manganese-sulfides, aluminum oxides, and titanium nitrides. Manganese-sulfides had a light gray color, a globular shape, and smooth well defined edges. Alumina inclusions had a darker appearance and were found both as single particles and in galaxies. An example of an alumina galaxy is presented in Figure 9.
Figure 8. Representative Alumina Inclusions Found in Acid Melted Heat E0660. Spectrograph of the Inclusions Indicated by the Arrows.
Figure 9. A Representative Alumina Galaxy Encountered in the Basic Melted Steel.
The zirconium-oxide inclusions were similar in appearance to manganese sulfide but were a darker shade of gray. An example of a zirconium oxide inclusion with a manganese-sulfide in the same field is illustrated in Figure 10.

Titanium-nitride inclusions were quite different from the other inclusions. They had a golden appearance under the microscope and sharp edges.

**Effect of melting practice.** The acid-melted heats E0660 and E0669 had slightly higher inclusion contents than the basic-melted steel. The basic steel exhibited an average of 12.6 oxide inclusions per mm² toward the plate center, and about 29.2 per mm² near the plate edge. The edges and corners also exhibited clouds of oxide inclusions. Some fields contained as many as 100 oxide micro-inclusions.

**Effect of calcium wire treatment.** Calcium wire treated heats exhibited slightly higher inclusion counts than non-wire treated heats. The heats that were treated with CaSi additions to the ladle, heats E0660 and E0669 exhibited 14.8 and 14.7 oxide inclusions per mm², respectively. The calcium wire treated heats, E0649 and V0680 exhibited 16.8 and 16.5 oxide inclusions per mm², respectively. However, calcium wire treatment reduced the number of oxide clouds present.

**Effect of deoxidation practice.** The acid-melted heat, G0019, deoxidized to produce a higher residual aluminum contained a larger number of oxide inclusions than the heats having a lower aluminum concentration. The higher aluminum heat averaged of 23.3 oxide inclusions per mm², compared to 16.8 and 16.5 for the low aluminum deoxidized heats E0649 and V0680, respectively. The oxides in the high aluminum heat were generally larger than in the low aluminum heats.

The zirconium deoxidized heat G0037 had 18.7 oxide inclusions per mm², slightly higher than the low aluminum deoxidized heats. The inclusions consisted of zirconia, complex-zirconia-alumina, and alumina.

The titanium deoxidized heat, X0036, had 19.8 hard inclusions per mm². The hard particles in this steel consisted of 80% oxides and 20% titanium-nitride inclusions.

**Discussion**

Regression analyses were conducted to establish relations between machinability and hardness, inclusion content, and microstructure. Two aspects of the tool wear curve were considered including the number of holes to squeal and the flank wear rate at 105 sfm.

Casting hardness had a significant effect on the number of holes to squeal. The tool wear rate increased and the machinability decreased as the hardness increased. The abrasive inclusion content had a similar effect.

The pearlite fraction, pearlite colony thickness, and spacing all had some effect on tool life. The number of holes to squeal decreased as the pearlite fraction increased and increased with the pearlite colony thickness and spacing.
Figure 10. Zirconia Inclusions Embedded in Manganese Sulfide, Encountered in Acid Melted Heat G37.
Relationship Between Number of Holes to Squeal and Micro Inclusion Content

The number of holes to squeal at 105 sfm is plotted as a function of hardness in Figure 11. The number in the boxes represent the total hard inclusions per mm² from the mid section of the plate. The error bars on the y-axis represent one standard deviation from the average number of holes to squeal. The relationship between hardness and the number of holes to squeal is described with a reciprocal-y or exponential fit rather than a linear fit.

The exponential model has been frequently used to describe the relationship between tool life and strength of the workpiece (17). The exponential model gave an $r^2$ value of 0.70 with lower inclusion contents producing better tool life. Incorporating the inclusion data in the regression analysis increased the $r^2$ value from 0.70 to 0.87.

The number of holes to squeal at 105 sfm is compared to the area fraction of inclusions in the normalized steels in Figure 12. All of these castings had a hardness in the range of 148 to 158 BHN. The inclusions were assumed to be spherical and the average diameter of small, medium, and large inclusions approximately 1.5 μm, 4 μm, and 7 μm, respectively. The equation used to calculate the inclusion area fraction was:

$$\text{Area Fraction} = \left[ \frac{\# \text{ Small inc. per mm}^2 \times \pi \cdot 0.0015 \text{mm}^2}{4} \right] + \left[ \frac{\# \text{ Medium inc. per mm}^2 \times \pi \cdot 0.004 \text{mm}^2}{4} \right] + \left[ \frac{\# \text{ Large inc. per mm}^2 \times \pi \cdot 0.007 \text{mm}^2}{4} \right] \times 100\%$$

The error bars represent 95% confidence interval from the average number of holes to squeal. The relationship between inclusion content and tool life appears liner trend, except for the acid-melted heat G19, which exhibited slightly higher number of holes to squeal than predicted. The linear fit through the six data points yields an $R^2$ value of 65%.

Relationship Between Wear Rate and All Variables

Hardness had a significant effect on the flank wear rate, as illustrated in Figure 13. The flank wear rate decreased linearly with hardness. Other factors affecting the wear rate include inclusion size, pearlite fraction, pearlite colony thickness, and spacing. The pearlite fraction, pearlite colony thickness and spacing affected the wear rate in a similar manner as holes to squeal.

Summary

This study was undertaken to determine the effect of several processing and microstructural variables on the machinability of cast steel. The materials studied were produced
Figure 11. Number of Holes to Squeal at 105 sfm Versus Hardness.
Figure 12. The Number of Holes to Squeal at 105 sfm Vs. Approximate Area Fraction of Inclusions in Normalized Steel (Hardness range 148-158 BHN).
Figure 13. Flank Wear Rate at 105 sfm Versus Hardness.
from both acid and basic furnaces using a variety of deoxidation practices. Machinability was evaluated by drilling procedure. The hardness, micro inclusion number density, and other microstructural features were measured for each material. The following conclusions were drawn from this study:

1. Casting hardness had a significant effect on both the number of holes to squeal and flank wear rate. The number of holes to squeal followed an exponential relationship with higher hardness associated with higher tool wear rates.

2. Higher oxide and nitride inclusion contents reduced the tool life. The tool life was reduced as either the number or the size of inclusions increased.

3. Within the range of deoxidants studied, the type of deoxidant was not found to significantly affect tool wear rates or life. A better correlation was found with the volume of deoxidation products rather than by whether the additions were comprised of aluminum, calcium, titanium or zirconium.

TECHNOLOGY TRANSFER TO THE STEEL FOUNDRY INDUSTRY

This task focused on accelerating the transfer of clean steel technology to the steel foundry industry. Progress has been made in the past ten years in identifying conditions that improve the quality of steel castings. The ability to identify the sources of macro-inclusions in castings allows the foundry to locate the cause of the problem. Physical simulations of pouring systems and foundry trials have identified areas such as metallostatic pressure, pouring technique, and sprue design as significant variables affecting air entrainment and the formation of reoxidation products. Melting practice has also been identified as an area where changes in the practice can result in higher quality castings. Techniques such as filtration and calcium wire injection have been used in specific applications to improve the quality of steel castings.

The goal of this task was to provide the steel foundry industry with the technical resources to implement clean cast steel technology. This goal was accomplished by providing foundries with experienced technical personnel to assist in implementing appropriate technologies. A video was produced for foundries to use in teaching personnel techniques for improving casting quality and cleanliness.

Clean Cast Steel Technology Video

A video was produced to illustrate techniques for improving casting cleanliness for foundry floor personnel. The outline was reviewed by technical steel foundry personnel to ensure that it covered the important areas and properly addresses the problems of the steel foundry industry. The outline covers the following areas:

1. What is an Inclusion and Why They are Important.
2. Where do Inclusions come from.
3. Entrapment of Molding and Melting Oxides.
A. Molding/Core System
B. Slag Control
C. Refractory Practice
D. Summary

4. Reaction of Oxygen and Steel.
   A. Pouring
   B. Gating Design
   C. Summary

A story board was then developed and reviewed by the Steel Founders Society Research Committee on September 29, 1998. A copy of the story board was sent to DOE personnel for review and comment.

The initial plan was to produce a standard VHS video tape which could be used by any foundry with a television and video cassette recorder. The steel foundry industrial members, however, preferred a computer format for the video. Computers have become very common in foundries and the production and distribution costs would be greatly reduced. The outline was then expanded to develop a text and visual aids then edited to address comments from the industrial sponsors and DOE.

The outline and story-board were then resubmitted for a final edit on January 15, 1999. The goal was to produce both a video that can be viewed on a computer and a booklet containing the text and visuals. The audio portion was done in English, but a Spanish version is being prepared. A detailed outline of the video is given in Appendix A.

About two hundred photographs were taken in operating foundries for the video. The photographs were used to provide a library of practices and to illustrate the best practices.

A Powerpoint presentation was then developed from the text and photographs and reviewed by the Carbon and Low Alloy Steering Committee and shown at the 1999 SFSA Technical and Operations Conference in Chicago, IL. This conference is attended by a majority of steel foundry's in North America.

The Powerpoint format was converted to a VHS format by copy produced. Approximately 150 copies of the tape will be made in both the NTSC and European PAL format.

OTHER AREAS OF ACCELERATED TECHNOLOGY TRANSFER

Ladle Shrouding

Continuously cast wrought steel producers have recognized stream reoxidation as a major
source of inclusions for several years and developed shrouds for reducing contact of molten steel with air. 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 by pouring through ceramic shrouds.

In the production of the cleanest and highest quality wrought 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 transferred to the pouring station, and a shroud attached to deliver metal to a tundish without contact with air.

This technology has matured enough to allow a shroud to be attached to foundry ladles. The improvement in metal cleanliness was dramatic. The cleanliness of castings from two heats is illustrated in Figure 14. The conventionally poured castings contained an average of 11.9 one-inch circles of macroinclusions with a sample standard deviation of 5.5, and the shroud-poured castings contained an average of 0.4 one-inch circles with a standard deviation of 0.7.

This foundry has expanded the use of shrouds to other castings and have continued to have dramatic improvements in casting quality and a reduced product cost. In addition, other foundries have begun evaluating shroud pouring technology, and five have contacted UAB for technology transfer assistance.

One produces large castings for the earth moving and mining industries. Shrouds and supplies necessary to attach the shroud to the ladle have been ordered, and a ladle stand to allow foundry personnel to work under the ladle with some safety.

The foundry has been conducting trials over the past nine months on a variety of casting shapes. The minimum improvement in casting surface quality has been a 60% reduction in macro-inclusions. In some cases, casting rework due to reoxidation products has been eliminated. The foundry is continuing with the trials.

Another foundry pours pump and dredge parts operations is now experimenting with the technology.

Clean Heat/ Dirty Heat Data Analysis

Most foundries experience some variation in casting quality from heat to heat. In two recent casting trials examining bottom pour nozzle configuration and filtration of steel castings, heat-to-heat variation was found to account for 20-30% of the variations in casting cleanliness. (18-20).

Long term trials have been conducted at four foundries to determine if a correlation could be made between variables in the melting and pouring practice and average heat casting quality. Variables that significantly affected clean/dirty heats have been selected and additional experiments conducted at three foundries to verify that the variables do significantly affect heat
Figure 14. Effect of Pouring Method on Surface Cleanliness Rating for Both Heats.
quality. The ultimate goal is to gain a better understanding of the influence of melting and pouring practice on casting quality and, subsequently, determine how to reduce the heat-to-heat variation.

Silicon, manganese, and aluminum concentrations were important factors in all four foundries. Carbon is often used an indicator, but recent research has shown that other oxidizable element also have a significant effect. 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.

The statistical analysis of the foundry data has indicated a correlation between the composition and the quality of the castings poured. The silicon concentration has been found to be a good indicator of casting quality in acid practices, and manganese is a good indicator in basic practices. These elements appear to reflect the oxygen potential in the metal and slag. Most wrought steel producers remove furnace slag because of its high oxygen concentration.

UAB is working with Dr. Von Richards at Tri-State University to develop thermochemical rationale for the data collected. Dr. Richards has developed a thermochemical model for the acid practice foundry to explain why the high silicon and manganese residuals after the boil are associated with lower oxygen potentials in the metal and hence cleaner castings. Higher refining temperatures increase the residual silicon and manganese concentrations which buffer the heat and reduce the oxygen concentration.

Miscellaneous Technical Services To the Steel Foundry Industry

Over the past year, technical assistance has been provided to twenty foundries. Technical assistance ranged from casting inclusion analysis to technical assistance in reviewing melting process data aimed at improving metal cleanliness.
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Appendix A

Clean Cast Steel Technology Video Outline
What is an Inclusion and Why they are Important.

A typical steel casting contains numerous secondary phase particles that can be labeled inclusions. These inclusions can be oxides, carbides, sulfides, and nitrides. The vast majority of these inclusions, however, do not significantly affect the properties or appearance of the casting. Most are microns in size and are well dispersed throughout the cast. (Visual 1) Some microinclusions such as sulfides affect mechanical properties of the casting but are easily controlled with alloy chemistry.

The most troublesome inclusion is the macroinclusion. (Visual 2) Macroinclusion are visible to the naked eye and primarily composed of oxides. Since these oxides are of lower density compared to the steel, the macroinclusion will typically float to the cope surface or vertical wall of the casting. Macroinclusions are large enough to degrade properties of the casting and require removal of the inclusion and weld repair. (Visual 3) 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.

High speed machining lines require a rough component with fewer surface and internal discontinuities than acceptable in traditional machining operations. (Visual 4) 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.

Even if the macroinclusion do not impact the physical properties of the casting, the visual appearance of macroinclusions reduces the perceived quality of the product.

Where do Inclusions come from.
Macroinclusions typically originate from two sources: materials used in production of the castings, such as molding and core sand, gating tile, ladle refractory and patch, and furnace refractory; and oxides generated from the reaction of molten steel and oxygen.

Entrapment of Molding and Melting Oxides.

Molding/core System

A significant source of inclusions is entrapped molding or coring materials. These materials become entrained into the metal stream and float to the cope surface where they form a tough and abrasive mixture of oxides and metal. There are several process anomalies that can produce these type of inclusions.

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molding area to the pouring floor. Rough mold handling will make good housekeeping procedures that much more critical and difficult.

Slag Control

(Visual 11) Slag control is a necessary and important function in the production of steel castings. Slag protects the molten steel underneath from exposure to air, excessive heat loss, and, in certain instances, removes harmful elements such as sulfur and phosphorus. Slag entrained into the metal stream during pouring, however, will produce detrimental cope surface inclusions. Furnace slags contain high concentrations of iron and manganese oxides which increase its fluidity, increasing their probability of entrainment.

(Visual 12) A good ladle maintenance practice is important in reducing slag inclusions. Slag adhering to the refractory near the nozzle will soften and remelt during the next heat placed in the ladle. The swift currents generate near the ladle bottom during a pour could entrain the softened slag and flow into the mold cavity.

(Visual 13) The most common way to entrain slag into a mold is by inadequately cleaning the spout or lip of slag after filling a teapot or lip pour ladle. With bottom pour ladles, slag can be entrained into the pouring stream if you are too close to the end of the heat. The vortex from the nozzle metal left in the ladle.

Refractory Practice

Ladle refractories are also an important source of casting inclusions. The use of low quality refractories, especially in the spout or nozzle area, can be eroded into the metal stream. Low melting point refractories can be more easily attacked by FeO and MnO in the slag to produce an oxide that will melt at temperatures below the pouring temperature of steel. Using ladle refractories beyond their useful life can also result in refractory inclusions. Ladle boards can be used from three to ten times, depending on conditions, but casting quality will decrease rapidly beyond that point.

Summary

(Visual 14)
1. Maintain good control of the sand system. Keep the proper sand distribution, moisture and binder level and mull the sand well. Design the pattern with molding in mind. Properly mold the pattern to ensure adequate mold density. Use care when setting the cores, closing the mold, and transporting the mold. Remove loose sand from the mold before closing and from the gating system after transport to the pouring floor. Cover all openings after cleaning to keep dust and sand from collecting in the mold cavity.

2. Maintain a good ladle maintenance practice. Adequately clean slag from around spouts and nozzles between heats. Thoroughly remove slag from the spout of teapot ladle before pouring. Know if you have enough metal in the bottom pour ladle to completely fill the mold without entraining slag.

3. Use quality (70% alumina or higher) refractory in ladles, especially around nozzles, spouts, and lips. Track the number of heats on the ladle refractory and know when to patch or reline. Do not overuse disposable ladle boards.

(Visual 15) Macroinclusions can also originate from oxides generated from the reaction of molten steel and oxygen.

Reaction of Oxygen and Steel

(Visual 16) Oxygen is a necessary component in the production of quality steel castings. Carbon boil in the furnace removes harmful gases such as nitrogen and hydrogen from the molten steel. The boil is typically initiated using a lance to inject oxygen into the steel. The reaction of carbon and oxygen at steelmaking temperatures produces carbon monoxide which bubbles through the metal and scavenges nitrogen and hydrogen from the bath. At the same time, oxygen will react with other oxidizable elements such as silicon, manganese, and iron, which form solid oxides which will float into the slag. The steel will contain between 300 to 500 ppm oxygen in solution after the boil and before block.

After the oxygen has boiled down the carbon concentration to the required level, the heat is blocked to remove oxygen from the steel and stop the boil. Heats are typically blocked with silicon, manganese and, sometimes, aluminum. These deoxidizers have a greater affinity for oxygen compared to carbon and react to form oxides reducing the oxygen concentration in the steel. After blocking, the steel will contain between 50 to 100 ppm oxygen. After blocking, the reaction of steel with oxygen becomes a detriment to the production of quality steel castings.
Steel at 2900°F reacts extremely rapidly with oxygen to form oxides. There are a number of sources for oxygen, including refractories, slags, mold binders, moisture, and atmospheric oxygen. By far, the largest source of oxygen is air. (Visual 17) Therefore, at tap, additional deoxidizers must be added to compensate for the absorption of oxygen from the air. Typically aluminum and silicon are added during to tap to deoxidize the steel. Deoxidation additions form micron sized oxides that are widely dispersed and do not easily float into the slag. These particles can agglomerate to form larger particles that will float into the slag if given enough time and stirring action. While deoxidation products do not cause surface macroinclusions, they can collect in the nozzle of bottom pour ladle and degrade the seal between the stopper rod and nozzle. (Visual 18) This will cause rough pouring streams and leakers. Foundries will use an oxygen lance to burn the nozzle and remove the buildup but this injects oxygen into the steel, increasing the likelihood of surface inclusions.

(Visual 19) Oxygen is added to the steel when it is exposed to air. A rough or turbulent tapping stream increases the exposure and mixes the air with the metal. A rough stream also stirs furnace slag into the metal. Furnace slags typically contain high concentrations of FeO and MnO which add oxygen to the steel. Some foundries have found that adding aluminum or calcium carbide to the furnace slag before or during tap helps reduce the FeO and MnO concentration and makes the slag more receptive to entrapping deoxidation particles.

(Visual 20) Calcium wire injection into the ladle after tap is also effective in removing deoxidation particles from the heat. Calcium reacts with alumina particles to form a lower melting point oxide which allows the particles to stick together more readily. The vaporization of the calcium stirs the heat, increasing the likelihood of the particles to collide and agglomerate. Calcium wire has been found to reduce or eliminate nozzle buildup and improve the steel flow from the nozzle. Samples taken from the ladle also indicate the steel is also microscopically cleaner. (Visual 20) Ladles can also be stirred with argon bubbles to help agglomerate deoxidation particles. The particles will attach to the bubbles and float into the slag. But there are several conditions that are necessary for argon stirring to improve the quality of the heat. The slag must be reducing and receptive to the particles. If the slag is oxidizing, metal flowing next to the slag will pick up oxygen and become dirty again. The argon must not cause the slag surface to break or air will be entrained into the steel. The best method to argon stir a heat is with a porous plug install in the bottom of the ladle. Stirring with a lance typically is difficult to control. Additional benefits to stirring include more uniform temperature in the ladle and reduced tapping temperature.

Pouring
(Visual 22) Transferring from a tapping ladle to a pouring ladle produces the same kind of conditions as when tapping from the furnace. Inclusions will be produced from the entrainment of air into the pouring stream. In some cases, deoxidizers are added to the pouring ladle to compensate for the oxygen increase. The larger inclusions will float out into the slag but the smaller inclusions will not float out unless allowed to float for an extended period of time. Inclusion formation can be reduced if the pouring stream is smooth and the drop height from the bull ladle to the pouring ladle is reduced as much as possible. Drop height of the metal is directly proportional to stream velocity which is proportional to surface turbulence and air entrainment.

(Visual 23) Pouring operations are similar to tapping and transfer operations with one exception. In ladles, large inclusions can float out into the slag and are removed. In pouring operations, large inclusions are entrained into the pouring stream, carried into the mold cavity, and collect on the cope surface. Therefore, pouring operations tend to be the largest sources for surface macroinclusions.

Decreasing the drop height of the metal will reduce the amount of air entrained during pouring. Drop height can be defined as the distance from the top of the metal to the lowest point in the sprue. For lip or teapot ladles, keeping the lip as close to the pouring cup will minimize the drop height. (Visual 24) For bottom pour ladles, it is important to correctly size the ladle nozzle to the mold sprue. The high metallostatic head pressure in a large full bottom pour ladle generates high velocities and flow rates. If the mold being filled has a relatively low volume, the ladleman will have to throttle the ladle to keep from overfilling the sprue or mold. The combination of high metal velocities and turbulent flow generated by throttling entrains large volumes of air. Water model experiments have measured as much as one cubic foot of entrained air for every cubic foot of metal poured.

(Visual 25) One method to eliminate air entrainment during pouring is to attach a ceramic shroud or nozzle extension to the bottom pour ladle. The shroud can be lowered to the mold bottom down a large riser and once metal starts flowing, the metal stream is protected from the surrounding air. The shroud must be sealed tightly to the ladle and the mold must be large enough to allow the shroud to be lowered to the mold bottom. A splash plate may also be necessary to prevent mold erosion from the high velocity metal exiting the shroud.

Gating Design

(Visual 26) Gating design has a direct impact on the quality of the casting. A good design will enable the ladle operator to fill the mold quickly and with the least amount of air entrainment possible. A bad design can destroy every previous effort made to reduce the exposure of metal to oxygen. The gating system should be designed for the pouring ladle,
allowing the bottom pour ladle operator to fill the mold without throttling the ladle. The gating system design should minimize the metal drop height and allow the mold to fill quickly and uniformly. A good pour time for a casting can be calculated using the formula - pour time (seconds) = \( \frac{2}{3} \) (pour weight)\(^{\frac{1}{2}}\) up to a maximum of 70 seconds. The runner must be filled quickly to reduce air entrained during pouring. Waterfalls from the ingates must be avoided and jets or impingements on mold walls or cores increase metal turbulence.

(Visual 27) Filters can be used to mechanically entrap macroinclusions and provide flow control for the gating system.

Summary

(Visual 28)

1. Limit the exposure of steel to air. Smooth tapping stream, high tapping rate, short metal drop heights, fully open bottom ladle nozzles reduce the surface turbulence of the metal and limit exposure of the metal to atmospheric oxygen. Ladle shrouding eliminates exposure of the metal to air during pouring. Ladles should be properly sized for the molds being poured to reduce throttling.

2. Calcium wire injection and stirring in the ladle reduces deoxidation particles in the metal and homogenizes metal temperature in the ladle.

3. Gating systems should be designed for the pouring ladle size. The runner system and the mold should be filled quickly and uniformly. Avoid waterfalls, jets, and metal stream impingement on mold walls and cores.