IDENTIFICATION OF POROSITY AND CAUSES OF INCLUSIONS IN INDUCTION MELTED 440 C STAINLESS PLATE CASTINGS

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IDENTIFICATION OF POROSITY AND CAUSES OF INCLUSIONS IN INDUCTION MELTED 440 C STAINLESS PLATE CASTINGS

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ABSTRACT

Several events can cause dispersed porosity and inclusions in stainless steel castings. The principal sources include dissolved gas rejected during solidification, shrinkage porosity, carbon monoxide gas holes associated with reoxidation products formed during pouring, deoxidation products, eroded molding sand, eroded ladle refractories and entrained slag.

Defects from several 0.40 inch thick plate castings were examined in the current technical effort to determine the principal sources of porosity and macro-inclusions in cast 440C stainless steel. The defects examined were comprised of silica sand, reoxidation products, and small amounts of entrained nitrogen. All of these phenomena are a result of turbulent pouring. Typical micrographs of inclusion defects are presented.

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Oxide macro-inclusions always have been troublesome in stainless steel castings. Reviews of the steel casting production process suggest a number of possible sources of nonmetallic inclusions including:

1. furnace refractories melted or fluxed during meltdown,
2. metal oxides produced during oxygen refining,
3. oxidation of the metal and deoxidizers including silicon and manganese during tapping,
4. formation of aluminum deoxidation products in the ladle,
5. fluxing and erosion of ladle refractories,
6. reoxidation of the metal during reladling,
7. reoxidation of metal during pouring into the mold cavity,
8. reoxidation of metal by reactions with mold binder decomposition products,
9. fluxing of mold refractories by oxides carried into the mold,
10. erosion of loose sand on cores and in mold cavities, and
11. thermal expansion defects resulting in loose sand falling into the molten metal stream during pouring and mold filling.

These inclusions can be classified by their source of oxygen which might include air, water in refractories, molding sand, and oxidized slag. Mechanical entrapment of oxides such as refractories and sands is also a possibility. Mechanical entrapment is an obvious source and has often been cited as the major source of oxide macro-inclusions. However, many sources of inclusions exist, and a summary is presented in Table I. This table is a compilation of information presented in References 1-20. The major inclusion sources include...
reoxidation of metal and entrapment of existing oxides in the metal, ladles and molds.

**Reoxidation**

There is substantial evidence that reoxidation is a major cause of oxide macro-inclusions in stainless steel castings. The results of an examination of 100 ceroxide defects cut from high alloy and stainless castings are summarized in Figure 1.(24) 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 carryover amounted to less than 5% of the total observed. 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 from air, refractories, or the mold.

The formation of deoxidation and reoxidation products is schematically illustrated in Figure 2.(16) Deoxidation products are small, typically 10 microns or less in diameter, and are composed almost exclusively of alumina \((\text{Al}_2\text{O}_3)\) in aluminum deoxidized carbon and low alloy steels. Reoxidation products generally consist of alumina particles in single or multiphase globules formed by the oxidation of aluminum followed by silicon, manganese and iron.(16,21) The matrix in which the alumina particles lie is typically rich in manganese and silicon oxides, but in extreme cases may contain considerable amounts of iron oxide. The presence of iron oxide may cause gas holes as the iron oxide is reduced by carbon to produce carbon monoxide during solidification.

Typical oxide macro-inclusions visually appear to be green to white powder. The inclusions consist of a mixture of corundum crystals, silica, and
manganese oxides. 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. (1, 5, 6, 8, 20, 19, 20)

Ladle Refractory Attack

Many investigators have concluded that ladle refractories are a major source of nonmetallic inclusions. Vingas and Zrimsek reported the main sources of inclusions in castings to be ladle refractories, ladle slags, oxidation of the deoxidizers, and eroded sand grains. (2, 19)

Lyman and Boulger similarly concluded that the major sources of ceroxide inclusions were reoxidation and refractory materials. (1) Castings poured from ladles lined with high alumina refractories contained more alumina inclusions than castings poured from ganister linings suggesting that alumina was being eroded by the molten metal.

It is certainly possible for liquid metal and the contained oxides to attack refractories. Liquid steel tapped at 1590 °C (2900 °F) or higher can produce a molten high silica phase in alumina-silica refractories containing less than 70% alumina. Refractories containing less than 70% alumina have a simple eutectic that melts at 1590 °C (2900 °F). Progressively higher temperatures produce progressively more liquid phase. The liquid lowers the refractory strength and can cause sagging or result in refractory erosion during filling or pouring from a ladle.

Mold Related Inclusions

There are several sources of mold related inclusions as metal enters the mold cavity. Obvious sources include poor housekeeping and molding practices that produce sand from loosely compacted molds, brittle sand, loose sand from rough spots on patterns, debris from overhead conveyors, core or mold crushes.
caused by rough handling, improperly sized core prints, and improper core placement. Correcting these problems lies more in improving the work practices than in altering the molding or pouring practices. However, Sanders has shown that inclusion defects cannot be eliminated solely by "good housekeeping practices". Inclusions were present in steel poured in clean graphite molds. (22)

Silica sand is a common ingredient of nonmetallic inclusions, although rarely found by itself. Lyman and Boulger (1) and Caine (23) analyzed inclusions and found many to contain free sand. Excluding the obvious sand grains, the nonmetallic material was found to contain about 50% silica, 20% alumina, 20% manganese oxide, and 10% iron oxide. (1) Silica sand was a major component of the inclusions and could be picked up either by direct erosion or by having the reoxidation products stick to the sand and then be pulled off by the flowing metal. Whatever the mechanism, free silica sand was a major constituent of the inclusion and was found blended with mixed oxide phases. (1) Air contained in the mold cavity and water in clay bonded sand molds provide opportunity for oxidation as the metal fills the mold cavity. Since silica is wetted by iron oxide, mold erosion and inclusion formation may be aggravated by oxidation which produces iron oxide and manganese oxide. (7) These materials wet and adhere to the sand, and the agglomerate can be eroded off by the flowing molten metal. Iron and manganese oxide dissolve silica to form a fluid iron silicate melt which may aggravate erosion.

**Background Information on the Current Study**

All of the plate castings examined in the current study were cast in an oil bonded silica sand. A typical sand mixture consisted of silica sand, 1.4% core oil, 1.4% water, and 0.25% wood flour. The molds were blown and then
baked to cure the oil. Castings were poured from 440C stainless steel containing 16 to 18% chromium, 1% carbon and 0.5% molybdenum. The metal was melted in an induction furnace, tapped at approximately 2900 °F into 400 lb teapot ladles, and poured at approximately 2840 to 2850 °F. The teapot ladle was lined using silica sand bonded with sodium silicate.

The typical pouring time was approximately 4 seconds. Metal was poured from the ladle through a shell pouring basin and strainer core in the sprue. The sprue fed directly into the center of the cast plate. The poured weight of the casting was approximately 27 lbs, and the plate weight was approximately 17 lbs. On most occasions the porosity did not show up until the plates were machined.

**Results and Discussion**

The as-received appearance of two defects in plate #784 is illustrated in Figure 3A. One of these defects is illustrated at a higher magnification in Figure 3B. Both defects were removed and vacuum epoxy mounted for a more careful metallographic examination.

Two areas in the defect contained oxide macroinclusions. One of the regions containing the macroinclusions is illustrated in Figure 4 at magnifications of 100 and 200X. Another area containing oxide inclusions is similarly illustrated in Figure 5 at magnifications of 100 and 200X. The mixed oxides are composed of silica, alumina, and manganese oxide, as will be shown in subsequent EDX spectra.

Another pore cut from plate #784 is illustrated in Figure 6. This pore consisted of an approximately spherical gas hole without any foreign debris. This pore appears to be the result of nitrogen gas entrainment, but could be a result of reoxidation debris present elsewhere in the pore (not on the metallographically examined plane).
The defects in plate #805 are illustrated in Figure 7. Two defects were visible in this plate as illustrated in Figures 7A and 7B, respectively. Both of these defects were cross-sectioned and mounted for further examination. The microstructure of the defect in sample #805-1 is illustrated at magnifications of 25 and 100X in Figure 8. The defect again is comprised of a small amount of gas and mixed oxides. The oxides are composed of manganese, aluminum, and silica oxides along with silica sand grains. The silica sand is readily distinguished under polarized light by its translucence and by the presence of thermal stress cracks.

A higher magnification micrograph of some of the mixed oxides is illustrated in Figure 9. The numbers and associated arrows point to areas analyzed by scanning electron microscopy using an energy dispersive x-ray (EDX) analyzer.

The spectrum obtained by scanning the area illustrated in Figure 9 is shown in Figure 10. The material illustrated in Figure 9 consisted principally of silica with some manganese and chromium oxides and a small amount of aluminum. The spectrum of the area indicated by region #1 in Figure 9 is illustrated in Figure 11. The light gray debris phase is composed almost completely of silica as shown by the EDX spectrum.

The spectrum obtained from region #2, a light gray phase, is illustrated in Figure 12. This phase is rich in manganese oxide as well as silicon oxide but it does contain small amounts of chromium, aluminum, and zircon. Finally the light colored phase labeled 3 in Figure 9 is composed principally of chromium and iron with a small amount of silicon and oxygen as shown by the EDX spectrum in Figure 13.

The presence of substantial amounts of silicon and manganese oxide in the inclusions strongly supports the theory of reoxidation during pouring. Oxygen
in air combines with the easily oxidizable silicon and manganese contained in
the steel to produce these reactive oxides. During solidification,
segregating at the liquid-solid interface carbon reacts with the mixed oxides,
especially iron oxide, to produce carbon monoxide gas porosity.

The appearance of a cross section of specimen #2 removed from plate 805
is illustrated in Figure 14. Again, considerable amounts of reoxidation prod-
ucts are associated with the gas hole.

The appearance of defects in plate #832 is shown in Figures 15A and 15B
at magnifications of 25 and 200X. The foreign material associated with the
defect and located in the bottom of the pore was principally sand with some
reoxidation products.

The appearance of defects in plate #22784 is illustrated in Figure 16.
These pores appeared to be nitrogen pinholes. While there may be some foreign
material associated with the hole in a plane not cut by the section of polish,
the holes appear spherical and are probably associated with entrain nitrogen.

Conclusions

All of the defects examined in these cast plates were composed of sand,
reoxidation products associated with turbulent pouring, and small amounts of
entrained nitrogen. All of these phenomena are a result of turbulent pouring.
There was no evidence of microshrinkage in any of the sections examined. It
is concluded that the defects are largely caused by turbulent pouring condi-
tions.
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### Table I. Sources of oxide macroinclusions by source of oxygen.

**A. REOXIDATION - reaction of liquid metal with oxygen**

<table>
<thead>
<tr>
<th>SOURCES</th>
<th>MECHANISM OF FORMATION</th>
<th>PREVENTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Air</td>
<td>liquid steel reacts quickly during pouring with air as a function of surface area exposed and time of exposure.</td>
<td>must minimize exposure to air by fast pouring, ladle alignment low to mold, compact pouring streams.</td>
</tr>
<tr>
<td>2. Refractories</td>
<td>moisture or poor refractories can be reduced by deoxidizers in steel.</td>
<td>must use dry, high quality refractories and metal attack and expose good refractory; patching must be dry and good quality.</td>
</tr>
<tr>
<td>3. Slag</td>
<td>furnace slags high in FeO can contribute to reoxidation slags and are especially harmful if left on refractories in ladle in spout or bottom pour area.</td>
<td>must not pour slag into casting; must clean slag out of ladle between uses.</td>
</tr>
<tr>
<td>4. Mold</td>
<td>mold binders high in moisture or other oxidizing components can contribute to reoxidation.</td>
<td>use organic additives or organic binders to produce a more reducing atmosphere.</td>
</tr>
</tbody>
</table>

**B. ENTRAPMENT - capture of an existing oxide in liquid metal**

<table>
<thead>
<tr>
<th>SOURCES</th>
<th>MECHANISM OF CAPTURE</th>
<th>PREVENTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Slag</td>
<td>slags high in FeO are very fluid and apt to be entrapped in pouring.</td>
<td>avoid large amounts of furnace slag, clean old slag from ladle pouring areas, avoid mixing acid and basic slags.</td>
</tr>
<tr>
<td>2. Refractories</td>
<td>metal can attack binder areas of refractory and allow erosion.</td>
<td>use good refractories resistant to metal attack and erosion, especially in the area of pouring.</td>
</tr>
<tr>
<td>3. Mold</td>
<td>scabbing or erosion can lead to trapped sand or mold wash.</td>
<td>use a proper sand mix and gating design to prevent scabbing and erosion.</td>
</tr>
</tbody>
</table>

Proper gating and filtering can help reduce oxide macroinclusion.
FIGURE 1. DISTRIBUTION OF INCLUSION SOURCES IN HIGH ALLOY AND STAINLESS STEEL CASTINGS.
FIGURE 2. STYLIZED FORMATION OF INCLUSIONS IN AS CAST STEEL DEOXIDIZED WITH ALUMINUM. (>0.01% Al.)
FIGURE 3. MACRO-APPEARANCE OF TWO DEFECTS IN PLATE 784.
FIGURE 4. MICROSTRUCTURE OF LENS SHAPED OXIDE AREA IN DEFECT 784-1.  
(A) 100X    (B) 200X
FIGURE 5. MICROSTRUCTURE OF OXIDE DEFECT IN 784-L.
(A) 100X  (B) 200X
FIGURE 6. APPEARANCE OF GAS DEFECT IN 784-2.
(A) 25X    (B) 100X
FIGURE 7. APPEARANCE OF TWO DEFECT IN PLATE 805.
FIGURE 8. MICROSTRUCTURE OF DEFECTS IN PLATE DEFECT 805-1.
(A) 25X       (B) 100X
FIGURE 9. MICROSTRUCTURE OF OXIDE DEFECT IN PLATE SAMPLE 805-1. 1000X. NUMBERS INDICATE AREAS ANALYZED BY SEM-EDX.
FIGURE 10. EDX SPECTRUM OF BULK AREA IN SPECIMEN 805-1.
FIGURE 11. EDX SPECTRUM OF AREA 1 IN SPECIMEN 805-1.
FIGURE 12. EDX SPECTRUM OF AREA 2 IN SPECIMEN 805-1.
FIGURE 13. EDX SPECTRUM OF AREA 3 IN SPECIMEN 805-1.
FIGURE 14. DEFECT WITH ASSOCIATED REOXIDATION PRODUCTS IN PLATE SAMPLE 805-2. (A) 25X  (B) 200X
FIGURE 15. DEBRIS IN PLATE DEFECT SAMPLE 832-1.
FIGURE 16. MICROSTRUCTURE OF PLATE SAMPLE 22784.
(A) 25X       (B) 100X