REMLETING PRACTICE FOR THE PRECISION CASTER

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ABSTRACT

The growth of the precision casting industry, especially in recent years, is associated with its ability to produce difficult, complex, near-net-shape castings. Coincident with increasing casting complexity is the need for stringent and consistent foundry procedures to maximize casting integrity and yield. In this paper, crucible/furnace lining interactions with the melt, alloy sequencing, temperature control, degassing practice, deslagging methods, and pouring practice are examined as to effect on casting integrity and yield.

Examples of cause and effect relationships of remelt practice to casting defects are examined. The conclusions indicate that casting integrity and yield are directly related to control of foundry practices. Improvements in foundry practice and its effect upon casting yield indicate a direct relationship to an understanding of the natural laws of physical chemistry.

INTRODUCTION

Molten metal and its associated melting, refining, degassing, deslagging and subsequent delivery to the shell, remains shrouded in mystique, "half-truths" and "black art", not unlike many of the other operations associated with the precision casting process. As considerable cost is expended up to the point at which molten metal enters the shell, failure to employ effective and consistent processes, principles and procedures often separates the profitable and quality precision casting houses from those that are not.
The days of the "Mickey Mouse" (easy) castings, as shown in Figure 1, are rapidly disappearing. The new and future parts being submitted are and will continue to become more complex and thinner near-net-shape castings. An example is shown in Figure 2; several years ago this would have been dismissed as impossible or not practical to produce. Major programs are continually being pursued by the gas turbine, firearms, and other market segments which involve the conversion of precision machined, forged and fabricated parts to near-net-shape, precision castings.

The future holds the promise of significant growth for the precision casting industry. However, no longer can the precision casting house charge its furnaces without regard to alloy source, melting and pouring practice. Increasingly stringent quality assurance steps pertaining to foundry practices are necessary to meet non-destructive test criteria and assure minimization of potential and future product liability. An urgent need exists for development of stringent and consistent foundry procedures.

In this paper the interrelationships of several critical precision casting foundry practices are investigated and related to casting integrity and yield:

- Crucible/Furnace Lining Interactions with the Melt
- Alloy Sequencing
- Temperature Control
- Degassing Practice
- Deslagging Methods
- Pouring Practice
From the examination of pertinent casting examples, the direct relationship of control of foundry practices to casting integrity and yield can be concluded. The interrelationship between foundry-related defects and remelt practices illustrates the strong relationship which exists between the improvement in casting integrity and yield and the understanding of the natural laws of physical chemistry.

CRUCIBLE/FURNACE LINING INTERACTIONS WITH THE MELT

Precision casting houses almost universally employ induction melting furnaces for remelt purposes. The induction melting furnace is unique among melting tools. Since there are no electrodes or fuels used, the metal in the furnace is in contact with only the lining and the atmosphere. In general, there is no contamination during melting, except that involved in the interaction with the atmosphere. Therefore, the alloy can be melted with almost no change in composition. In addition, other unique characteristics of induction furnaces include stirring of the melt in a characteristic pattern by electrodynamic effects, unlimited temperature capabilities (often misused), and a steep thermal gradient between the melt and induction coil (Ref. 1).

With only limited refining capability compared with other melting processes, induction melting does offer the best method for holding tight specifications on a variety of alloys, including those with limited solubility. As with any melting method, the associated characteristics affect interactions between the metal to slag, metal to refractory and slag to refractory. Each of these will be looked at briefly as they affect both furnace performance and alloy composition. (Note: A summary of furnace refractory recommendations to specific alloys, systems and conditions will not be attempted as it is beyond the scope of this paper and best left to the expertise of refractory producers and suppliers.)

Metal to Slag Interactions

Metal to slag interactions typically, although not exclusively, may involve the following:

- Interaction with atmosphere
- Intentional slag covers
- Intentional slag pH adjustments
- Slag viscosity adjustment additions

Slag on the surface of a melt may be intentional; a product of interaction with the atmosphere, originating from "dirty" melt stock and/or resulting from metal to refractory reaction. The slag present can be acidic, neutral or basic and viscous or non-viscous in nature. The typical slag which forms naturally upon melting in the atmosphere is highly oxidized and acidic in nature. This results in an attraction of readily oxidizable elements to the slag from the melt as defined by natural laws involving changes in free energy of formation as illustrated schematically in Figure 3. This causes the fade of certain elements and the subsequent enrichment of others until an equilibrium is reached in the slag between the melt and atmosphere. (This will be covered in greater detail later.)
Figure 3. Schematic representation of elemental fade in an induction furnace.

Figure 4. Schematic representation of melt line erosion which can result from slag chemistry adjustments to accomplish specific desired metal to slag interactions.

Slag blankets specifically designed to protect the melt from interaction with the atmosphere involving additions to the melt surface can be employed. While effectively minimizing nitrogen and oxygen pick-up, they leave the melt susceptible to hydrogen pick-up. This is due to the slag blanket formed, thereby creating an unbalanced partial pressure relationship for oxygen and nitrogen in the melt, leading to rapid pick up of hydrogen which is able to diffuse through the slag blanket due to its small atomic size.

Intentional additions of lime (CaO) or calcium carbide (CaC₂) to the melt surface is often pursued to improve sulfur (desulfurization) removal efficiencies. The slag in this condition is highly basic. On the other hand, intentional additions of silica (SiO₂) to the melt creates a highly acidic slag which facilitates boron removal or optimal incorporation of "free machining" additions such as sulfur (S) and selenium (Se). In either case, melt line wear, similar to that shown schematically in Figure 4, can result if the furnace refractory is not compatible with the slag pH and/or the desired reaction is not initiated intermediate in the charging cycle, such that the wear pattern is distributed to a greater extent. Lastly, when confronted with thin, watery, silaceous type slags, it is common practice to make slag coagulant additions to enhance the "stickiness" or viscosity of the slag, as well as to allow an attraction surface for the fine, non-metallic inclusions contained in the melt.

Metal to Refractory

Ideally, refractories used in induction furnaces are considered inert with life limited by erosive wear, abrasive wear and thermal fatigue situations. Chemical interactions between the melt are neither desired nor normally considered. However, lining life/wear (reactivity) in contact with the melt is directly related to the state of oxidation, contamination, superheat temperature and time at temperature.
Most of the common refractories used in induction melting are extremely stable and offer excellent life in contact with molten metal in an oxidized condition. However, should the bath enter a reducing condition due to a heavy slag and/or a bridging condition, the refractory bonding materials, namely SiO₂ (silica), B₂O₃ (boron) and P₂O₅ (phosphorous), are reduced. This leads to rapid and catastrophic subsurface refractory breakdown and production of a large volume of slag. The extent of this is vividly illustrated in Figure 5. The bonding breakdown during reduction causes reversion of the Si, B and P into the melt, creating potential metallurgical or alloy specification problems.

Recent developments in remelt alloy quality, available in master heats which have been induction melted and argon-oxygen-decarburized (AOD), stress refractory stability as a crucial factor in refractory life and metal quality. Many of the refractory systems of lesser purity and stability are finding limitations. In specific instances, the SiO₂ (silica) used as a binder, in the presence of a highly refined (low oxygen) melt, breaks down as the molten metal attempts to regain oxygen equilibrium. This condition can create rapid, erosive wear of the crucible and generate large amounts of slag. This slag, more often than not, finds its way into the final castings, thereby resulting in casting imperfections, reduced quality and expensive rework. Although not occurring with each heat or alloy system, the number of cases occurring since the availability of induction melted, AOD master alloy indicates the desirability for awareness of the problem and, should it occur, the substitution of higher purity refractory systems to realize the benefits this master alloy family has to offer.

At present, there is increased usage of rammed linings in larger (300+ lbs.) induction melting furnaces as a result of exceptional life and melt cleanliness due to high refractory stability. However, to enhance rammed lining life even further, some casting houses are frequently "patching" high wear areas. Unfortunately, the "patch" materials employed are generally higher in SiO₂ (silica) content, making them less stable than the base, rammed refractory and subject to high erosive wear. Potentially this can lead to "slag" and "blackspot" related defects in subsequent castings produced.

Even without the occurrence of severe lining breakdown and/or erosion, there are many non-metallic particles present in molten metal in the furnace. These are due to refractory particles, oxides from the charge materials, additions, and oxides formed during meltdown. The electromagnetic stirring,
Figure 6. Schematic representation of the non-metallic particle buildup mechanism.

Figure 7. Non-metallic particle buildup on an 88% Al₂O₃ crucible after melting 11 heats of Cobalt Alloy 31 (AMS-5382) at 2715°F.

characteristic of induction furnaces, serves to force metal away from the furnace wall, while attracting the non-metallic materials toward the wall as illustrated schematically in Figure 6. Buildup begins and continues, with little effect from the underlying refractory. This buildup can proceed to the extent that melting efficiency is reduced, pouring is affected and charging interference is encountered. An example of this phenomena is shown in Figure 7.

This problem can be approached in two manners. First, additions of more corrosive oxides (SiO₂) will allow the Al₂O₃, MgO, CaO and 3Al₂O₃ • 2SiO₂ to become feed material, thereby countering the buildup. Obviously, this method must be approached with care. Secondly, if buildup occurs at lower superheat temperatures on alumina or magnesia refractories, simply increasing superheat will remove the buildup. As it is undesirable, in general, to pour at higher superheats, it is preferred to cool the melt to the originally intended pouring temperature prior to tap.

Temperature plays an important role in metal to refractory reactivity. Higher temperatures give characteristically greater erosion and loss of refractory. Lower temperatures, while seemingly desirable, can create buildup of non-metals subsurface. Therefore, one must watch closely refractory performance in choosing a melt temperature to maximize refractory life (assuming satisfactory metal delivery).

Slag to Refractory

This area of interaction is associated, to a great degree, with metal to slag interactions, whether intentional or unintentional, as discussed above. In general, refractory life is dramatically affected by slag characterization, especially the relative basicity or acidity. Normal oxidized slag is acidic, which allows the use of silica, alumina and chrome bonded alumina linings. Highly basic slags require chrome-magnesite or magnesite linings. Obviously,
the nature of the slag can be changed through the addition of various slagging agents. Whatever the lining used, it should be compatible with the slag. Changes in the relative slag pH for special refining of sulfur, boron, etc., can dramatically affect lining life by creating melt/slag line wear as schematically illustrated in Figure 4.

ALLOY SEQUENCING

Almost without exception, cast alloys contain many elements other than those required by the material specification. Most of these "extraneous elements" are present in quantities less than .05% and are considered "trace elements". Often, however, even at these levels they can have a profound effect upon the mechanical and/or foundry properties, sometimes beneficial but frequently detrimental. This is especially true for elements with low melting points such as Pb, Sn, Sb, etc.

The precision casting industry is based on its ability to cast near-net-shapes in many different alloys and alloy systems. This creates the potential of "residual" elements or non-required elements greater than .05% being acquired in the succeeding heat as the result of the furnace skull left from the previous heat. This must be controlled or serious problems could be encountered on one or more of the following:

- Mechanical Properties
- Phasial Balance
- Heat Treat Response
- Machinability
- Alloy Cleanliness
- Fluidity
- Hot Tear Resistance

Assuming a conservative 3% skull factor, it can be seen that maintaining production through a precision foundry without regard to sequencing of alloys can result in the addition of an undesirable element approaching 3% in the succeeding heat. The resultant effect upon mechanical and/or foundry properties, if not the ability to meet the imposed specification, is obvious.

While it would be ideal to change the crucible/furnace lining or run a wash heat with each alloy change, it is nearly always impractical from an economic and productivity standpoint. Therefore, a sequencing chart, presented in Figure 8, is offered as a guide for making decision as to whether or not a wash heat is needed.

Abnormal penetration of the refractory by the melt can be a problem with certain alloys, especially those characterized by excellent fluidity. This occurs in spite of proper refractory characterization and installation. Alloys typically of concern are high carbon iron and cobalt base materials, as well as high boron containing materials. Special precautions should be taken in sequencing the subsequent heat to account for enhanced skull pick-up.
### Sequencing of Heats

<table>
<thead>
<tr>
<th>Heat Sequence</th>
<th>Low Alloy Steels</th>
<th>Tool Steels</th>
<th>High Carbon Steels</th>
<th>Medium Carbon Steels</th>
<th>Nickel Base</th>
<th>Cobalt Base</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat 1</td>
<td>A A A A</td>
<td>700 A</td>
<td>C C C C</td>
<td>C C C C</td>
<td>C C C C</td>
<td>C C C C</td>
</tr>
<tr>
<td>Heat 2</td>
<td>A A A A</td>
<td>700 A</td>
<td>C C C C</td>
<td>C C C C</td>
<td>C C C C</td>
<td>C C C C</td>
</tr>
<tr>
<td>Heat 3</td>
<td>A A A A</td>
<td>700 A</td>
<td>C C C C</td>
<td>C C C C</td>
<td>C C C C</td>
<td>C C C C</td>
</tr>
<tr>
<td>Heat 4</td>
<td>A A A A</td>
<td>700 A</td>
<td>C C C C</td>
<td>C C C C</td>
<td>C C C C</td>
<td>C C C C</td>
</tr>
</tbody>
</table>

**Notes:**
- A: Accepted Sequence
- D: A to D sequence
- E: A to E sequence
- F: A to F sequence

**Legend:**
- Heat numbers indicate the order of heat processing.
- Steels are categorized based on their carbon content and application.
- Cobalt and nickel bases are used for specialized applications.

**Figure 8:**
- Proceed with caution when sequencing elements, as contamination is possible.
TEMPERATURE CONTROL

The importance of temperature control of molten metal in a precision casting foundry cannot be overemphasized. Excessive superheat upon pouring is the cause of many casting defects, as well as inefficiencies such as longer melt times, premature crucible/furnace lining life and additional energy cost. Conversely, a pouring temperature which is too low can cause casting defects also, in addition to excessive furnace skulling. Figure 9 summarizes casting defects which can occur as a result of poor temperature control.

Gassing

Figures 10 and 11 illustrate a typical range in severity of gas defects. Temperature, or more specifically the degree of superheat, has a pronounced affect upon gas absorption in molten metal, primarily from the atmosphere. Figure 12 shows the influence of superheat temperature on nitrogen and oxygen pick-up in AMS-5355 material upon melting. Figure 13 introduces the variable of time at temperature to illustrate the additive effect present. This strongly illustrates the need for temperature control, the lowest possible temperature consistent with proper shell filling, and timeliness in furnace tapping.

Figure 9
Detrimental Temperature Effects

<table>
<thead>
<tr>
<th>Temperature Too High</th>
<th>Temperature Too Low</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gassing</td>
<td>Misrun</td>
</tr>
<tr>
<td>Shrinkage</td>
<td>Cold Shuts</td>
</tr>
<tr>
<td>Elemental Fade</td>
<td>Hot Tears</td>
</tr>
<tr>
<td>Hot Tears</td>
<td>Misrun</td>
</tr>
</tbody>
</table>

Figure 10. Severe gas condition on Type 436 stainless steel (AMS-5354) caused by repetitive melting at excessive temperature (3100°F). Nitrogen = .089%; Oxygen = .025%

Figure 11. Mild (relative to Figure 10) gas condition found on Type 8630 Low Alloy steel (AMS-5334) caused by excessive melt temperature (3150°F). Nitrogen = .012%; Oxygen = .025%.
Shrinkage of liquid metal occurs through three distinct regions as shown in Figure 14 (Ref. 2). Those regions are: 1) liquid contraction, 2) solidification contraction, and 3) solid contraction. Figure 14 graphically displays the magnitude of specific volume change of a low alloy steel upon pouring. Note the relative contribution of each of the areas to the total shrinkage encountered. We can not control the shrinkage due to solid contraction or solidification contraction, but we may control the amount of shrinkage due to liquid contraction through superheat temperature selection.

Using the graph in Figure 14, it can be determined that pouring at a +200°F (93°C) superheat yields a liquid contraction which is 15% of the total, while pouring at a +400°F (204°C) superheat results in a 26% contribution to total shrinkage. As the gating system is used to deliver and feed the metal during solidification, it is readily apparent that the gating and feeding system required for +200°F (93°C) superheat, as compared to a +400°F (204°C) superheat, is quite different. Attempting to pour metal at +400°F (204°C) into a gating system designed for +200°F (93°C) superheat can produce castings with shrinkage defects as characterized in Figures 15 and 16.

Elemental Fade

The fade or loss of a given element during melted is related to 1) reactivity to the atmosphere, and 2) partial pressure relationships. Reactivity to

Figure 12.

Figure 13.

Figure 14. The change in specific volume of low alloy steel during solidification.
the atmosphere is the prime cause of fade in air melted alloys. When molten metal is allowed to come into contact with the atmosphere, various elemental constituents of a molten alloy will undergo reactions with nitrogen and oxygen (the prime constituents of the atmosphere) to derive a lower energy state. Due to lower reactivity, nitride formation is much lower than oxide formation. Also, the nitrides formed are of similar density to the molten metal remaining in the melt and do not contribute to elemental fade.

The reaction of the molten metal with oxygen, however, is much more reactive. Figure 17 (Ref. 3) presents the change in free energy upon formation (reaction with oxygen) at a given temperature. The lower the reaction on the graph, the more likely the reaction will occur and the more quickly it will proceed to completion.

Figure 18 (Ref. 5) shows a simplification of the loss (fading) order. For an iron base alloy, a line could be drawn through iron oxide on this table with all elements which form oxides above the line fading, while those below the line will become enriched (gain) due to the loss of
<table>
<thead>
<tr>
<th>Oxide</th>
<th>Heat of Formation (Kilo-cal. per gram atom O)</th>
<th>Melting Point (°C)</th>
<th>Density g/cm³</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>Cr</th>
<th>Mo</th>
<th>V</th>
</tr>
</thead>
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<tr>
<td>CaO</td>
<td>152</td>
<td>&gt;1490 (&gt;2500)</td>
<td>3.4</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>MgO</td>
<td>144</td>
<td>&gt;1490 (&gt;2500)</td>
<td>3.6</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TiO₂</td>
<td>141</td>
<td>&gt;3100 (&gt;1200)</td>
<td>2.0</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>127</td>
<td>3070 (1570)</td>
<td>3.5</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>V₂O₅</td>
<td>156</td>
<td>2530 (1270)</td>
<td>4.0</td>
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<tr>
<td>TiO₂</td>
<td>169</td>
<td>3000 (1640)</td>
<td>4.3</td>
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<tr>
<td>Na₂O</td>
<td>101 Sublimes</td>
<td>2.3</td>
<td></td>
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<tr>
<td>SiO₂</td>
<td>95 Sublimes</td>
<td>1600 (1670)</td>
<td>2.3</td>
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<tr>
<td>B₂O₃</td>
<td>94 Sublimes</td>
<td>1070 (980)</td>
<td>1.8</td>
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<tr>
<td>MnO</td>
<td>91 Sublimes</td>
<td>2000 (1650)</td>
<td>5.5</td>
<td></td>
<td></td>
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<tr>
<td>ZrO₂</td>
<td>89 Sublimes</td>
<td>1600 (2760)</td>
<td>5.5</td>
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<tr>
<td>ZnO</td>
<td>85 Sublimes</td>
<td>1800 (1800)</td>
<td>5.3</td>
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<tr>
<td>P₂O₅</td>
<td>73 Sublimes</td>
<td>1300 (150)</td>
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<tr>
<td>SrO</td>
<td>68 Sublimes</td>
<td>2305 (1130)</td>
<td>6.95</td>
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<tr>
<td>FeO</td>
<td>66 Sublimes</td>
<td>2560 (1470)</td>
<td>5.7</td>
<td></td>
<td></td>
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<tr>
<td>NiO</td>
<td>58 Sublimes</td>
<td>Unstable at high temp.</td>
<td>7.45</td>
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</tr>
<tr>
<td>SnO₂</td>
<td>52 Sublimes</td>
<td>1250 (600)</td>
<td>5.2</td>
<td></td>
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<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>PbO</td>
<td>51 Sublimes</td>
<td>1615 (820)</td>
<td>9.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CuO</td>
<td>40 Sublimes</td>
<td>2250 (1255)</td>
<td>6.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

*Figure 18. Table of Oxide Properties.*

*Figure 19. Relative elemental fade by alloy system. The values shown relate to the percent lost of the amount present.*

...those that tend to fade. From Figure 18, it is readily apparent that the oxide densities formed are less than that of iron; thus, they will tend to rest on the melt surface as a slag.

The discussion to this point has established only those elements subject to fade which, in the case of most iron, nickel and cobalt base alloys, are C, Cr, Mn and Si. These elements have profound affects upon mechanical properties, phasial distribution, heat treat response, and foundry performance; primarily, fluidity. Thus, their retention is of primary performance in any foundry operation.

The elemental fades resulting are dependent upon the following:

- Alloy Type
- Furnace Type
- Melt Frequency
- Melt Time
- Melt Temperature
- Melt Stock Quality

*Figure 19 illustrates relative, comparative fades for various alloy systems as determined on air induction melted heats from many different precision foundries, furnace sizes, melt frequencies, melt times and temperatures. However, all the melt stock used was of induction melted, AOD refined quality. Higher losses would be expected in lower quality melt stock material. Note the synergistic effect of relative alloy content in the iron base alloys and the similarity in total alloy content to fade percentages in the cobalt and nickel base alloys.*

Temperature has a pronounced effect upon the loss (fading) rate of oxidizable elements. Figures 20 and 21 illustrate the influence of temperature and time, respectively, on AMS-5355 material with regard to Mn and Si content. The relative percentage of each element lost has significant effects upon phasial balance, an important consideration in this alloy, and foundry performance (fluidity).
Figure 22 illustrates a typical misrun defect. Generally, this type of defect is considered the result of insufficient superheat (pouring temperature). However, excessive superheat temperature and/or holding times can increase gas content and fade fluidizing elements (such as silicon), whereby the fluidity of the alloy is decreased to the point of misrun, or in some instances, cold shutting occurs.

**Hot Tears**

Hot tearing defects are caused by a variety of foundry factors including:

- Early shell movement
- Poor casting and gating design
- Too high or low superheat
- Trace element contamination

Most air melted alloys have poor hot strength characterization, thereby making them susceptible to hot tearing upon all but the most careful (gentle) shell movement up to one hour after casting. A strong indication that this is the cause is apparent when the cracks are in the ingate area or when the cracks are of the "gate-crack" variety.

Figure 22. Typical misrun defect found associated with castings generally thought to be poured with too little superheat, although conditions identical to this can result from gas absorption and/or elemental fading (primarily; silicon) which can have a pronounced effect on fluidity.
Hot tearing can be caused by excessive superheat, which sets up higher thermal gradients, and thus, more solidification stress leading to tear susceptibilities. Too little superheat can lead to partially welded cold shuts, which then become lines of weakness, leading to hot tearing.

Molten metal contamination with low melting point trace elements such as Pb, Sn, Sb, Zn, S, etc., can lead to grain boundary segregation and/or phase formations which cause pronounced hot tearing tendencies. The best recourse is to charge high quality materials of known composition and not scrap or revert materials of unknown pedigree. Typical hot tears are shown in Figures 23 and 24.

Cold Shuts

Metal which loses its ability to develop a homogeneous bond upon the intersection of two opposing metal streams is said to cold shut. An example of this is shown in Figure 25. At times, poor introduction of metal into the shell will cause cold "shots" to form, which become encapsulated in the succeeding metal flow. Assuming proper gating, cold shuts occur for two reasons, haphazard pouring and poor fluidity. A decrease in fluidity can be the result of gas pickup and silicon fade.

DEGASSING PRACTICE

In general, the presence of gases in metals usually causes a reduction in mechanical properties and the increased potential for gas porosity. Gases in metals are due to:

- Entrapment during pouring and solidification
- Change in gas solubility upon solidification
- Chemical reactions upon pouring
Mechanical entrapment (as opposed to shrinkage entrapment) is not normally considered a problem as a proper, nonaspirating gating system in conjunction with a sufficiently permeable mold will eliminate this source of gas. In practice, however, many problems related to this gas phenomena occur as the metal delivery (gating) system is usually not optimal due to casting design and/or economics. The shell permeability, while impressive in bench testing, rarely can keep up with the gas evacuation required at normal pouring rates. An example of this type of defect is given in Figure 26.

With a given metal delivery system and pouring rate, the one thing that can be done to assist in the elimination of mechanically entrapped gas is to (once again) deliver metal to the shell at as low temperature as possible. In the pouring of iron, nickel and cobalt base alloys, a significant temperature difference exists between the shell and the molten metal. During pouring, the atmosphere in the shell undergoes, which best can be described as, an "explosive" expansion according to the "ideal gas law",

\[
P V = n RT,
\]

where 
- \( P \) = Pressure
- \( V \) = Volume
- \( n \) = Mass of Present Gas
- \( R \) = Boyles Constant
- \( T \) = Absolute Temperature.

It is readily apparent that the atmosphere volume is directly proportional to temperature. A typical 1000°F (538°C) differential between metal and shell temperature translates into an instantaneous 40% increase in shell atmosphere volume which must be displaced via the metal delivery system and/or shell permeability. In many cases the end result is entrapped gas and/or castings with misruns. Examples of these are shown in Figures 27 and 28.

The change in gas solubility upon solidification is generally the main source of gas defects in castings. There are four main gases that are of concern: hydrogen, nitrogen, oxygen, and carbon monoxide, each of which is discussed separately. Examples of this type of defect are shown in Figures 10 and 11.
The minimization and control of soluble gas is of utmost importance as it is responsible for the following non-desirable characteristics in precision castings:

- Gas (bubble) defects
- Non-metallic inclusions
- Embrittlement
- Mechanical property reduction
- Fluidity decrease

Hydrogen

Figure 29 shows the solubility of hydrogen in pure iron (Ref. 4). At ambient temperature, the solubility is only approximately 3 to 5 parts per million (ppm). In equilibrium, 10 ppm of hydrogen would occupy approximately the same volume as the metal at ambient temperature (Ref. 5). This leads to the great susceptibility of gas-related defects if hydrogen pick-up is encountered.

Unfortunately, there is no simple method of removing hydrogen in air melted alloys. Care must be exercised to keep the hydrogen pick-up to a minimum, which most often originates from dissociation of moisture in the atmosphere (the reason gas porosity is more of a problem in warm, humid weather), insufficiently dried materials such as refractories, charge materials, oil, grease and rust.

There are ways to minimize the potential of hydrogen induced defects which involve one or more of the following:
- Maintain oxidizing atmosphere at melt surface (keep surface from becoming covered with slag).
- Purge the melt with a dry insoluble gas such as argon or carbon monoxide (carbon boil).
- Additions of Ti, Zr, Cb and/or Ta. (These should follow degassing adds for oxygen and nitrogen or their effectiveness is drastically reduced.)
- Maintain an argon cover over the furnace during melting.

A point to remember is that maximum pickup of hydrogen occurs after additions are made for oxygen and nitrogen. Therefore, the melt should be poured in a timely fashion once degassed.

**Nitrogen**

Approximately 75% of the atmosphere by weight is nitrogen. This fact, coupled with the fact that nitrogen is much less reactive than oxygen, causes nitrogen to be a significant contributor to gas porosity. Figure 30 shows the solubility limits for nitrogen in pure iron, while Figure 31 illustrates solubility changes upon the addition of alloying elements (Ref. 4). It is apparent that alloy steels containing significant amounts of Cr, Mn and/or V have greater accommodations for nitrogen than unalloyed or lowly alloyed materials. Therefore, discretion should be used in the need for degassing additives for nitrogen. It should be mentioned here that certain 300 Series stainless alloys, as well as cobalt base casting alloys, contain intentional nitrogen levels of .15-.25%, without any incidence or tendency to form nitrogen-related gas porosity upon solidification.

Figure 32 shows the denitrifying power of various elements (Ref. 4). This table indicates that, should nitrogen gas porosity be suspected, additions of Ti or Zr could be used to precipitate the nitrogen as nitrides rather than gas bubbles. Al also could be used, although not as effectively, and the use of larger amounts can lead to excessive aluminum nitride precipitation on the grain boundaries and the classic "rock-candy" fracture surface in cast steel. An example of this phenomena is shown in Figure 33.

![Image](image1.png)

**Figure 30.** Solubility of nitrogen in pure iron at one atmosphere of pressure.

![Image](image2.png)

**Figure 31.** The change in nitrogen solubility with common alloy additions in iron at 2200°F.
Figure 32. Denitrifying power of various elements.

<table>
<thead>
<tr>
<th>Element</th>
<th>Constant</th>
<th>Value at 2912°F (1600°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>%[Al] x w/o N</td>
<td>0.55</td>
</tr>
<tr>
<td>Si</td>
<td>%[Si]% x w/o N</td>
<td>14.0</td>
</tr>
<tr>
<td>Ti</td>
<td>%[Ti] x w/o N</td>
<td>0.00014</td>
</tr>
<tr>
<td>V</td>
<td>%[V] x w/o N</td>
<td>1.5</td>
</tr>
<tr>
<td>B</td>
<td>%[B] x w/o N</td>
<td>0.55</td>
</tr>
<tr>
<td>Zr</td>
<td>%[Zr] x w/o N</td>
<td>0.00014</td>
</tr>
</tbody>
</table>

Figure 33. "Rock-Candy" fracture associated with 4140 (AMS-5338) alloy. Al = .28%.

Oxygen

Historically, everyone talks about "deoxidation" of molten metal to lower and/or eliminate the tendency to form gas defects upon solidification. As most casting alloys contain significant amounts of Si, as well as other elements which react readily with oxygen, and as oxygen is very reactive especially at elevated temperatures, the propensity to contribute significantly to gas porosity is nearly nil. However, oxygen is present in the form of oxide inclusions which can have important effects upon a metal's mechanical properties as well as foundry performance (fluidity).

The selection of a deoxidant is simplified because many elements, as shown in Figures 17 (Ref. 3) and 18 (Ref. 4), form stable oxides. Frequently, silicon is added in some form either pure or alloyed to improve fluidity, to deoxidize and to replenish silicon which is lost or fades during melting. The choice of any deoxidizer should be based on the following:

- Moderate reactivity.
- Clean (free of slag).
- Reaction product has good flotation (low relative density).
- Reaction product formed is "sticky" so it can be removed (deslagged).

Recent research has indicated the desirability of using two or more deoxidizing elements in conjunction with one another. While this may make the overall deoxidizing potential greater, many of these prealloyed additions contain significant amounts of slag as a by-product of their manufacture, causing significant non-metallic inclusions in the final product when used as a deoxidizer. This may create rejection problems in critical aerospace and medical parts.
Carbon Monoxide

Gas defects due to carbon monoxide are almost entirely due to chemical reaction upon pouring due to the presence of "pyrolytic" carbon in the shell. "Pyrolytic" carbon is formed during wax burn-off if the furnace atmosphere becomes reducing in nature due to insufficient oxygen. With precision casters attempting to gate more parts to a "tree" and the trend toward larger and larger parts, the wax load in a burn-off furnace may now create an insufficient oxygen condition during combustion, leading to "pyrolytic" carbon formation. To assure against potential "pyrolytic" carbon formation, excess oxygen must be present at all times during burn-off. A common Orsat gas analyzer can be used to audit and assure proper wax combustion during burn-off.

Degassing - An Overview

The primary gases in metal; hydrogen, nitrogen and oxygen, originate from many sources which include:

- The Atmosphere
- Furnace and Ladle Linings
- Melting Stock
- Rust and Oil
- Additions
- Turbulence - Aspiration

The purpose of degassing operations is to:

- Tie up the gas in a precipitate to minimize gas porosity.
- Promote globular, rather than stringer, inclusions.
- Refine the grain size.
- Enhance fluidity.
- Agglomerate the products of degassing and float them out of the molten metal.

In actual practice, degassing adds can cause more harm than good either by increasing the non-metallic inclusion count, thus causing fluidity and mechanical property problems, or by putting elements such as silicon above the specification. This is especially true in master alloy manufactured using induction melting and AOD refining which is characterized by excellent metallurgical cleanliness and low total gas content. In other instances, degassing additions are made to alloy systems which do not require degassing due to their tolerance for dissolved gas. Also, some degassing adds which work effectively in one alloy or alloy system will perform marginally or create definite problems in another. An example of this is shown in Figure 34.

Figure 34. Surface characterization present on Type 416 w/Se stainless after degassing with CaMnSi. Selenium-containing stainless steels cannot tolerate calcium-containing degassing adds.
Figure 35 lists the alloy systems and their relative accommodation of dissolved gas. Those listed as "low" most often require degassing, while those of "moderate" accommodation may require degassing upon successive remelting. Those listed as "high" most often can be melted and poured without degassing additions. Many studies have shown better casting surface characterization with less rework required on castings produced from melts without degassing adds. Obviously, one must make a decision based on experience.

DESLAGGING METHODS

Slag is composed of metallic oxides, some simple, some complex, which due to their density tend to "float". This is in contrast to nitrides which have similar density to molten metal and form intermetallic compounds. In general, remelted alloys always contain a greater quantity of non-metallic oxide inclusions as compared to the materials from which the melt was found. The origin of these "slag" inclusions can be from one or more of the following:

- Quality of the melting stock.
- Interaction with the atmosphere.
- Interaction of the melt and furnace and/or transfer ladle refractories.
- Additions made.

The formation of oxide (slag) inclusions reduces the molten metals fluidity, causes "black-spot" defects on polished and critical surface castings, and may lead to massive slag defects such as those pictured in Figures 36 and 37. It was stated earlier that melting is, to some extent, a refining operation. Steps can be taken to minimize the potential detrimental effect of non-metallic oxide (slag) inclusions.

![Figure 36. Massive slag defects associated with a CF8M casting.](image1)

![Figure 37. Massive slag defect in a WCB casting.](image2)
Significant differences exist in the density of the molten metal and contained non-metallic oxide (slag) inclusions, as shown in Figure 18. Allowing time with the power-off between melting and pouring, for the non-metallic oxides to float to the surface, will suffice for more efficient "skimming off" of the slag. Commonly, slag "grip" or "grabber" is used, especially in conjunction with "watery" or silaceous slags, to render the slag viscous (sticky) such that effective removal is possible with ordinary skimming techniques. Two areas of caution; first, the material from which the slag "grip" is made is often high in calcium, thereby creating the potential for large sulfur or selenium losses if used on free machining grades of steel such as type 303 and 416. Secondly, as with any addition to a melt for refining purposes, it is not always possible to remove all of the material added from the melt, thereby increasing the potential for defects.

After using careful deslagging, many precision casters may find poorly characterized casting surfaces due to very fluid silaceous slag such as that shown in Figure 38. The cause of this problem in many occurrences can be traced to the use of small silica crucibles used for transfer ladles in many precision casting foundries. The relative low cost and high thermal shock resistance, which allows them to be put in and taken out of shell preheat ovens, finds them in common use. Unfortunately, high quality, low oxygen molten metal can cause a breakdown of this crucible, leading to silaceous slag formation.

Figure 38. CF8 casting with silaceous slag defects.

POURING PRACTICE

The capacity to fill a shell is related to an alloy's fluidity, its solidification and cooling characteristics. It is not related to either viscosity or surface tension (Ref. 5). Fluidity, solidification, and cooling characteristics are temperature related, and thus, metal delivery (pouring) parameters such as the height and speed of pour affect filling as they affect the temperature gradient within the shell. In this section we shall review the foundry-related practices which contribute to maximizing the percentage of quality castings. Those that are of direct concern are 1) Pouring Height, 2) Pouring Speed and 3) Filtering.

Pouring Height

The height above the pouring cup at which the metal is poured affects the velocity of the stream and the positions at which metal enters the shell. In general, the higher above the pouring cup a metal stream originates, the greater the gas absorption of the stream and the greater the amount of turbulence and gas aspiration into the shell. The accuracy of pouring down the sprue is reduced, and the potential for cold "shots" is increased. However, with accurate pouring down the sprue, increased height has produced acceptable castings where less height would not due to the creation of an effective higher metal head.
Pouring Speed

The speed at which the metal is delivered to the shell depends on whether or not it is desirable to have uniformity of temperature throughout the shell and riser initially. If uniformity is desired, then it is poured fast, which minimizes sensitivity to hot tearing due to the low thermal gradient. Conversely, pouring slowly establishes a high thermal gradient, which, while detrimental to hot tearing, helps to assure casting soundness by establishing directional solidification back towards the riser (Ref. 6).

Unfortunately, the two rates of pouring both offer advantages and disadvantages. The actual rate used must take into account the alloy type, gating system, bottom or top feeding, venting, susceptibility to hot tearing, shrinkage and the complexity of the part itself. In general, a compromise is reached by pouring fast and establishing a thermal gradient through exothermic usage, or conversely by pouring slowly and using a fluidized bed or kaowool wrap to minimize the thermal gradient.

Filtering

In producing high price, complex precision castings, it is advantageous to employ any method which will increase yield and/or reduce rework (if allowed), if it is cost effective. It is common knowledge that non-metallic oxide inclusions originating from the melt, furnace and ladle refractories find their way into the castings in spite of efforts to the contrary. Recent advances in filter technology offer choices to the precision caster which include pre-formed filters which fit into the pouring cup or gating system. These involve slotted, foam or extruded (honey-combed) varieties which are designed to filter our non-metallic oxide inclusions.

Unfortunately, filter efficiencies and thermal shock resistance are not that impressive in many cases, and in some, the large non-metallic oxide inclusions are filtered while many small ones originating from filter erosion are added. Filters are being used to minimize slag-related defects in castings which would be better served through an upgrading in melting stock and/or melting procedures. Figure 39 illustrates one proven filter concept which has been shown to be cost effective upon evaluation in demanding aerospace parts.

CONCLUSION

Life in a precision casting foundry would be pleasant, indeed, if molten metal remained unaltered in composition so that melting and pouring was all that was needed. Unfortunately, metal is altered in chemistry and foundry-related properties upon melting due to interaction with the refrac-

Figure 39. Slotted filter designed to be placed in the pouring cup prior to pouring. Holes and slots are available in various sizes.
tories and atmosphere it comes in contact with. In addition, pronounced differences in casting quality can be obtained at different superheats, pouring heights and speed. Our goal then is to maximize foundry practices for efficiency, productivity, casting integrity and yield using the principles developed in this paper.

Using as examples the castings shown in Figures 2 and 40, a typical approach can be critiqued. In general, castings of small and/or thin sections, especially deep, thin sections, are poured with high superheats (greater than +300°F (149°C) superheat as delivered to the shell). Even then, difficulties with fill are encountered and misrun is prevalent. Increasing the superheat even more may not enhance filling, which can be a source of puzzlement and frustration.

A better approach is to take the fundamental principles which have been stressed in this paper and apply them to the filling problem. First, is it not true that increasing the superheat only increases molten metal fluidity and its ability to fill the shell only if the molten metal gas level, non-metallic inclusion content and chemistry (primarily, silicon) remain constant? Secondly, is it not also true that introduction of metal at greater superheat causes greater gas aspiration from the shell upon pouring, thereby creating additional resistance to filling? Questions now are raised as to whether the increase in fluidity due to extra superheat has been offset by increased gas absorption, non-metallic inclusions and silicon loss.

Yes, one could degas, deslag and add back the silicon, but each of these steps alone leaves the potential for extraneous defects to occur and mistakes to be made. The goal here is to use the basic laws of physical chemistry to simplify the foundry procedures and obtain high quality and yields of castings with less rework required.

An alternate approach, and one which is consistent with respect to the principles brought forth, is to minimize the superheat temperature, which in turn will minimize fluidity loss due to absorbed gas, non-metallic inclusion increases and silicon loss. In addition, upon pouring, gas aspiration is reduced, thereby enhancing filling and surface quality even further. This practice maximizes fluidity without excessive superheat, while at the same time, allows for increased productivity and lower melting costs due to less kilovolt (KW) consumption and improved refractory life. In addition, significantly less feeding is needed so that the gating system can be reduced, thereby enhancing efficiencies even further.

In light of the above discussion, it is obvious that the use of a high quality melting stock will significantly simplify the melting process. The fundamental principles discussed are consistent with high quality melt stock, such as induction melted, AOD refined material, to assure the preservation of quality.
in the metal poured. By starting with a material low in gas, low in non-metallic inclusions and with chemistry optimized, the foundry operation can be as simple as melt and pour (Ref. 7). Add to this, an argon cover gas over the furnace, such as that shown schematically in Figure 41, and further gains in element retention, metallurgical cleanliness, minimizing gas absorption and fluidity can be realized.

Therefore, for maximum efficiencies, productivity, casting integrity and yield in a precision casting foundry, it is suggested that the melter start with high quality melting stock and protect that quality through application of the basic principles discussed in this paper. Consistent foundry practices developed from an understanding of these basic principles will result in quality castings.

REFERENCES


