Chapter 2

Theory and Background Details

As discussed in previous chapter, all casting processes are measured for their efficiency mainly against their rejection rate for parts due to defects directly related to casting process variables. Reduction of this problem is then main purpose of every foundry. There are many reasons related to casting defects across all of the casting industry. Some of the major defects observed in general foundry area are discussed in brief as below. Main defects related to manual pour method in investment casting process are discussed further later. Also, difference of fluidity and and cooling rates for steel alloys used compared to high carbon and high silicon elements in investment casting in investment castings is discussed. This will help to clarify necessity of changes to conventional bottom pours system to uses it for lo thermal masses of steel and investment casting process.

2.1 Brief Defect Review and Examples of Defects in Casting Processes

A properly designed casting, a properly prepared mold and correctly malted metal should result in a defect free casting. However, if proper control is not exercised in the foundry sometimes it is too expensive a variety of defects may result in a casting. Fig. 2.1 shows a fish bone diagram for cause of effects.

Figure 2.1: Fishbone diagrams for defects in castings [37]
These defects may be the result of

1. Improper pattern design.
2. Improper mold and core construction.
3. Improper melting practice.
4. Improper pouring practice.
5. Because of molding and core making materials.
6. Improper gating systems.
8. Inadequate melting temp and rate of pouring.

It creates a deficiency or imperfection.

1. Casting defects are often very difficult to characterize due to the intrinsic complexity of the casting process.
2. All defects will fall into one or more of the established categories of casting defects.
3. The proper identification of a particular defect is the prerequisite to correcting and controlling the quality of castings.
4. The nature of a casting defect can only be determined by correctly categorizing the shape, appearance, location and dimensions of the defect.
5. Once appropriately classified, the possible causes can be examined and the corrective action can be taken.

2.1.1 Generalised Defects in Casting[37]

Main reasons of casting defects are related to following prepossess in any foundry. But pouring process consistency and method is one of the the major factors for some common defects described below.

1. Gas defects
2. Shrinkage cavities
3. Molding Material Defects
4. Pouring Metal and Metallurgical defects
2.1.1.1 Gas Defects

1. Blow Holes and Open Blows

- Cavities, mostly with smooth walls; bright or oxidised.

- In the case of large blowholes with corrugated walls too as shown in fig. 2.2. Always spherical form, even in large expansions (then always flat cavities). Frequently accompanied by slags and oxides.

![Figure 2.2: Blow holes/Open holes](image)

- **Typical characteristics:** Of rounded shapes, location always in the upper part of the castings and beneath cores or undercuts. Seen in the form of Individual blowholes or in large accumulations, mostly with different sizes.

- **Preferred defect locations:** Usually found in casting areas at the top of the mould. Often above larger cores. Found in thick parts, but also in thin walls. Found beneath undercuts and large cores. Apart from presence of moisture, they occur due to poor venting and lower permeability of the mold.

2. Air Inclusions

- The atmospheric and other gases absorbed by the molten metal in the furnace or during the flow in the mold, when not allowed to escape would be trapped in the casting and weaken it as shown in fig. 2.3
• High pouring temperature increase the amount of gas absorbed.

• Due to poor gating design such as straight spruces in unpressurized gating, abrupt bends and turbulence causing practices in the gating which increase the air aspiration.

• Low permeability of the mold itself.

3. Pin Hole Porosity

• Agglomeration of small, rounded cavities up to around 5 mm in size. Surface of the cavities mostly smooth and polished, occasionally with graphite. clearly visible pinholes in the casting skin; surface is often oxidised as shown in fig. 2.4

• Typical characteristics: All cavities have the same size and the long form is always oriented perpendicular to the surface, arranged at outer edges in the line bisecting the angles.
• **Preferred defect locations:** Outer edges and corners, as well as work piece surfaces, defects always in the immediate vicinity of the surface. Often at mould parting lines or transitions to cores these are mostly arranged like strings of pearls/beads.

### 2.1.1.2 Shrinkage Defects

1. **Internal Shrinkage Cavities**
   - Defect is almost always identifiable during machining as shown in fig. 2.5. Zones of visibly "loose" micro-structure, occasionally sponge-like structure or an agglomeration of numerous small pores.

   ![Figure 2.5: Internal shrinkage cavities [37]](image)

2. **Dispersed Shrinkage**
   - Accumulation of small, crack-like cavities. Only visible after machining. Cross sections up to around 8 mm long and 1-2 mm wide, up to 2 cm deep.
   - All cavities are the same size and always oriented perpendicular to the surface, arranged at the outer edges of the lines bisecting the angles as shown in fig. 2.6.

   ![Figure 2.6: Dispersed shrink[37]](image)
2.1.1.3 Molding Material Defects

1. Cuts and Washes

- Sand washout, combined with sand and/or slag inclusions because of low strength or molten metal flowing at high speed as shown in fig. 2.7

![Figure 2.7: Cuts and washes [37]](image)

- **Preferred defect locations:** Mostly close to the gate or on edges, which tend to heat.

2. Run Out

- During the casting, metal runs out of the box at the parting as shown in fig. 2.8

![Figure 2.8: Run out [37]](image)

- **Typical characteristics:** Casting is incomplete or fully missing.
- **Preferred defect locations:** The upper part of a casting is mostly missing.
3. Rattails

- Defect involves a sand expansion defect, which can frequently occur in highly compacted parts of the mould as shown in fig. 2.9.

![Figure 2.9: Rattails [37]](image)

- **Typical characteristics:** Scratches appear on the surface of the casting, which can be partly arranged in parallel.

- **Preferred defect locations:** On areas of the mould cavity covers but primarily on the bases. Most of the times identified on the surface in the cast condition.

2.1.1.4 Pouring Metal and Metallurgical Defects

1. Mis-Runs

- Metal unable to fill the mold cavity completely as shown in fig. 2.10.

![Figure 2.10: Mis run [37]](image)
2. Cold Shut

- Cold shut is caused when two metal streams while meeting in the mold cavity do not fuse together properly, thus causing a discontinuity or weak spot as shown in fig. 2.11.

![Figure 2.11: Cold shut [37]](image)

3. Cold Shot Inclusion/ Spray Bead

- Spray beads are pearl or bead shaped inclusions, which are only loosely bonded with the metal. They are partly already visible at the surface, they are often not exposed until the machining as shown in fig. 2.12.

![Figure 2.12: Cold shot Inclusion/Spray bead [37]](image)
The beads are created by turbulence's during casting or by the effect of spray in the mould, metal particles prematurely solidify in drip or spherical form. These splashes oxidise very easily and the oxide skin prevents the spray beads from being re-incorporated by the subsequent melt flow.

4. Slag Inclusion

- Irregular inclusions or cavities left behind by inclusions, which have fallen out. Mostly on the surfaces in the top of the mould. Frequently grouped together with gas cavities, often with particles of mould material too. Tough slags often form lumps, the easily fusible slags float that upwards in the mould form skins, which at times can separate the whole casting wall. Occasional lustrous carbon on slag skins as shown in fig. 2.13.

![Figure 2.13: Slag inclusions [37]](image)

**Typical Characteristics:** Glassy inclusion, several phases can be frequently identified under the microscope. Skins wrinkled or creased, often bonded with a large number of mould material particles (scar like arrangement)

**Preferred defect locations:** As coarse slags at places which were in the upper part of the mould and under large area cores and core prints. Scar shaped finely distributed, frequently in the direction of flow on the surface of the work piece. As slag skin often running in a transverse direction to the casting wall. Occasionally relatively coarse slags inside castings too.

5. Hot Tears

- Material partition in liquid /solid state, which occurred as the stresses, which occurred in the casting in the area of the elastic deformations, were larger than
the strength of the material.

- Stresses can occur in case of uneven cooling conditions (differences in wall thicknesses). Special design of the casting can prevent contraction, shrinkage onto the core. Hot cracks primarily occur in steel castings as shown in fig. 2.14.

![Figure 2.14: Hot tears](image)

- **Preferred defect locations:** At sudden, steep transitions in wall thicknesses. At wall thickness transitions with too small radii.

6. **Dross**

- It is an irregularly shaped interruption in the material as shown in fig. 2.15.

![Figure 2.15: Dross](image)

- **Typical characteristics:** Dark scars, foamy dark surfaces, very finely distributed. Dross worsens the mechanical properties. Dross mainly consists of magnesium.
oxy-silicates and magnesium sulphides, and is a product of the reaction of magnesium with oxygen, sulphur and silicon.

7. Inclusion of Foreign Metal

- Material not homogeneously formed.

- Typical characteristics: These are visible irregularities in the micro-structure as shown in fig. 2.16.

- Preferred defect locations: Found on the inside of the casting, partly extending out to the surface too. During machining, the inclusions are worn down by the machining tool.

![Figure 2.16: Inclusions of foreign metal [37]](image)

8. Manifestation

- Roughness must be assessed relative to the grain size of the casting selected. Under certain circumstances a work piece cast in coarse sand with fully uniform surface must be assessed as being smooth, although it is rougher than a “rough area” on a work piece cast in fine grained sand.

9. Rough Casting Surface / Roughness

- Roughness must be assessed relative to the grain size of the casting selected. Under certain circumstances a work-piece cast in coarse sand with fully uniform surface must be assessed as being smooth, although it is rougher than a “rough area” on a work-piece cast in fine grained sand as shown in fig. 2.17.
As seen above most of these defects are common in castings, pouring method is one of the main reason associated with these defects. Optimized pour method and variables will definitely reduce most of these defects. In our work we will concentrate on specific investment casting foundry process and related defects, namely cold shunts and inclusions related to pour process and variables related to it. In the sub chapter 2.1.2. importance of fluidity for low carbon steel is discussed for the reasons they can not be poured for conventional bottom pour method.

### 2.1.2 Fluidity Difference in SS 304, Cast Iron and Brass, (For Comparison Only)

As mentioned earlier investment castings are mainly used with alloy steels like stainless steel grades like SS 304, SS 304L, CF8 etc. In this study we are considering SS 304 as our experimental alloy. Following table 2.1 shows the Chemical Composition of SS 304, Grey Cast Iron (HT 200) and Brass (Yellow) grades for some common alloys some of which affect fluidity of molten metal namely Si and C and Al.
Table 2.1: Chemical composition of SS 304, HT 200, Al-Sil2

<table>
<thead>
<tr>
<th>Chemical Composition</th>
<th>SS 304</th>
<th>Grey Cast Iron (HT 200)</th>
<th>Brass (Yellow)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>0.08 % Max</td>
<td>3.4-3.9 %</td>
<td>-</td>
</tr>
<tr>
<td>Manganese</td>
<td>1.50 % Max</td>
<td>0.5-0.8 %</td>
<td>-</td>
</tr>
<tr>
<td>Silicon</td>
<td>1.50 % Max</td>
<td>1.6-2.0 %</td>
<td>-</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>0.040 % Max</td>
<td>0.15 % Max</td>
<td>-</td>
</tr>
<tr>
<td>Sulphur</td>
<td>0.040 % Max</td>
<td>0.12 %</td>
<td>-</td>
</tr>
<tr>
<td>Nickel</td>
<td>9.0 - 12.0 %</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Chromium</td>
<td>18.0 - 2.21 %</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>2.0 - 3.0 %</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Aluminum</td>
<td>-</td>
<td>0.15-0.35%</td>
<td>-</td>
</tr>
</tbody>
</table>

As seen in Table 2.1, Carbon % is very less in SS 304 compared to Cast iron (2% and above) and it is clear the fluidity at melting phase is less compared to Cast Iron. Also for non-ferrous alloys like Cast Copper (Yellow brass), Al % is higher (up to 0.35%) and increases fluidity making it more cast-able alloy [48]. Carbon and Silicon addition add more fluidity to base metal iron at molten phase. It is obvious that SS 304 has a tendency to lose its fluidity early in molten phase compared to Cast iron and Brass grades. In general, addition of Si, C and Al results in increased fluidity allowing it more time to solidify and can be poured at a longer time for same thermal mass as of SS304. This is one of the main reasons for not using bottom pour for steel grades. As in the bottom pour system, the area between stopper nozzle and ladle contact being very thin, SS 304 alloy layer at that area freezes rapidly, blocking the flow of the alloy through nozzle.

Table 2.2: Comparison For Heat Transfer Properties and Densities for SS 304, HT 200, Brass (Yellow)

<table>
<thead>
<tr>
<th>Density, Cp, Latent heat of Fusion</th>
<th>SS 304</th>
<th>Grey Cast Iron (HT 200)</th>
<th>Brass Yellow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (gm/cc3)</td>
<td>7.9</td>
<td>7.2</td>
<td>8.5</td>
</tr>
<tr>
<td>Cp (J/g-°C)</td>
<td>0.50</td>
<td>0.46</td>
<td>0.40</td>
</tr>
<tr>
<td>Latent Heat (Kj/Kg)</td>
<td>272</td>
<td>106</td>
<td>168</td>
</tr>
</tbody>
</table>

Table 2.2 shows what happens when iron/carbon mixtures are cooled from liquid to solid. A "Phase" is a form of material having characteristic structure and properties. It is a form of the material which has identifiable composition, structure and boundaries separating it from other phases in the material volume. The diagram below shows the phases present when Fe-C alloys (Carbon up to 7%) are cooled from liquid to solid. The left side of the diagram represents pure iron and the right hand of the diagram represents an alloy with 6.67% C. which result on cooling in the formation of cementite. This is a intermetallic compound (iron carbide-Fe3 C) which although not 100% stable is but is to all practical purposes a stable phase. The phase diagram shown is therefore a meta-stable phase.

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CHAPTER 2. THEORY AND BACKGROUND DETAILS

Now from table 4.3 it is clear that SS 304 has less carbon (0.08% max) compared to Grey Cast Iron Grade HT 200 (3.4-3.9%). This comparison is taken for an example for phase change temperature and time required between solid to liquid phase. So Carbon addition increases the fluidly and in turn casting ability of high carbon iron or cast iron compared to SS 304 for longer time (lower latent heat at lower temperature). So is the same with non-ferrous cast grade of Brass (yellow). It has Aluminum content to increase its fluidity also.

Based on above, two challenges had to be tackled for bottom pour in investment casting process.

1. Insulation of Molten metal in the conventional bottom pour needs to be improved to reduce the heat transfer of SS 304 in molten state with atmosphere as well as ladle coating.

2. Reduce Ladle Size of conventional Bottom Pour Ladle (> 1100 kg so far) with a more easy to use leverage for small thermal masses of steel. This is required as most of the investment casting shells are light (in our study 20 kg on an average) and had to be maximize for 200-300 kg only for practicality of holding molten SS 304 even after special coating and faster pour, to overcome these 2 reasons, modifications were done as needed. Also it the main aim was to see the feasibility of bottom pour with high cooling rate at molten phase and achieve optimization of pour parameters using the same semi-automated system.

Figure 2.18: Iron phase diagram and carbon content [62]
2.2 Introduction to Investment Casting Process

2.2.1 Global Casting Processes and Basic Categorization

Fig. 2.19 shows the types of casting processes used globally for making castings from various materials, metals. It is mainly classified as per mold types namely expendable mold and permanent mold. Expendable mold casting is a generic classification that includes sand, plastic, shell, plaster, and investment (lost-wax technique) moldings. This method of mold casting involves the use of temporary, non-reusable molds.

Non-expendable mold casting differs from expendable processes in that the mold need not be reformed after each production cycle. This technique includes at least four different methods: permanent, die, centrifugal, and continuous casting. This form of casting also results in improved repeatability in parts produced and delivers near net shape results.

Figure 2.19: Types of casting manufacturing processes [41]

2.2.2 Investment Casting Process

Investment casting process is widely used for highly precision as cast products mostly in Aerospace and Automotive industries. Process is also known as lost wax casting process. The investment casting process consists of making wax patterns, making wax tree, put first coat of zircon silica followed by back up coats of shell, de-waxing, preheat of shells and metal pouring followed by finishing processes as shown with conventional flow diagram of the process in fig. 2.1 Shelling first coat of zircon shell and pouring molten metal /alloy are very crucial to the process. These are the origin for the defects in cast products. To achieve best results with this first coat and pouring most of the foundries are using various automation techniques, though for smaller manufacturers it is difficult to adapt
these heavy and expensive available systems. Based on the high precision as cast products, investment casting is the most commonly used yet difficult to control process [7]. One of the process steps is shelling of wax pattern trees. This consists of initial coating of fine zircon slurry. This coating is important for surface quality and heat transfer properties in the process.

To achieve optimum results with this shelling process uniform thickness in all intricacies of the wax trees is required. If this process is not consistent to the optimal set parameters various defects are found in final casting products. Metal pouring is also a critical part of the investment casting process. Multiple variables involved with pouring are, pouring temperature, preheated shell temperature, metal flow consistency, time to fill the mold etc. Inconsistency of these parameters leads to high cost of quality due to rework, scrap increasing lead times [11] for delivery and reduced profits. These problems are worse with manually operated investment casting foundries. In this work, defects related to manual operations in first coat shelling and pouring are discussed. The defects are mainly generated due to inconsistency of the process due to human errors, safety issues etc. In general process follows steps as below.

1. Wax Pattern Making: Making wax patterns of required part shape and size with appropriate shrink related to specific process and is about 1.8% in general except for large or odd shaped features as shown in fig. 2.21. Wax patterns are inspected for wax defects like sag, dimensions or any visual defects like flow lines, surface roughness etc.
2. Wax Assembly: Putting wax patterns in shape of tree called wax tree as shown in Fig. 2.22. It involves metal feeding systems like gating and runner systems. This is a very critical step to avoid any metal related defects due to improper gating.

3. Investing and Stuccoing: After Wax tree is assembled, it is then dipped into Zircon slurry tank to coat it uniformly as shown in Fig. 2.23. It is then dried properly and then dipped again for next layer with higher viscosity and sand shower (Stucco). The process continues till 7-8 layers of shell and a hard mold of shell layers are formed. This is one of the most important processes in investment casting process and variability in the same may cause lots of defects like scalping, roughness, sand inclusions, shell burst/failure during pour etc.
4. De-waxing: After wax tree is shelled or invested, it needs to be de-waxed. This process involves putting wax shells into autoclave with hot steam passing over and through shells as shown in fig. 2.24. This melts the wax inside shell and gives shell without wax and giving exact shape of hollow cavity of wax tree including required parts. After de-waxing, shells are again kept for drying as humidity/moisture introduced due to steam interaction.

5. Firing/Preheating: This is again a critical step and only involves in very few casting processes to reduce the heat transfer from molten metal to mold and atmosphere. In this process, de-waxed shells are put in the gas/oil/electric fired oven to heat them in the range of 900-1000 °C as shown in fig. 2.25 This removes remaining moisture from de-waxing as well and improves permeability of shells. Generally no accurate
control is kept of shell temperature prior to pour as it is based on oven temperature only.

Figure 2.25: Preheating of shells in oven prior to pour

6. Casting/Pouring: Preheated shells are taken out right before furnace metal is ready in ladle to pour. Small foundries generally use hand pour small ladle system as shown in fig. 2.26. This has to be done as fast as possible to reduce heat losses to atmosphere while pouring. This process is very crucial for defects and quality of castings. In this study this process is focused for optimization for variable like melt temperature, shell temperature and pour height. The figure shown is manual pouring method and is used in most of the small scale investment casting foundries.

Figure 2.26: Pouring of de-waxed shells

7. Knockout/Cut-off: After molten metal inside the shells are cooled, then outside silica shell is knocked out by hand or pneumatic hammers as shown in fig. 2.27.
Now the metal trees with runner/gating systems and parts are cutoff to separate parts. This is done usually by welding torch or bansaws.

![Knock out of poured shells](image)

**Figure 2.27: Knock out of poured shells**

8. Finishing: After part separation, excess gating material is removed by hand grinding or buffing as shown in fig. 2.28. Once finished and visual defect parts are removed from the lot, parts are shot/sand blasted as required to give finished parts.

![Finishing/De-burring of knock out castings](image)

**Figure 2.28: Finishing/De-burring of knock out castings**

9. Quality inspection: After finishing process, quality department checks the parts as per quality plan given by the customer as shown in fig. 2.29. It usually involves checking of critical dimensions, hardness check, NDT inspection and correctness of process parameters related to specific part.
As seen from fig. 2.21 to fig. 2.29, it is observed that all these process can be automated but in this work we will be focusing on simple and economical automation techniques in the pouring process.

### 2.2.3 Defects Related to Manual Pour in Small Investment Casting Industry

When history was checked for the bottom pour it was realized that is used commonly for specific industries and advantages of this process are limited only to those certain alloys and big casting industry only. Things needed to be studied and analyzed why it is not been used for smaller mass of metal and still get advantages of the process. When survey was done for smaller investment casting foundries (< 100 T/Month), it was found that pouring was done by manual method using crucibles, tea pot ladles etc. Typical crucible pouring method is show as in fig. 2.30a and fig. 2.30b. These type of practices lead to main defects like inclusions and cold shuts.
As discussed before in brief, Inclusions are produced mainly due to,

1. First Dip Inconsistency
2. Insufficient Drying of First Coat
3. Slurry Mixture Consistency (Zircon Shell Content & Fluidity)
4. Scalping of First Coat in De-wax causing slurry particles in shell
5. Foreign material present in Preheated Shell While Pouring
6. Handling of shell issues (i.e. Pour Cup left open in shop)

Similarly Cold Shuts are produced mainly due to Inconsistency of Pouring Temperature Control

1. Inconsistency of Pouring Angle
2. Inconsistency of Pouring Height
3. Inconsistency of Pour Time (Pour Rate)
4. Inconsistency of Preheated Shells
5. Critical (intricate) areas of shell getting colder faster
6. Thin Sections in castings

Based on above and literature survey it was interesting that these defects are mainly related to manual shelling and pouring process in investment castings. Although Shelling is been done with automation in bigger Investment casting foundries, bottom pour was
hardly ever tried in Investment casting process. It was mainly due to alloys used in Investment castings are mainly steel, Stainless steel or super alloys and had a real fast cooling curve compared to alloys like cast iron, brass, copper, bronze etc.

It was interesting to see if bottom pour can be used for investment casting Industries with some different bottom pour ladle system and some automation techniques included to ease the operation of the bottom pour. Bottom pour might give better quality castings and remove human errors caused by high temperature and natural errors. Currently most of the small scale investment casting foundries is using hand pour as shown in fig. 2.31 and fig. 2.32 as above. So use of crane, control of pour flow using modified bottom pour system was a motivating factor to see if inclusions and cold shuts can be removed taking advantages of widely used bottom pour method in other types of bigger foundries and different alloys.

2.2.4 Bottom Pour and Investment Castings

As seen & discussed, it is clear that inclusions and cold shuts are main defect in Investment castings. So far Investment casting manufacturers have not used bottom pour process for production mainly for the reasons below,

1. Investment casting uses super alloys of steel mainly with melting point between 1530-1570 °C. Taking high super heat on these alloys is not advisable due to oxidation as well as safety reasons.

2. Most of the super alloys with Ni and Co have very high cooling curves, i.e. tendency to lose the temperature very rapidly.

3. Usually Investments casting size or tree size is smaller than large cast iron or Aluminum grade alloys made by green sand method casting process. So as
From points 1-4 above it is obvious that we need a specific refractory material to significantly reduce the heat transfer rate between molten metal to atmosphere and to the inside coat of the ladle. Also we need faster transfer of molten metal in ladle to shell with constant flow for each pour. There is also a need of sophisticated temperature measurement equipment to exactly measure shell preheat temperature prior to pour process starts.

To do so following simple automation techniques and methods are suggested,

1. Crane/Conveyor is needed to operate the bottom pour system which is independent of manual movement causing ease of movement.

2. Special design of bottom pour ladle for low thermal masses (<400 kg capacity) is required.

3. Special insulation ceramics is needed to reduce heat transfer of molten metal to atmosphere compared to traditional bottom pour ladles.

4. Automatic exact indirect temperature measurement is needed to reduce errors in temperature measurement. This is applicable mainly to temperature of preheated shells coming out of firing oven just prior to pour.

Next chapter discusses about the literature review regarding current automation already in use for casting industry. Work done related to investment castings shells heat transfer properties that is related to objectives defined in introduction chapter are also discussed.