IMPROVING THE STEEL CASTING PROCESS USING AUTOMATED INCLUSION ANALYSIS

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ABSTRACT
This paper studies the effects of changes in melting and ladle practices (deoxidation, slag, refractory types, etc.) in steel foundries on steel cleanliness. The effects of deoxidation and pouring practices on the size, type and number of inclusions were compared for steel foundries using induction and arc furnaces of capacity 1 to 20 tons. Samples collected from the furnace, ladle, and cast products were analyzed using an automated Aspex Metals Quality Analyzer. This study summarizes the optimum deoxidation and ladle treatment for inclusion reduction and modification in the smaller industrial furnaces used by foundries where the use of traditional ladle furnaces is impractical.

1. INTRODUCTION
An increase in demand for higher quality steel is forcing steelmakers to ensure that their steel products meet more stringent “cleanliness” requirements. The mechanical properties of steel are affected by the volume fraction, size, composition, and morphology of inclusions [1]. Hence, the exact determination of non-metallic inclusions is essential to the success of research aimed at increasing toughness of steel parts.

In cast steel, non-metallic inclusions are the primary sites at which void nucleation occurs. The voids nucleated at the particle sites grow until they coalesce by impingement or by the process of void sheet coalescence [2]. Void sheet coalescence requires fracture of the ligament between the voids created at the larger non-metallic inclusions. Figure 1 shows that inclusions cause voids, which will coalesce and induce fracture if they are larger than a critical value.

Inclusions tend to be larger than other second phase particles in steels, such as those precipitated during heat treatment, ranging in diameter from about 0.1–10 μm or more. The characteristic inclusion volume fraction and the inclusion spacing have been shown to greatly influence the toughness of steel. Fracture toughness was determined to be indirectly proportional to the volume fraction of inclusions present in the sample [3]. Elements having high oxygen affinity are used as deoxidizers of cast steel. Figure 2 shows that Al has the best deoxidation ability, followed by Ti, Zr, and Si [4]. Deoxidation products, such as alumina inclusions, constitute in many cases the majority of the indigenous inclusions [5]. Aluminum is most commonly used for deoxidation of steel castings. Calcium treatment is used to reduce the harmful effects of Al₂O₃ inclusions. The addition of calcium promotes partial reduction of the Al₂O₃ inclusions, giving rise to the formation of liquid calcium aluminate with low melting point and spherical morphology, which can easily float out. Most of these liquid inclusions separate easily from the melt, and those not removed are less harmful to the mechanical properties of the final steel product. The reaction sequence followed is:

\[ \text{Al}_2\text{O}_3 \rightarrow \text{CA}_6 \rightarrow \text{CA}_3 \rightarrow \text{C} \rightarrow \text{C}_{12}\text{A}_7 \]

where, C and A denote CaO and Al₂O₃, respectively [6].

![Figure 1: Void nucleation on non-metallic inclusions and steel fracture [2].](image1)

![Figure 2: Deoxidation results of the common deoxidizers [4].](image2)

Calcium treatment also modifies the intergranular fine MnS inclusions to globular CaS inclusions, which are less harmful to the mechanical properties due to the spherical shape [7]. Figure 3 shows SEM and EDS images of how calcium treatment modifies MnS and alumina inclusions.
2. PROCEDURE

2.1 Plant Trials:

Plant trials were conducted at three foundries with different deoxidation practices in the furnace and ladle as summarized in Table I. Two foundries were induction furnace based (IF) and one foundry had electric arc furnaces (EAF).

During the plant trials, steel samples were collected from the furnace and the ladle, before and after the addition of deoxidants. In addition, samples were cut from castings produced from the same melt. Microscopic specimens were prepared from these samples and a 10 mm² area was analyzed in each specimen for inclusions using the Aspex MQA for automated inclusion analysis.

<table>
<thead>
<tr>
<th>Plant A (IF)</th>
<th>Charge Weight (lbs.)</th>
<th>Furnace additions (in wt. %)</th>
<th>Ladle additions (in wt. %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>-</td>
<td>Added at tap: Al (0.1%)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>FeTi (0.035% Ti)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>FeSiZr (0.04% Si, 0.03% Zr)</td>
<td></td>
</tr>
<tr>
<td>Plant B (IF)</td>
<td>1400</td>
<td>Al (0.08%)</td>
<td>Added at tap: CaSi (0.08% Ca, 0.3% Si)</td>
</tr>
<tr>
<td>Plant C (Acid EAF)</td>
<td>40,000</td>
<td>FeMn+FeSi Block additions</td>
<td>Added at tap: Al (0.07%) Wire fed in ladle CaSi (0.06% Ca, 0.10% Si)</td>
</tr>
<tr>
<td>Plant C (Basic EAF)</td>
<td>40,000</td>
<td>FeMn+FeSi Block additions</td>
<td>Added at tap: Al (0.068%) Wire fed in ladle CaSi (0.04% Ca, 0.08% Si)</td>
</tr>
</tbody>
</table>

2.2 MQA Analysis:

In the Aspex MQA system, a focused electron beam is moved across the specimen in an array of fairly coarse steps, as shown in Fig. 4. The mechanical fields are subdivided into smaller fields. For example, a 4X4 mm square sample field can be broken down into 16 fields of 1X1 mm square that are defined electronically. That is, the beam is displaced by the scan system so that each 1mm area is treated as a separate field, reducing the number of time-consuming mechanical stage motions sixteen-fold. As the electron beam moves across each field, the brightness or intensity of the back scattered electron detector (BSED) signal is recorded and transferred to the computer memory as representing the brightness of a single pixel (Fig. 4b). Once the signal is bright enough to indicate that an inclusion is present at the position, the software initiates a particle-sizing sequence using a rotating chord algorithm. Once the coarse scanning (indicated by the dots) identifies an inclusion, the center is identified and chords are drawn with the beam on the inclusion to define the size and shape of the inclusion. This is a fast process because the instrument only spends time collecting detailed sizing data where inclusions are known to be present, rather than spending time capturing and analyzing vast numbers of essentially empty pixels. Subsequently a number of size and shape parameters are computed from the lengths of the chords.

After inclusions have been fully characterized for size and shape, an EDS spectrum is acquired to determine the elemental composition of each inclusion. While the system is programmed to identify the inclusions based on the library set of definitions determined by size and composition information during the run, the data for this study was evaluated offline by the Automated
Feature Analysis Data Viewer software after the sample had been completely analyzed and the data stored. The inclusions are classified into various classes based on their composition as determined by user-defined rules.

3. RESULTS AND DISCUSSION

3.1 Plant A

In the trial at Plant A, a heat of medium-carbon steel (WBC) was produced in an induction furnace and tapped into a 1000 lb capacity ladle. Al, FeTi and FeSiZr were added as deoxidants in the ladle. Figure 5 compare the area fraction covered by inclusions at the various stages of liquid processing, as measured by the MQA system.

The area fraction represents the volume fraction of the inclusions. The area of alumina and TiO₂ inclusions increased after the Al and FeTi additions in the ladle. The area of the oxide inclusions increased during the pour and also the casting had more inclusions than in the ladle. This indicates that there is significant reoxidation during pouring and the melt transport through the gating system. Also, there is insufficient time to float inclusions in the ladle.

3.2 Plant B

In this plant trial, one induction furnace heat was followed from melting through deoxidation and pouring of a medium-carbon steel (8625 alloy) in a 1400 lb ladle. For deoxidation, Al was added in the furnace just before tap followed by a CaSi addition in the tap stream. Figure 6 shows the area fraction covered by inclusions for samples collected during various stages of the casting process. Figure 7 show the ternary chemical mapping for sulfides and oxides before and after Ca additions in the ladle. The region of calcium aluminates (CA) is circled on the ternary oxides diagram.

After Al treatment in the furnace, there was an increase in alumina inclusions and the total oxygen. The composition and number of inclusions changed after the Ca treatment in the ladle with most of the alumina inclusions forming calcium aluminates (CA). Significant reoxidation was observed with all of the oxide inclusions increasing from the ladle through casting. MnS inclusions were first observed in the furnace and remained fairly constant through the ladle and casting.

As seen in the ternary oxide and sulfide mappings, contrary to the Ca modification of the alumina inclusions, there was limited Ca modification of the MnS inclusions. Adding Ca in the form of CaSi ferroalloy during tap is inconsistent in its metallurgical effectiveness. CaSi ferroalloy was observed to float on the melt surface often flashing indicating vaporization of Ca followed by rapid combustion in air. Ca is highly volatile with a boiling point of 1500°C making it difficult to add to the steel without losing it to vaporization. Injection of calcium below the surface of the steel through wire or powder injection would be more effective as it suppresses Ca boiling because of the higher ferrostatic pressure [9].
1. Furnace after block
2. Ladle before calcium wire treatment
3. Ladle after calcium wire treatment
4. Ladle at mid-ladle pouring.
5. Sample from the final casting.

Figure 8 shows the fraction of area covered by inclusions for both acid and basic processes. In the acid process, the area of inclusions decreased after addition of the Ca due to the formation of calcium aluminates (CaAl). Also in this process, MnS inclusions were modified to CaS. In the basic process, many of the alumina and MnS inclusions were not successfully modified. Overall, the acid process had more inclusions than the basic process.

Figure 9 summarizes the inclusion composition for the acid process using a ternary mapping system for sulfides and oxides. After the Ca addition, the MnS inclusions decreased and replaced...
by CaS inclusions. This is a desired transformation due to the
globular morphology of CaS. Also, a significant amount of CA
formation was observed with a decrease in both MnO and Al2O3
inclusions.

Figure 9: a) Sulfides Mn-Ca-S and b) oxides (Mn+Si)-Ca-Al mapping
for casting process, before and after addition of Ca in the ladle (Plant
C, Acid process).

Figure 10 shows the ternary chemical mapping of the
sulfide and oxide inclusions for the basic process. Contrary to
the acid practice, there was not much of a decrease in MnS and
Al2O3 inclusions in the basic practice. Also, formation of the
desired CaS or CA inclusions was not observed in the basic
process. This can be explained as more CaSi wire was added to
the ladle in the acid process (0.06 wt. %) as compared to the
basic process (0.04 wt. %). The amount of Ca in the basic
process was not sufficient to cause the modification of MnS and
alumina inclusions.

Figure 10: a) Sulfides Mn-Ca-S and b) oxides (Mn+Si)-Ca-Al mapping
for casting process, before and after addition of Ca in ladle (Plant C,
basic).

4. CONCLUSIONS
In this research, a new Metals Quality Analyzer is used for
calculating the volume fraction and spacing of inclusions in
steel casting. The MQA provides an automated, efficient and
fast way to characterize and measure the non-metallic
inclusions. The volume fraction and composition of the
inclusions changes significantly during the melting and
treatment of cast steels in foundries, which is primarily due to
early deoxidation and further reoxidation during pouring. Ca
deoxidation was found to be beneficial when added as wire and in
sufficient quantities. It modified MnS to CaS with globular
morphology, which is less harmful to physical properties. Ca
also transformed alumina to calcium aluminates (CA) with
lower melting point and spherical morphology, so they could
easily float out, resulting in cleaner steel. However, the calcium
addition can only be effective if it is injected in the form of
calcium wire below the surface of steel in sufficient quantities,
or otherwise most of it will vaporize without reacting with the steel
melt.

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6. REFERENCES
Steel Ingot Casting”, Metallurgical and Materials
Fracture of AISI 4340 and 18 Ni-200 Grade Maraging
Achieve High Toughness in steels”, AIST Trans, 4(5),
2007, pp.132-139.


