'Pin-Pointing' Ductile Iron Pinhole and Slag Defects

Among the findings of this Grede experiment were two pinhole-producing red flags: high magnesium and low pouring temperatures.

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Here are many tasks involved in producing a quality casting and an even greater number of variables that can screw the cast part. Pinholes are just one of many headache-causing defects that foundrymen must control.

You might say that a casting with pinholes (very small holes scattered throughout the casting) is similar to a faulty parachute. Upon discovering the problem, it’s safe to say that the customer isn’t going to be happy with the manufacturer. And if it goes unnoticed until in use, you have a far more serious problem on your hands.

This article explains the dynamics involved in pinhole creation, and details one ductile iron foundry’s discoveries on how this problem can be eliminated.

A Pinhole Primer

When procedures aren’t followed with care, pinholes can be a serious defect on ductile iron castings. At times, the pinholes may be hidden below the surface of the casting and aren’t discovered until at the machining shop. These pinholes are usually either isolated or few in number, and although frequently located at a distance from the ingates, slag or dross is always nearby. If much slag enters or forms in the mold cavity, the number of pinholes may increase considerably.

The principle constituent involved in pinhole reaction is FeO reacting with C to form CO bubbles. While pinholes or pinhole defects may be categorized as evolution, reaction, aspiration, entrapped or other pinhole types, this article deals specifically with reaction pinholes associated with slag or dross (Fig. 1).

Fig. 1. These photos illustrate pinholes on a 10.75-in. bluestained ductile iron crankshaft. Seen at left is an example of large open surface pinhole and nearby surface markings at inner end of the crankshaft. Subsurface pinholes frequently appear as dimples on the bluestained surface.

A typical slag formation temperature on cooling is about 2532°F (1400°C); however, this temperature depends on the %C and %Si in the iron, as indicated in Fig. 3. The temperatures in Fig. 3 refer to the beginning of selective Si oxidation on cooling which initiates silicous slag formation. Above this temperature, C is preferentially oxidized rather than Si. The oxidation of Si to a slag particle is associated with entry into the SiO2-FeO system, in which FeO becomes a dominant part of the slag composition as temperature decreases.

Because iron is more than 95% of the iron composition, and iron oxidizes more readily as temperature decreases, there is a continuing increase in %FeO in the slag during the temperature regime from pouring to solidification. The FeO in the slag provides the pinhole bubble reaction FeO + C -> Fe + CO.(Q).

Mg and other deoxidizers can alter this course of slag formation. With Mg in ductile iron, the slag initiation temperature may be raised above the temperature in Fig. 3. Figure 4 shows the course of slag initiation and growth with falling temperature for a DI composition.

In addition, MgO, Al2O3, and CaO are present. At a lower temperature, the %FeO would increase.

The principle effect of Mg, then, is to raise the temperature at which reoxidation begins the slag formation process on melt surfaces. Slag composition moves in the same direction as on gray irons; as the Mg is gradually oxidized from the melt. Formation of this slag in furnaces and ladles, in gating systems and mold cavities can lead to its appearance on casting surfaces as shown in Fig. 2. Reaction pinholes accompany this process. In addition, casting surface dross defects become evident.

Role of Magnesium and Pouring Temperature

A 2² factorial experiment investigated the effect of Mg and pouring tempera-
ture on pinhole scrap during foundry production. In this foundry, cupola iron is calcium carbide desulfurized to below 0.01% S, and flows into a channel holding furnace for base iron at about 2700°F (1482°C). Treatment with MgFeSi occurs in a tundish ladle targeting 0.045% Mg maximum. The iron is stream-inoculated from a pouring vessel similar to a bottom-pour ladle. The test castings were poured during production runs, and two production-run trials were sampled for pinhole defects. In total, 16 castings were produced and sampled for each of the four combinations of Mg and temperature, as listed in Table 1.

In all production runs, pinhole occurrence was most severe in the first ladle of the run. Two things were identified that are different at the beginning of a production run—more Mg is charged and the initial pouring temperature is variable. Therefore, none of the test molds were poured from the first three ladles of the run. The first two molds and last two molds from the ladles tested were then pulled, and pinholes were counted in every casting.

Results were graphed and statistically analyzed using the procedure outlined in Design and Analysis of Experiments. The statistics verified—with a very strong interaction factor between the two—that high Mg and low pouring temperature increase the number of pinholes per casting. Figure 5 shows the average pinholes per casting for the Mg vs. temperature combinations. When Mg content was high and pouring temperature was low, the number of pinholes per casting increased dramatically. The entire designed experiment was run again to check for repeatability. Again, the same results were observed, verifying the effects of high Mg content and low pouring temperature on an increase of pinhole occurrence.

An interesting observation in the experiment was that vertical mold cavities 1 and 3 (top cavities) are much more prone to pinholes than cavities 2 and 4, likely due to the top cavities' extended reoxidization and reduced temperature. This effect was evident in both trials. During the trial, maximum to minimum was 0.061-0.043% Mg and 2604-2498°F (1429-1360°C) pouring temperature.

Both trials of the 2^3 designed experiment showed that high Mg content, combined with low pouring temperature, drastically increased the average number of pinholes per casting. The best case ladle in both trials was the low/high pouring temperature ladle, which produced no pinholes. Ladles

Table 1. Designed Experiment Data

<table>
<thead>
<tr>
<th>MOLD ID</th>
<th>Number of Pinholes on Casting</th>
<th>Avg. of Mold</th>
<th>Avg. Beg/End</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Mg/High Temp.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beg/End Mg (0.0540/0.0430)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beg/End Temp (2598°F/2549°F)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1^a</td>
<td>9</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>2^a</td>
<td>5</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>3^a</td>
<td>25</td>
<td>4</td>
<td>21</td>
</tr>
<tr>
<td>4^a</td>
<td>15</td>
<td>13</td>
<td>11</td>
</tr>
</tbody>
</table>

| High Mg/Low Temp. | | | |
| Beg/End Mg (0.0640/0.0420) | | | |
| Beg/End Temp (2549°F/250°F) | | | |
| 1^a | 14 | 7 | 10 | 5 | 4.8 |
| 2^a | 15 | 8 | 6 | 5 | 5.3 |
| 3^a | 25 | 4 | 21 | 13 | 16.8 |
| 4^a | 20 | 10 | 14 | 10 | 12.8 |
poured with either high Mg and high temperature or low Mg and low temperature showed an increase in pinholes over the best case ladle, but not nearly as severe as the high Mg, low temperature ladle. No lugs with poor graphite occurred in any of the trials. This suggests that it is best to keep pouring temperature high and Mg levels low to minimize this pinhole type. The low range used in the designed experiment was about 0.035% Mg at the end of the ladle.

**Target: Cupola Base Iron Tundish-Pouring System**

The slag pinhole problem occurred on only one of the foundry's three melting/pouring systems—castings poured from cupola base iron passing through a desulfurizing vessel to below 0.01% S and into a holding vessel. Mg treatment occurs in a tundish ladle at an analysis, which, after stream inoculation, will have about 3.60–3.75% C, 2.1–2.4% Si and 0.035–0.045% Mg.

The treated iron is poured into a box-shaped bottom pour ladle fitted with a nozzle and stopper rod. The pouring of vertical-gated molds occurs in 4–6 sec via the program-controlled stopper rod. This pouring device and be carried into the pouring stream. Further, slag can be generated by reoxidation as the pouring device is filled from the treatment ladle. If the pouring device metal level is low, it is particularly easy for slag to flow through the device into the mold-filling stream.

Slag accumulation in both the treatment ladle and pouring device is seen as a source of slag entering the mold cavity. In addition, slag may be generated in the mold cavity itself as temperature decreases. Chemical composition of the slag at points in this system is summarized in Table 2.

The total %FeO and liquid can increase on a falling iron temperature. A liquid slag phase can easily form a spherical cavity (Fig. 1) when it is lodged at the casting surface during mold filling. Slag accumulation of this composition type is thus proven to occur in this melting and pouring system, and is the cause of the reactive pinhole type.

**Cupola Base Iron Holder-Converter System**

A second melting and pouring system in this foundry uses the same cupola melted base iron. Iron is transferred by ladle from the cupola holding furnace to a graphite rod holding furnace. The slag composition in this furnace is listed in Table 2. Again, the FeO in this slag is high at 42%. A converter provides Mg treatment and the iron is transferred to a pressure pour furnace.

Initially, the converter maintains a more or less reducing Mg atmosphere during Mg treatment. The pouring furnace doesn't have a turbulent mixing action that causes reoxidation, as does the pouring box. Further, the tapping stream moves from under the metal level in the pouring trough. The pouring stream comes from under these slags, so little slag enters the pouring stream from under the slag-metal interface.

**Electric Melting Converter System**

A third melting and pouring system is virtually free of the defects. It consists of coreless melting furnaces for base iron, converter ladles for Mg treatment and pressure pour furnaces for automatic pouring. All slag that might come from the melting furnaces and converter ladles

<table>
<thead>
<tr>
<th>Oxide</th>
<th>1 BS</th>
<th>2 BS</th>
<th>3 BS</th>
<th>4D*</th>
<th>5 BS</th>
<th>6D*</th>
<th>7 BS</th>
<th>8 BS</th>
<th>9D*</th>
<th>10F*</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALO₂</td>
<td>1.14</td>
<td>3.97</td>
<td>4.30</td>
<td>11.34</td>
<td>43.28</td>
<td>6.9</td>
<td>7.75</td>
<td>5.67</td>
<td>11.59</td>
<td>4.07</td>
</tr>
<tr>
<td>SIO₂</td>
<td>0.30</td>
<td>0.10</td>
<td>1.40</td>
<td>8.62</td>
<td>2.79</td>
<td>0.71</td>
<td>1.34</td>
<td>2.50</td>
<td>8.82</td>
<td>2.01</td>
</tr>
<tr>
<td>MgO</td>
<td>29.85</td>
<td>9.65</td>
<td>12.75</td>
<td>1.69</td>
<td>1.78</td>
<td>2.85</td>
<td>3.20</td>
<td>0.06</td>
<td>0.06</td>
<td>0.10</td>
</tr>
<tr>
<td>KO</td>
<td>0.45</td>
<td>0.10</td>
<td>0.50</td>
<td>0.70</td>
<td>0.80</td>
<td>0.90</td>
<td>1.00</td>
<td>1.10</td>
<td>1.20</td>
<td>1.30</td>
</tr>
<tr>
<td>MnO</td>
<td>0.94</td>
<td>0.13</td>
<td>1.32</td>
<td>6.62</td>
<td>2.79</td>
<td>0.71</td>
<td>1.34</td>
<td>2.50</td>
<td>8.82</td>
<td>2.01</td>
</tr>
<tr>
<td>FeO</td>
<td>45.95</td>
<td>39.95</td>
<td>39.03</td>
<td>12.56</td>
<td>42.12</td>
<td>15.7</td>
<td>25.0</td>
<td>21.6</td>
<td>42.11</td>
<td>20.77</td>
</tr>
<tr>
<td>TC**</td>
<td>1.89</td>
<td>1.67</td>
<td>1.69</td>
<td>1.78</td>
<td>2.85</td>
<td>3.20</td>
<td>0.06</td>
<td>0.06</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>S</td>
<td>1.60</td>
<td>0.95</td>
<td>1.23</td>
<td>2.47</td>
<td>0.01</td>
<td>1.25</td>
<td>0.65</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
</tr>
</tbody>
</table>

*BS = Bulk Sample; D = Dross Sample; F = Film Sample
**Total Carbon

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Fig. 4. This chart illustrates the formation of reoxidation films and slag on ductile iron as a function of temperature on cooling in air.
can be trapped in the pressure pour furnace as in the system described above.

**Other Process Variables**

Reoxidation slag pinhole problems are affected by certain metal composition variables.

- **Base Iron Silicon—**Low %Si greatly increases reoxidation to FeO in the metal handling system and, thus, produces more of the fluid reactive slag and subsequent pinhole defects.

- **Carbon Equivalent—**At CE levels high enough to promote flotation, the iron precipitates its excess oxides along with C. Slag initiation, dross formation and reoxidation occur as a result.

- **Percent Residual Mg—**High %Mg in ductile iron increases slag pinhole incidence, especially when combined with low pouring temperature, as indicated by the factorially designed experiment cited earlier. Slag initiation temperature is raised by high %Mg.

- **Superheating and Pouring Temperatures—**Increasing superheating temperature over about 2700°F (1482°C) usually is accompanied by more extended reoxidation temperature and time during pouring and the associated reoxidation reactions.

Fig. 5. Shown here on Trial 1, pinholes increased dramatically when Mg was high and temperature was low. Trial 2 also reinforced this conclusion.

- **Casting Configuration and Casting—**Mold cavity geometry, such as horizontal sections that fill slowly, can provide locations where slag in the iron can accumulate. Larger horizontal areas in horizontally parted molds are particularly subject to reactive slag pooling and pinhole gas hole formation. Turbulent gating systems—which aspirate air and mold moisture—add to these reoxidation slag accumulations.

- **Nitrogen—**Nitrogen is usually quite low in ductile iron and ordinarily shouldn't cause pinholes. When present in core and mold materials, however, it can cause evolution gas holes and pinholes. With good foundry practices, nitrogen shouldn't be a problem.

**Adhere to Procedures**

Using today's state of the art ductile iron processing, foundries can clearly produce castings with a very low incidence of slag and pinhole defects. The best results are obtained when melting and pouring is controlled so that only a minimum of reoxidation slag may enter the mold cavity. This requires pouring equipment that permits effective slag accumulation on top of the iron and quiescent pouring from below the surface slag.

Slag pinhole defects are only a problem where these conditions aren't met. The reoxidation slag is considered the fundamental cause of most pinhole problems in the processes studied. This conclusion is true for both gray and ductile irons.

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