Chapter 2

Mechanisms of Leaker Formation as Discussed in Published Literature

2.1 Introduction

A problem in the form of castings rejected due to lack of pressure tightness has been identified, it remains to find possible solutions to this problem within the published literature.

Leakers in castings can be caused by a wide range of common casting defects. In order to understand the formation of leakers the mechanisms of formation of these defects must first be identified.

Currently the most concise report dealing specifically with the formation of leakers was written by LaVelle in 1962 [1]. This paper leads through three steps necessary in the understanding and control of leakers;

- Determination of possible causes of leakers.
- Identification of most likely causes for a given example.
- Application of methods to reduce the occurrence of the most likely causes.

These steps form a solid framework within which a logical and more complete guide to the mechanisms of leaker formation in high pressure die casting can be found.

2.2 Determination of Possible Causes of Leakers

Within all the papers dealing with the subject of leakage formation there is general agreement with the following statement.

To allow leakage to occur a path must exist through each surface layer and the centre of the casting. A mechanism for leaker formation may refer to a defect that allows a path through any one of these three layers on the condition that the other two already allow passage of fluid, or it may refer to a single defect that traverses all three of these layers. A number of other combinations are possible.

The reason for breaking the casting up into these three regions is the widely held belief that the structure of the cast alloy varies significantly between these regions. This is due to the manner in which high pressure die casting cavities are filled by the molten alloy and the thermal forces acting on them during solidification. While no one disagrees with this statement and the weight of evidence suggests that it is true, the extent of structural variation and the thickness of the layers will vary greatly depending on the casting design and the conditions under which the casting was made.

Nonetheless, a “typical” high pressure die casting will consist of two relatively sound surface layers formed when the first jets of incoming molten alloy coat the die surfaces, and a more porous inner region formed as the remaining alloy fills the central parts of the casting and solidifies. When using a die casting alloy such as CA313 this central region is characterised by interconnected shrinkage porosity formed as the eutectic portion of the alloy shrinks upon solidification and is unable to completely fill the voids between the already formed dendrites. Thus, in the words of Walkington [2];

“The shrinkage cracks inside the casting that were formed at the last point to solidify may be interconnected and can form a path through the centre of the casting. Thus any defect that will provide a path for gas to get through the skin is a potential candidate for causing leakers.”

A small number of published papers discuss the formation of leakers, making reference to a number of defects that will allow such passage of fluid through the various parts of the casting. Table 2 .1 summarises, in alphabetical order, the possible causes proposed by LaVelle [1], Walkington [2], Holz [3], and Murray [4].

Cold Flakes
Cold Shuts
Drag Marks
Gas Porosity
Oxide Films
Particulate Inclusions
Secondary Operations that Remove or Damage the Surface Layer
Shrinkage Porosity
Soldering
Surface Cracks

Table 2.1 Summary of Possible Causes of Leakers Found in Published Literature. [1, 2, 3, 4]

Using previous work in the field, the first of three steps in understanding and controlling the formation of leakers has been completed. To complete the next two steps our knowledge of each of the potential causes listed in Table 2 .1 must be furthered. For each potential cause the following questions are to be answered:

- Under what conditions and in what manner is a given cause likely to cause a leaker?
- What mechanisms govern the formation of a given potential cause?
- What strategies exist for reducing the occurrence of a given potential cause?

With this knowledge and an ability to accurately identify each defect type the second and third steps in understanding and controlling leaker formation become possible. The following section seeks to answer these three questions for each potential cause of leakage.

2.3Understanding the Possible Causes of Leakers.

2.3.1Cold Flakes

Mechanisms of Leaker Formation due to the Presence of Cold Flakes

Cold flakes may lead to leakers in one of two ways.

- A cold flake entering the runner system may become lodged in the gate. This will change the metal flow through the gate leading to changes in metal flow throughout the entire cavity. Such a change in the flow pattern may lead to the formation of cold shuts in areas of the casting. Leakers due to cold shuts are discussed in full in Section 2.3.2.
- Cold flakes that pass through the gate will not be re-melted by the surrounding alloy [5] and thus a discontinuity will be present within the casting. The possible effects of these discontinuities are discussed now.

Iwahori et al [6] discuss the “remarkably low interfacial strength” between cold flakes lodged in the casting and the surrounding alloy. This low strength may lead to cracking along this plane under the influence of solidification or ejection stresses. A crack such as this may be of sufficient size to lead leakage. Figure 2 .1 shows a case where fracture has occurred along a cold flake during tensile testing. Iwahori et al [6] give another example where a cold flake in the casting lead to cracking under stresses caused by ejection.

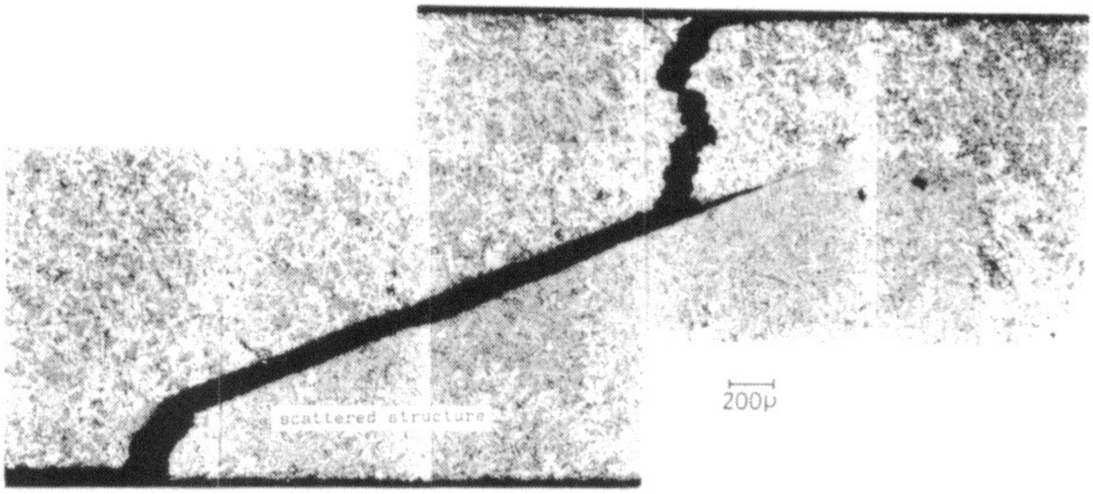

Figure 2.1 Fracture Along the Face of a Cold Flake [6]

Walkington [2] discusses the effect of these cold flakes when stresses applied do not lead to cracking. Even in this case it is thought that the discontinuity along the face of the flake may be sufficient to provide a path for leakage through part of the casting. Walkington specifically mentions cold flakes lodged in the surface layers providing a passage through this critical region.

Mechanisms Governing the Formation of Cold Flakes

The formation of cold flakes is well described by Iwahori et al.

"When molten metal is poured into the shot sleeve and is brought into contact with the wall surface of a shot sleeve, it is rapidly cooled, forming solidified layers on all surfaces, and then the solidified layers are dislodged by the plunger when the molten metal is injected. These layers are fractured, and then incorporated into the molten metal..." [6]

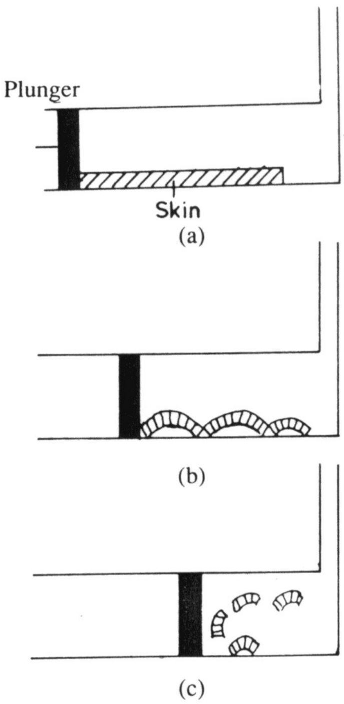

Figure 2.2 Mechanism of Cold Flake Formation [7]

Figure 2.2 shows the formation and subsequent breaking and dispersion of a skin layer. This skin layer forms due to the low temperature of the shot sleeve. Iwahori et al showed using thermocouple measurements that the heat lost by the molten alloy to the shot sleeve is the most significant mode of heat loss prior to entry to the cavity. This is demonstrated in Figure 2.3. We see that in their experiments the temperature of the alloy drops rapidly upon entry to the shot sleeve. At this lower temperature solidification will begin within the shot sleeve. The rate of heat loss is dependent on the surface area to volume ratio of the poured alloy and the relative temperatures of the two surfaces. The conditions used in Iwahori et al's experiments are representative of conditions in many common castings so we can assume that in the vast majority of castings solidification will begin on the shot sleeve walls and cold flakes will be present to some extent.

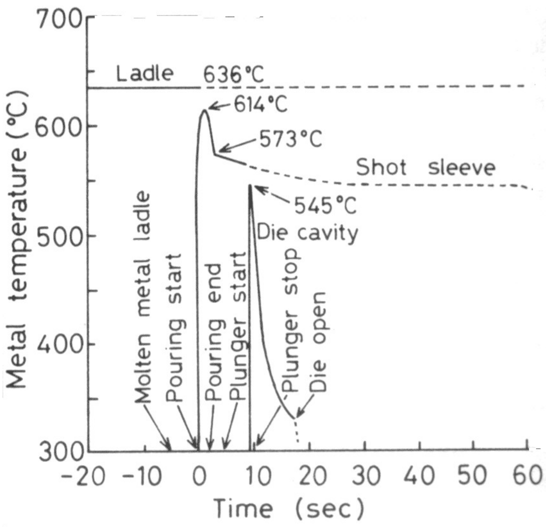

Figure 2.3 Heat Losses From Alloy During Casting Cycle [6]

Whether these cold flakes form problems within the casting either due to gate blockages or planes of weakness within the cavity will be determined by the size, number, and distribution of these cold flakes.

Murray [8] states that in some instances increasing the size of the cold flakes may improve the quality of the casting as the larger flakes may be trapped early in the runner system, avoiding problems caused by cold flakes blocking the gate or cold flakes in the casting itself. This goes against the conventional logic of reducing the size and extent of cold flakes, highlighting the fact that the best strategy for reducing the effect of cold flakes on casting quality is very case specific.

Modeling and measurement of the temperatures along the shot sleeve indicates that the temperature of the shot sleeve varies along its length. This raises questions of whether cold flakes formed near the plunger end of the shot sleeve will have a different effect to cold flakes formed near the runner end of the shot sleeve. Due to different temperatures along the length of the shot sleeve the size of cold flakes will also depend upon where they are formed within the shot sleeve.

Strategies for Reducing the Formation of Leakers Due to the Presence of Cold Flakes

Taking the approach that a reduction in the total amount of cold flakes formed will reduce the occurrence of leakers caused by blocked gates or cold flakes lodged within the casting, we have the following approaches available.

- **Increasing the shot sleeve temperature,** by appropriate use of insulation and/or heating, or redistribution of cooling, will lessen the heat transfer rate from the alloy to the shot sleeve.
- **Increasing the metal pouring temperature** will increase the amount of heat the metal can lose before cold flakes form. Due the extra heat that will be removed by the shot sleeve, the equilibrium temperature of the shot sleeve will also increase.
- **Decreasing the settling time in the shot sleeve** will lessen the amount of heat lost before the alloy is injected. Thus the size of any cold flakes will be reduced.
- **Increasing the shot fill ratio** by;

1. reducing the volume of the shot sleeve by using a smaller diameter shot sleeve or introducing a longer sprue post, or
2. increasing the shot weight,

will decrease the surface area to volume ratio of the molten alloy.[1] This will lead to a reduction in the heat lost by the melt as a proportion of total heat, thus reducing the amount of cold flakes.

If it where found through experimentation or carefully considered design that a strategy of increasing the size of any cold flakes will lead to a reduction in the amount of leakers, then the above strategies could be reversed.

2.3.2 Cold Shuts

Mechanisms of Leaker Formation due to the Presence of Cold Shuts

In essence, a cold shut is a visible discontinuity in the casting. A discontinuity provides a void through which a fluid may leak, ie. a leaker. In many cases cold shuts

[1]Note that these strategies will work best when the shot fill ration is less than 30%. Reducing the diameter of the shot sleeve may significantly increase the surface area to volume ratio above 80% shot fill ratio. Appendix B presents plots of surface area to volume ration versus shot shot fill ratio which demonstrate this clearly.

are quite shallow, only manifesting themselves in the skin layer, and in such a case a further passage is required throughout the rest of the casting.

Cold shuts are often opened up by solidification stresses or act as crack initiators resulting in larger cracks in the casting, thereby providing a ready path for leakage.

Mechanisms Governing the Formation of Cold Shuts

In its most basic form a cold shut is formed when "the metal streams filling the die cavity begin to freeze before the cavity is entirely filled." [3]. The reasons for this occurring are many and varied but can essentially be broken into two essential requirements;

- A die filling pattern that results in converging metal streams.
- Sufficient heat loss occurring during die filling to cause these metal streams to begin to solidify before they fuse together.

Both of these are related to a variety of die design and process variables. We will briefly discuss the many causes of cold shuts discussed in the literature.

Superficial Cold Shuts Caused by Metal Lamination

These cold shuts are formed when "the first metal to enter the cavity solidifies against the die walls and does not remelt during subsequent filling." [5]. A small discontinuity in the surface of the casting will result from this.

Deep Cold Shuts Caused by Damaged Metal

LaVelle [1] refers to "damaged" metal forming due to turbulence and agitation as the metal streams traverse the cavity. Such turbulence will result in oxides being formed at the head of the stream and some solidification may also occur. When this damaged metal converges with another stream it will be unable to bond properly, leaving a discontinuity in the casting.

These cold shuts will occur at locations filled by metal that has traveled long distances through the cavity . This can be anywhere on the casting depending on the metal flow paths within the cavity.

LaVelle breaks these cold shuts into two groups depending on their location on the casting. For cold shuts occurring at a consistent location distant from the gate it is likely that the cause of the cold shut is the designed flow path within the die coupled with an excessive heat loss during die filling. This excessive heat loss is due to the interaction between the heat transfer rate to the die and the cavity fill times achieved. This interaction is well summarised by Herman [9]. He suggests a formula, Equation 2 .1 , to calculate the "Ideal Fill Time" of a given casting based on a range of thermal parameters. If the actual fill time of a casting exceeds this ideal fill time then the regular occurrence of cold shuts is likely.

$$t = kT\left(\frac{T_i - T_f + SZ}{T_f - T_d}\right)$$ **Equation 2.1 [9]**

where;

t = Ideal filling time, seconds.

k = Empirically derived constant, s/mm. (A measure of the heat transfer rate between the molten metal and the die.)

T_i = Temperature of the molten metal as it enters the die, °C.

T_f = Minimum flow temperature of the metal, °C.

T_d = Temperature of the die cavity surface just before the molten metal hits it, °C.

S = Percentage of solids allowable in the metal at the end of die filling, %.

Z = Constant based on latent heat of casting alloy, °C/%.

T = Typical casting thickness, mm.

The values returned by this equation are of limited use unless the die designer has enough experience with similar castings to make good judgments on appropriate values for the input parameters. However, the list of input parameters provides a good idea of the parameters that will affect the formation of cold shuts distant from the gate.

The other type of cold shuts identified by LaVelle are cold shuts that occur inconsistently at various locations on the castings. These are caused by swirling flow patterns caused by poor runner and gate design or by the partial blocking of the gate. LaVelle's assertion is confirmed by the work of Davis et al. [10] who found that as the extent of gate blockages increased the occurrence of cold shuts was similarly raised. As well as the non uniform and swirling flow that results from the blocked gates Davis et al also note that the blocked gate will lead to an increased fill time. In their later paper [5] Harding et al specify that the highest incidence of cold shuts and gas/shrinkage porosity occurred in areas of the casting that were “back-filled” by the metal streams. Figure 2.4 shows how back-filling will occur on a flat plate casting. We see that a large wedge in the centre of the casting is left unfilled by the incoming metal due to the blocked gate. This area will be back-filled later during cavity filling.

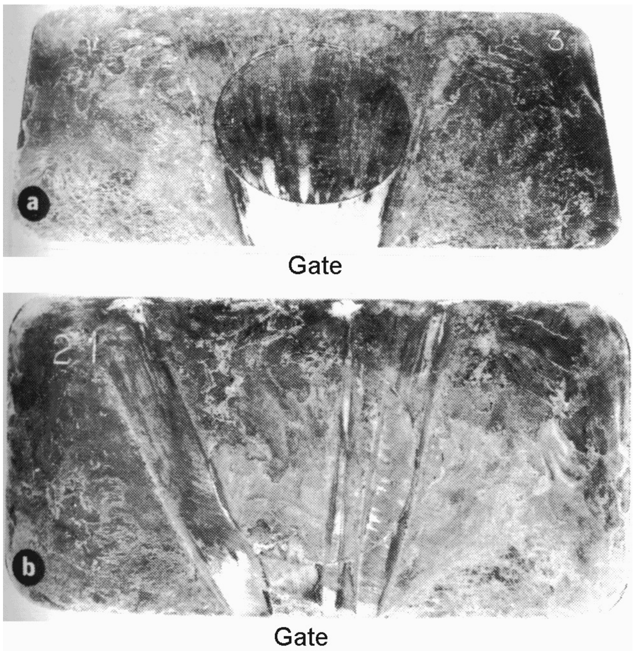

Figure 2.4 Flow Lines on Flat Plate Castings Showing Difference Between Casting Filled by Full Width of Fan Gate (a) and Casting Filled by Partially Blocked Gate (b). [5]

Gate blockages may form in a variety of ways. Harding et al [5] make reference to metal droplets and streams splashing ahead of the main flow and solidifying in the gate before the arrival of the main metal flow. They also noted the formation of a band of fine chilled grains around the periphery of the gate, gradually closing the gate as the cavity fills. Cold flakes, as discussed in the Section 2.3.1, are also a major cause of gate blockages.

The occurrence of cold shuts by any of the above mechanisms will be affected by a number of other factors.

Factors that have been found to affect the formation of cold shuts in zinc castings [11] would also be expected to affect the formation of cold shuts in aluminium castings. The injection pressure was noted as a critical factor in this paper. A low injection pressure will result in a slowing of the plunger leading to an increase in the cavity fill time. The use of overflows to increase the local heat in the die is also noted as a common method of decreasing the incidence of cold shuts in areas distant from the gate.

LaVelle [1] identifies alloy contaminated with oxide inclusions and films as having a reduced fluidity, increasing in the likelihood of cold shuts. This also suggests that the base fluidity of the alloy will have an effect on the occurrence of cold shuts.

Holz [3] discusses the effect of a cracked die allowing cooling water to leak onto the cavity surface. When this water is evaporated a gas pocket will result, retarding the filling of the cavity. Holz also notes that the application of an excessive amount of die lubricant will lead to the formation of gas pockets and thus cold shuts as the lubricant is volatilised. Stuhrke and Wallace [12] refer to the effect that the choice of die lubricant will have on the die heat transfer rate and thus the ideal fill time allowable in the casting.

Strategies for Reducing the Formation of Leakers Due to the Presence of Cold Shuts

The above discussion demonstrates that a large number of factors affect the formation of cold shuts. It is therefore important to carefully consider which of the following strategies are most appropriate in a given case.

- **Changing the metal flow pattern.** Designing the runners, cavity, overflows, and vents in order to minimise turbulence and avoid long flow paths converging at the end of the cavity, as well as allowing efficient venting.
- **Reducing the cavity fill time achieved** will minimise the amount of heat lost by the molten alloy during cavity filling.
- **Increasing the die temperatures** will decrease the rate of heat loss from the molten alloy, increasing the ideal fill time.
- **Increasing the metal holding temperature** will increase the amount of heat the metal may lose before solidification begins, increasing the ideal fill time.
- **Reducing the metal settling time in the shot sleeve** will reduce the occurrence of gate blockages as well as increasing the temperature of the metal as it enters the cavity, increasing the ideal fill time.
- **Increasing the shot sleeve temperature** will reduce the occurrence of gate blockages as well as increasing the temperature of the metal as it enters the cavity, increasing the ideal fill time.
- **Eliminating oxides and other inclusions in the melt** will increase the fluidity of the casting alloy.
- **Selecting a high fluidity casting alloy** will increase the ability of the metal to fill the cavity, increasing the ideal fill time.

- **Correct selection and application of die lubricant** will lower the heat transfer coefficient between the alloy and die and prevent the build up of gases during cavity filling.
- **Avoidance of problems such as excessive flashing or cracked dies by correct process control** will reduce disruption to the alloy flow paths.

2.3.3 Drag Marks

Mechanisms of Leaker Formation due to the Presence of Drag Marks

The formation of drag marks involves damaging the surface of the casting as the casting is ejected. This damage will remove a portion of the casting surface exposing internal shrinkage porosity or other defects. Drag marks also damage the surface of the die leading to problems such as soldering, see Section 2.3.9. The presence of drag marks also indicates that high stresses are occurring during casting ejection, suggesting that problems such as casting cracking may occur, see Section 2.3.10.

Mechanisms Governing the Formation of Drag Marks

Drags marks are a symptom of interference between the casting and the die. This interference causes damage to both surfaces during the sliding motion occurring during die opening, core retraction, and/or casting ejection. Walkington [2] cites build up on the die due to soldering or carbon build up as the most common cause of drag marks. He also lists mechanical problems such as peened over die portions, cracked dies, or bent cores as possible causes. Dies with insufficient draft angles or undercuts will be more prone to drag marks.

Damage sustained by the die will increase the likelihood of drag marks. Neff [13] recommends eliminating hard inclusions in the melt to reduce the amount of abrasion the die undergoes.

Problems similar to drag marks can occur during the trimming of the die. Titone [14] discusses the situation where variation in the dimensions of the casting due to variations in the temperature of the casting may lead to poor fit in the trim press and surface damage of the casting. Trim presses that shear the gates and any flash between the trim press and the face of the casting are more likely to damage the surface of the casting than those which shear the gates between the two halves of the trim press.

Strategies for Reducing the Formation of Leakers Due to the Presence of Drag Marks

- **Designing castings with ample draft angles** will minimise stresses during die opening, core retraction, and/or casting ejection.
- **Using strategies discussed in Section 2.3.9 to minimise the occurrence of soldering and scale build up** will reduce interference between the casting and the die.
- **Eliminating hard inclusions in the melt** will reduce damage to the die due to abrasion.
- **Designing trim presses to shear the gates between the two halves of the press and trimming all castings at constant temperature,** eg. cooling all castings to room temperature before trimming, will reduce damage during trimming.

2.3.4 Gas Porosity

1Mechanisms of Leaker Formation due to the Presence of Gas Porosity

The majority of studied papers discount gas porosity as a common cause of leakers. LaVelle [1] states that in general gas porosity forms in separate bubbles. Unless there is some other mechanism for linking these separate pores it is unlikely that they will assist in the formation of leakers. However, there are papers that present a logical case for leakers caused by gas porosity.

Murray [4] states that as gas pores are randomly distributed, there will be situations in which the pores are linked and leakage may occur. He also cites a specific case of gas porosity where linkage of the pores is highly likely. These gas pores are caused by the volatilisation of liquids present on the die face at the time of metal injection. In this case as the pores are caused by a stream of gas emanating from a particular point on the die, they may well form a chain of gas pores from the surface of the casting into the casting centre.

Holz [3] discusses essentially identical situations but refers to the defects that result as non-fill, ie. severe cold shutting. Due to the resistance offered by the pressurised gas, gaps will be left in the casting. It is a matter of terminology whether these gaps are referred to as non-fill or gas porosity, since the mechanism and resulting defects are the same.

Walkington [2] does not discuss gas porosity as a major cause of leakage but does present Figure 2.5 as an example of a leaker. In this case gas porosity near the gate of the casting coupled with skin removal during machining has lead to the formation of a leaker.

Another possible factor that may affect the likelihood of a leaker being formed is an interaction between the presence of gas porosity and the ability to feed shrinkage porosity. Johnson et al [15] note that gas evolved during the cooling of sand cast gun metal alloys retards liquid metal feeding, increasing the extent of interdendritic shrinkage porosity. This increases the likelihood of a leaker occurring.

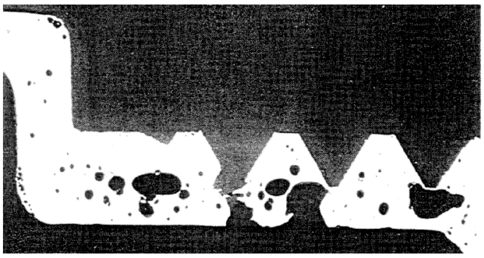

Figure 2.5 "Large Gate Pores ... Exposed by Machining to Create a Leaker." [2]

Some papers on high pressure die casting [16, 12, 1] speculate that the highly pressurised gases present in this form of casting may actually assist in shrinkage feeding. During the application of intensification pressure any gas pores present will be pressurised, allowing them to act as pressure reservoirs when the applied intensification pressure ceases to be effective. Shrinkage feeding will be assisted in the locality of these pressurised pores.

The main difference between these two theories lies in a difference in the pressure of any gas present. A difference in the gas pressure may well affect any interaction between gas and shrinkage porosity. At present, any relationship between gas porosity and shrinkage feeding remains un-proven by published work.

Mechanisms Governing the Formation of Gas Porosity

Gas porosity in high pressure die casting is usually the result of air entrapped in the molten alloy during injection and gas from volatilised liquids present on the die surface [3]. Gas porosity due to dissolved hydrogen released during cooling has very little effect as the high pressures and rapid solidification used in high pressure die casting prevent the formation of any significant pores [1].

Gas Porosity Due to Volatilised Liquids

Die lubricant or cooling water on the die face at the time of metal injection will be evaporated by the incoming molten metal and will be trapped within the casting.

Die lubricant or water will remain on the casting surface after spraying if the amount sprayed on is in excess of the amount that can be evaporated due to the heat in the die. This will happen when an excessive amount of die lubricant/coolant is sprayed onto the die face or when the die is cooler than usual, as is the case during the first few shots of production.

Another mechanism that results in water being present on the die face is the case of a cracked die cavity insert that allows water to leak from the die cooling lines onto the die face.

Gas Porosity Due to Air Entrained in the Metal

Air entrapment can occur in the shot sleeve, in the runner, at the gate, or in the cavity. Gas entrapment in the shot sleeve is due to the waves and turbulence that will occur on the surface of the poured metal when conditions are not optimised. Optimising the conditions involves determining the appropriate amount of settling time after pouring, the correct first stage velocity, the optimum acceleration to reach this first stage velocity, and an appropriate point at which to begin acceleration to second stage velocity. Figure 2 .6 shows the air entrapment that will occur in a shot sleeve when the first stage velocity is too high or too low.

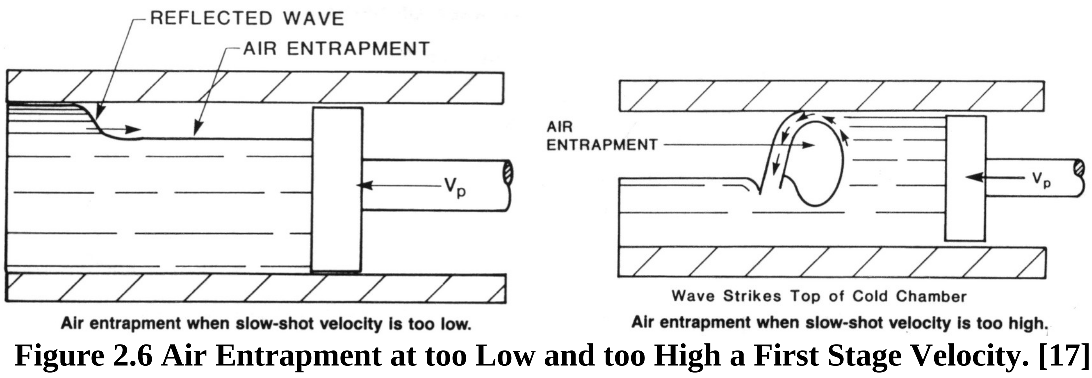

Figure 2.6 Air Entrapment at too Low and too High a First Stage Velocity. [17]

When the first stage velocity is correctly determined and set the wave formed by the advancing plunger will be equal to the remaining height of the shot sleeve, preventing the wave from breaking as for too high a plunger speed or from reflecting off the sprue post as for too low a plunger speed. This wave is shown in Figure 2.7. Plunger velocities that result in this condition were theoretically determined, and experimentally confirmed, by Garber [17] for a range of shot sleeve sizes and various levels of shot sleeve filling.

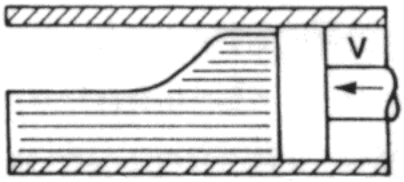

Figure 2.7 Wave Formed at Critical First Stage Plunger Speed. [17]

When the shot sleeve is greater than 50% full it is satisfactory to accelerate the plunger from rest to this critical velocity effectively instantaneously. At shot fill ratios less than 50% it is necessary to control the rate at which the plunger accelerates to this critical velocity. Optimum acceleration profiles were determined by Thome et al [18] using the same principals of fluid flow used by Garber. Their work indicated that for shot fill ratios less than 25% it is very difficult to form a steady wave in the shot sleeve. Figure 2.8 gives the optimum acceleration profiles for a range of shot fill levels. When plunger velocities or accelerations deviate from these optimum values the level of gas entrapped in the molten alloy will increase. Gas entrapped in this early part of the cycle would be expected to become fairly evenly distributed throughout the casting by the time it has passed through the runner and gate.

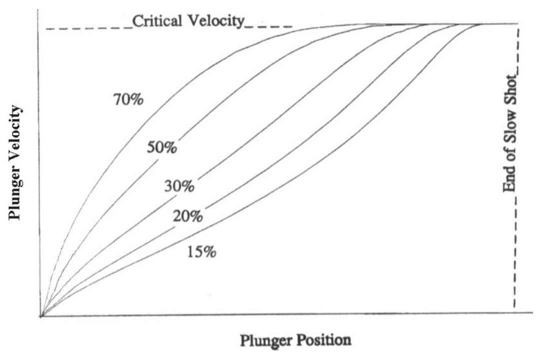

Figure 2.8 Optimum Acceleration Profiles For Different Shot Fill Ratios. Each Plot is Scaled to its Critical Velocity and Plunger Position at Shot Sleeve Full Point. [18]

These theoretical derivations of optimum plunger accelerations and velocities are complemented by approximate formulae presented by Herman [9], Equation 2 .2 and Equation 2 .3.

$v = C\left(\frac{100-f}{100}\right)\times\sqrt{\frac{D}{25.4}}$	**Equation 2.2 [9]**

Where;

v= Critical slow shot velocity, m/s.
f = Percentage of shot sleeve initially filled with molten alloy, %.
D = Plunger diameter, mm.
C = Constant, 0.579 m/s.

and;

$$\text{Acceleration}\left(\text{m/s/m}\right)=1.75+0.01\times\text{Plunger Diameter}\left(\text{mm}\right) \quad \text{Equation 2.3 [9]}$$

The final consideration in the occurrence of gas entrapment in the shot sleeve is the change over position at which the plunger accelerates to high velocity. In order to minimise gas entrapment this needs to occur after the shot sleeve is completely filled, [9].

Air entrapment in the runner system will occur when the runner is not properly streamlined. Herman [9] recommends constantly decreasing the runner area from the sprue to the gate runner. Figure 2.9 shows a case where a poorly streamlined runner and gate will lead to air entrapment and cavitation.

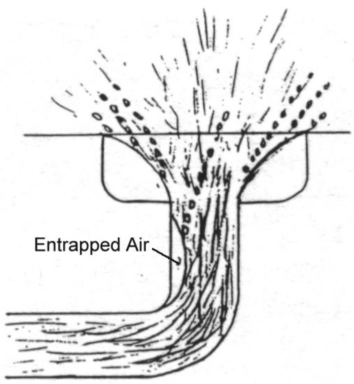

Figure 2.9 Air Entrapment in a Poorly Designed Runner. [2]

Air entrapped at the gate is due to combinations of poorly designed runners and insufficient shot control. In a well designed casting the metal flowing through the gate is atomised resulting in very finely distributed gas porosity [16]. If the casting is improperly designed or the process is poorly controlled then the flow through the gate will be unsteady and uneven gas porosity will result.

Within the cavity itself gas can become entrapped if the venting is insufficient or if the vents are sealed before the cavity is filled [19]. Figure 2 .10 shows how a high speed injection of molten metal may prematurely seal the vents resulting in gas entrapment in the centre of the casting.

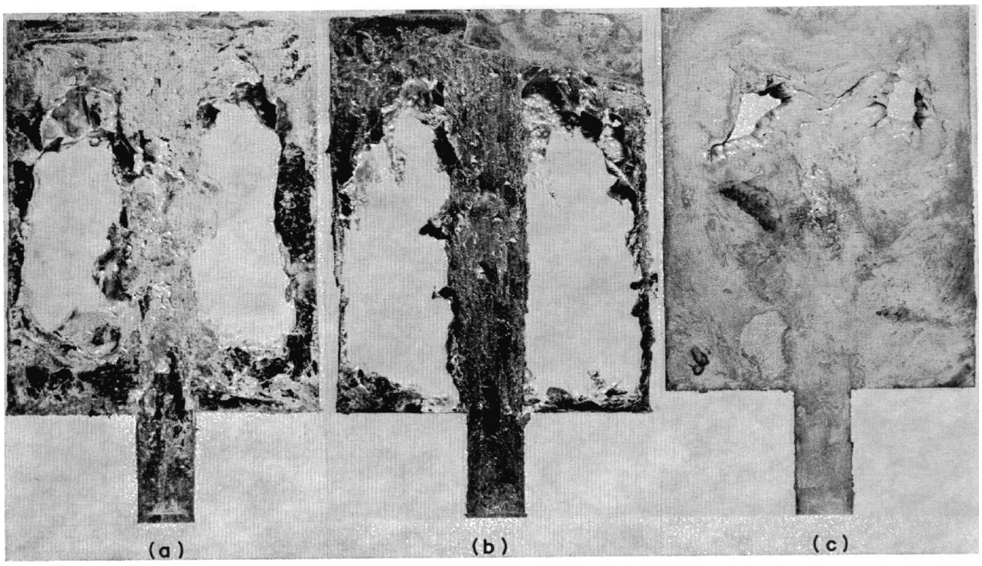

Figure 2.10 Short Shots in Zinc and Aluminium Alloys Showing How Gas Entrapment Can Occur in the Cavity. Shots A, B, and C Differ in the Amount of Metal Ladled. [12]

Strategies for Reducing the Formation of Leakers Due to the Presence of Gas Porosity

- **Proper selection and application of die cooling and lubrication spray** will avoid the build up of liquid on the die surface.
- **Inspection of dies and repair of cracked dies** will avoid water from cooling channels being present on the cavity surface.
- **Calculation and application of optimum first stage plunger accelerations and velocities** will avoid gas entrapment in the shot sleeve due to breaking or reflected waves.
- **Calculation and application of the ideal shot change over position** will avoid gas entrapment in the shot sleeve due to premature acceleration to high velocity.
- **Using the maximum practical shot sleeve fill ratio** will minimise wave formation and gas entrapment in the shot sleeve.
- **Allowing sufficient time for ladled alloy to come to rest** will lessen gas entrapment in the shot sleeve.
- **Designing runners with smooth curves and constantly decreasing area** will lessen gas entrapment in the runner and gate.

* **Designing cavities and vents to allow the free escape of air** will avoid gas entrapment within the cavity.

2.3.5Oxide Films

Mechanisms of Leaker Formation due to the Presence of Oxide Films

Oxide films lodged in the casting may provide a large enough discontinuity for leakage to occur. The plane of the oxide film also provides a weakness within the casting, increasing the likelihood of cracking within the casting. Beyond this, LaVelle [1] and Walkington [2] cite converging flow paths failing to fuse due to oxide films as a cause of cold shuts.

Miller [20] notes that a reduction in fluidity will occur due to the presence of oxide films and that this will increase the likelihood of cold shutting. Oxide films often lodge in the gate leading to gate blockages and the associated problems discussed in Section 2.3.2. Oxides lodged in the gate are discussed by Titone [14] in the context of difficulties in trimming the casting. The presence of oxides in the gate leads to damage due to “Break-Under” when trimming. The casting shears preferentially along the planes of weakness around the oxides, leaving an uneven trimmed surface. In many cases this problem leads directly to rejection of the casting. Some leakers may be caused by surface layer removal due to break-under.

Mechanisms Governing the Formation of Oxide Films

Oxide films will form on any molten alloy surface exposed to oxygen. This occurs most extensively in the holding furnace but may also form during metal ladling and settling in the shot sleeve. [2]

As the metal traverses the gating system and cavity, thin oxide films will form on the leading metal. This problem will be multiplied by splashes and thin streams of metal moving ahead of the main flow [2].

The distribution of the oxides throughout the molten alloy and the resulting casting will depend upon when and how they are formed. The above mechanisms will lead to oxides concentrated in given regions. Oxide films formed earlier in the process, ie. in the melting furnace, will be dispersed more evenly throughout the melt. Excessive oxides in the melting furnace are often the result of re-introduction of casting flash in the feed metal. This high surface area casting by-product contains a large amount of oxide.

Strategies for Reducing the Formation of Leakers Due to the Presence of Oxide Films

- ✶ **Regular skimming of the holding furnace** will prevent the long term build up and dispersion of oxide films.
- ✶ **Using metal ladling techniques that minimise the pick up of the oxide layer, or the use of a dosing furnace,** will avoid the introduction of oxide skins from the holding furnace into the machine shot system.
- ✶ **Minimising the amount of time spent in the ladle and shot sleeve** will reduce oxide formation during these stages.
- ✶ **Smooth, streamlined flow through runners and cavities** will reduce turbulence, exposing less alloy to the surrounding oxygen.
- ✶ **Well designed and properly functioning die venting or the use of evacuated dies** will remove the bulk of the air in the die. [1]
- ✶ **Removal of casting flash from metal to be re-melted** will reduce the re-introduction of oxide films into the molten metal.
- ✶ **Placing ceramic filters somewhere along the metal handling line between the melting furnace and entry in the shot sleeve** will eliminate many inclusions including oxide films before they reach the shot sleeve. [1]

2.3.6Particulate Inclusions

Mechanisms of Leaker Formation due to the Presence of Particulate Inclusions

Large numbers of inclusions within the molten alloy lead to a number of problems that lead indirectly to leakage. As mentioned in Section 3.2 the presence of inclusions in the melt will reduce the fluidity of the casting alloy, increasing the incidence of cold shuts. Similarly the effect of inclusions on die abrasion and hence soldering and drag marks is mentioned in Sections 2.3.9 and 2.3.3.

Walkington [2] discusses the effect of “shotting” on the casting quality. Balls of pre-solidified metal formed due to unsteady gate conditions lodge in the casting providing discontinuities and fracture initiation points. These can provide paths for leakage.

Walkington also discusses the presence of flux inclusions and the association between these inclusions and other defects. The presence of inclusions acts as a “nucleation” point where defects such as gas or shrinkage porosity are more likely to occur.

Mechanisms Governing the Formation of Particulate Inclusions

Figure 2.11 presents a list of inclusions typically found in die cast aluminium alloys. Of this list the most common inclusions found in the melt are oxides and sludge.

Type	Formula	Morphology	Density (g/cm³)	Dimensions(μm)
Oxides	Al_2O_3	Particles Skins	3.97	0.2-30 10-5000
	MgO	Particles Skins	3.58	0.1-5 10-5000
	$MgAl_2O_4$	Particles Skins	3.6	0.1-5 10-5000
	SiO_2	Particles	2.66	0.5-5
Salts	Chlorides Fluorides	Particles	1.98-2.16	0.1-5
Carbides	Al_4C_3 SiC	Particles Particles	2.36 3.22	0.5-25
Nitrides	AlN	Particles, Skins	3.26	10-50
Borides	TiB_2	Particle Clusters	4.5	1-30
	AlB_2	Particles	3.19	0.1-3
Sludge	Al (FeMnCr)Si	Particles	>4.0	

Figure 2.11 Typical Inclusions in Die Cast Aluminium Alloys. [21]

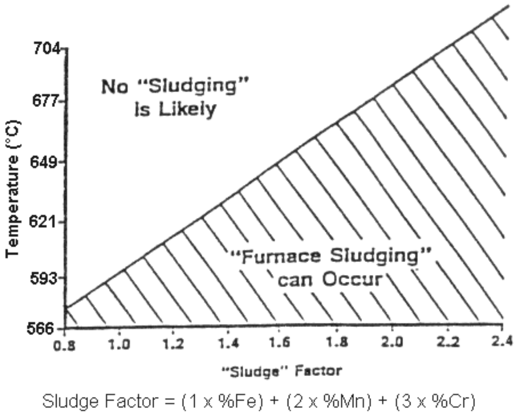

Figure 2.12 Tendency for Sludge Formation as a Function of Temperature and Sludge Factor [13].

Oxides result from the molten alloy coming into contact with oxygen. Oxide particles are often left on furnace walls and subsequently knocked into the melt. Metal that has been overly agitated during melting and delivery to the die cavity will contain an excessive amount of oxide inclusions.Sludge forms due to a chemical reaction between iron, manganese and chromium in the melt at low metal temperatures. A commonly used method of determining the probability of sludge formation is the calculation of a melt sludge factor that depends on the weight percentages of iron, chromium, and manganese in the molten alloy. The likelihood of sludge forming for an alloy with a known sludge factor at a given temperature is given by Figure 2.12.

Shotting will occur when small particles of metal splash ahead of the main flow during injection. These particles will solidify rapidly due to their small size. It is unlikely that they will be re-melted when the remainder of the flow encircles them [5]. Splashing in the runner system is caused by a lack of streamlining and/or inadequate control of the plunger speed.

Strategies for Reducing the Formation of Leakers Due to the Presence of Particulate Inclusions

- **Metal cleanliness during melting and holding** will avoid contamination with oxides and other particles.
- **Control of alloy composition and furnace temperatures** will prevent the formation of sludge particles.
- **Streamlined design of runner and control of plunger speeds** will minimise shotting.

2.3.7Secondary Operations that Remove or Damage the Surface Layer

Mechanisms of Leaker Formation due to Secondary Operations.

A range of secondary operations that may have an effect on the integrity of the casting are possible. The most commonly used secondary operations that may lead to leakage are trimming, shot blasting, and material removal via machining.

The various types of damage that may occur during trimming are discussed by Titone [14]. Drag marks and break-under occurring during trimming may lead to leakage as discussed in Section 2.3.3 and Section 2.3.5 respectively. The mechanical stress applied during trimming may also cause the formation of cracks in the casting that will lead to leakage.

Anderson [22] discusses the positive effects of shot blasting in terms of sealing surface porosity. In this situation the process of shot blasting was seen to significantly reduce the percentage of leakers formed. In other situations we might expect that shot blasting may destroy a thin surface layer exposing porosity below the surface. The relative size of the shot particles would be expected to affect the outcome of the shot blasting.

Machining operations that remove part of the casting will provide any existing leak paths through the rest of the casting with a ready exit point. In a similar manner to damage caused during trimming, stresses induced during machining operations may cause cracking, leading to leakage.

Strategies for Reducing the Formation of Leakers Due to Secondary Operations

Strategies for avoiding damage during trimming were discussed in Section 2.3.3. Avoiding the formation of leakers due to shot blasting and machining can be done using casting design to avoid the formation of leak paths that may be exposed by these operations.

Herman [9] discusses the preferential formation of shrinkage porosity at the last point to solidify and thus the way the casting can be thermally manipulated to locate any shrinkage porosity away from critical areas. Shrinkage porosity within the casting wall can be moved away from a surface to be machined by increasing the heat transfer rate through the die at this surface. Herman refers to this process as manipulation of the casting's "Neutral Thermal Axis" (NTA).

Similarly, placing areas to be machined closer to the gate where defects such as cold shuts are less likely to occur will decrease the likelihood of these defects combining with material removal due to machining and causing leakage.

Avoiding leakers due to secondary operations involves careful planning and designing. As discussed in Section 2.2 it is believed that the surface layers of most die castings are the soundest part of the section. Machining operations that remove this layer will inevitably cause problems with leakers. Careful consideration of machining needs during the casting design stage is essential.

2.3.8Shrinkage Porosity

Mechanisms of Leaker Formation due to the Presence of Shrinkage Porosity

When a hypoeutectic alloy, such as CA313, is solidified under equilibrium conditions solidification will begin with the formation of dendrites followed with the solidification of the surrounding eutectic. The voids that will result from un-fed volumetric shrinkage during solidification will take the form of voids between the dendrites. Figure 2.13 gives an example of such interdendritic porosity. Such a pattern of voids will leave a path for leakage through any part of the casting that has solidified in this manner. Both LaVelle [1] and Walkington [2] assert that inter-dendritic porosity is a common feature of high pressure die castings cast in long freezing range hypoeutectic alloys. Given such a scenario it is apparent that leakage paths will be present in areas of a casting where shrinkage porosity is present.

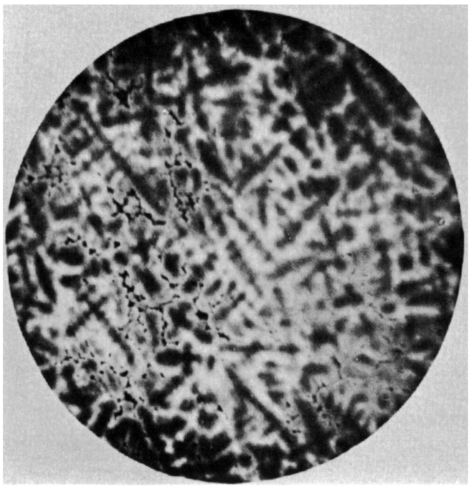

Figure 2.13 Interdendritic Shrinkage in Sand Cast Gun Metal Casting (Approximately 40 × Magnification) [23]

As mentioned in Section 2.2 it is thought that the outside surface of castings are the first part of the casting to solidify. Therefore shrinkage porosity is rarely present on the as-cast surface. For leakage to occur a second mechanism must act in combination with the shrinkage porosity. However, Walkington [2] discusses a case where shrinkage porosity can occur at the as-cast surface due to local hot spots on the die. In such a case leakage could occur directly through this porosity.

Mechanisms Governing the Formation of Shrinkage Porosity

The amount of volumetric shrinkage an alloy undergoes is a property of the alloy. Figure 2.14 shows the amount of volumetric shrinkage that occurs for a range of aluminium silicon alloys.

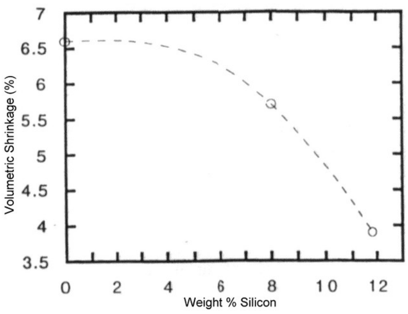

Figure 2.14 Solidification Shrinkage in Aluminium Silicon Alloys [24].

Garber and Draper [25] demonstrated that the amount of shrinkage that occurs during cooling and solidification cannot be altered by changing the process. They could, however, alter the way that this shrinkage acts on the casting. By manipulation of the casting cooling rate they could cast a sound block of smaller dimensions than the die (ie. the casting has shrunk away from the die), or cast a block of identical dimensions to the die (ie. the casting has not shrunk away from the die) where the shrinkage manifested itself as porosity within the casting.

We must consider two important points in dealing with shrinkage porosity;

- by changing the casting alloy we can alter the amount and distribution of shrinkage porosity, and
- by changing the process used to cast the alloy we can alter the distribution of shrinkage porosity.

Effect of Alloy Properties on the Formation of Shrinkage Porosity

Figure 2.14 shows the effect of alloy composition, specifically the weight percentage of silicon present, has on the total shrinkage. We can see that over the range of commonly used aluminium silicon alloys the volumetric shrinkage varies between 6.5% and 4%. This variation in the amount of shrinkage will have a lesser effect on the properties of the final casting than the variation in the solidification process, and the resulting porosity distribution, caused by the change in alloy composition.

The most concise demonstration of the effect of alloy composition on the resulting distribution of shrinkage porosity, and indeed its effect on pressure tightness, was performed by DePue and Pennington [23]. Figure 2 .15 demonstrates two radically different porosity distributions generated in a gun metal (88% Cu, 8% Sn, 4% Zn) sand casting by altering the silicon level in the alloy (at levels below 1%).

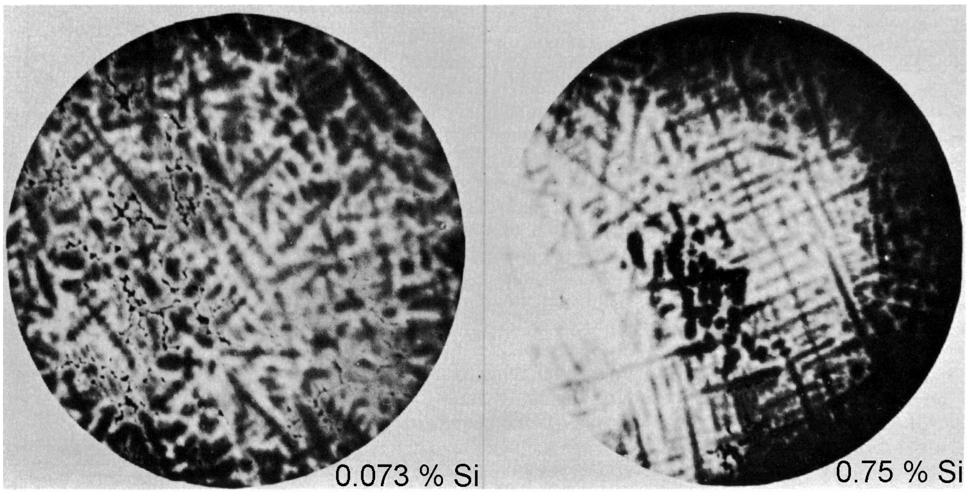

Figure 2.15 Shrinkage Porosity Distributions at Different Alloy Compositions. (Both Micrographs at Approximately 40 × Magnification) [23].

The amount of silicon in the alloy alters the amount of low melting point “delta” phase present in the solidifying casting. The higher silicon level results in more delta phase which in turn has greater mobility, while liquid, between the more widely spaced dendrites. This increases the distance over which the solidifying delta phase can feed the developing shrinkage. At low silicon levels the delta phase can only feed shrinkage over very sort distances, resulting in channels where the metal that was in the centre of the channel has fed shrinkage at the more rapidly solidifying channel boundary. At higher silicon levels the delta phase can feed over longer ranges resulting in large pores where metal has fed other solidifying areas. This situation is somewhat similar to what would happen during sand casting of aluminium alloys of varying degrees of silicon as the mechanisms of solidification are similar. On going work by Otte [26] and Taylor [27] demonstrates the effect of other elements, notably iron, on shrinkage porosity and hence pressure tightness in sand castings. However, looking at solidification during high pressure die casting, three major departures from equilibrium mean that the description of the formation of shrinkage porosity is more complicated. These departures are:

- The rapid rate of cooling and solidification.
- The high pressures applied during solidification.
- Solidification begins while the alloy is in the shot sleeve and progresses during injection.

Despite these departures from equilibrium conditions it is widely believed that the mechanisms controlling the formation of shrinkage porosity in high pressure die casting are largely similar to those seen in sand casting. LaVelle [1] discusses the effect of the freezing range[2] of the casting alloy on the distribution of shrinkage porosity. He favours the use of short freezing range alloys in castings where pressure tightness is required as these alloys will develop shrinkage pores in the form of isolated holes. As the alloy's freezing range increases the shrinkage porosity becomes more interconnected in nature providing paths for leakage. This effect of freezing range on the shrinkage porosity distribution is identical to that observed by DePue and Pennington, but LaVelle does not present results that confirm this mechanism in high pressure die casting.

No papers were found that directly contradict LaVelle's discussion, yet it is clear that some confusion exists as to the manifestation of shrinkage porosity in high pressure casting. Comparing papers by Kalghatgi [28], Murray [4], and Walkington [2] with that by LaVelle we note a number of statements that are indicative of this confusion.

Both Kalghatgi and Murray refer to an increase in the amount of shrinkage porosity present as the composition of the casting alloy approaches that of the aluminium silicon eutectic, ie. the alloy freezing range is reduced. However, Walkington states that shrinkage porosity is more prevalent at lower silicon levels, where the freezing range is increased. These statements appear contradictory, indeed, when taken out of context they are all inaccurate. Apart from the small difference due to the differing overall shrinkage, Figure 2.14, there will be no difference in the total volume of

[2] Freezing range indicates the temperature range from the beginning to the end of solidification.

shrinkage voids in a casting unless molten alloy is fed through the gate during solidification. As discussed by Herman [29], large scale feeding of a typical high pressure die casting is unlikely to occur due to the thin gates used in this process and the generally thin section castings made. The reason for the differing views of Kalghatgi, Murray, and Walkington, is most likely to be differences in their definitions of shrinkage porosity.

The results presented by Kalghatgi indicate that in fact it is the occurrence of large shrinkage pores in the centre of the casting section that increases with decreasing freezing range. Shrinkage porosity at lower percentages of silicon may be more evenly distributed so that individual pores are not visible to the naked eye.

This ambiguity in defining shrinkage porosity in high pressure die casting makes it difficult to accurately define the effect of alloy composition on shrinkage porosity in high pressure die casting. The majority of published opinion indicates that the mechanisms described by DePue and Pennington are applicable to aluminium high pressure die casting, yet this is not confirmed by any reliable published data. Work by Kulunk et al [30] indicates that strontium has an effect on pressure tightness in high pressure die casting due to an effect on the feeding of shrinkage porosity because of a change in the solidification of the eutectic and the size of sludge particles. This work uses a graded measure of pressure tightness and is very limited in its scope. While it shows that strontium may increase pressure tightness in a particular case, it does not prove a strong effect of strontium upon shrinkage porosity.

Effect of Process Variables on Formation of Shrinkage Porosity

By altering process variables and die design we can change the manner in which the cavity is filled and any subsequent feeding that may occur. In other forms of casting a common method used to minimise the effects of alloy shrinkage is feeding of the alloy from the gate or riser. Johnson et al [15] studied the effect of using directional solidification in sand casting of bronze alloys to enhance feeding of

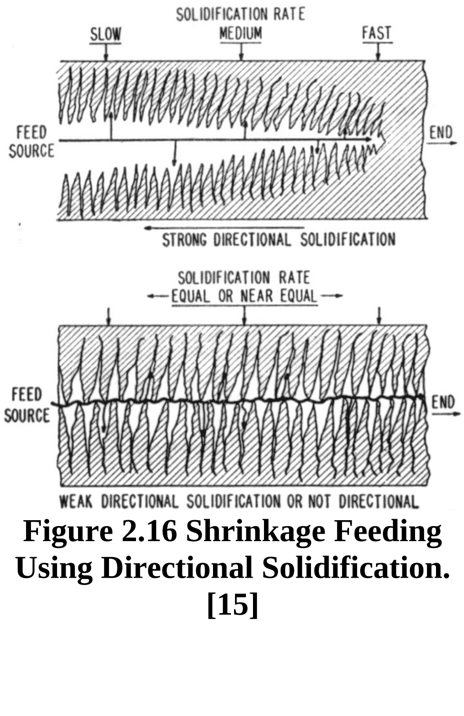

Figure 2.16 Shrinkage Feeding Using Directional Solidification. [15]

shrinkage. Figure 2.16 gives a comparison of a casting with strong directional solidification and one with weak directional solidification. We can see the benefits of feeding the solidifying casting. However, solidification conditions in a high pressure die casting are significantly different to those experienced in this sand casting.

Herman [29] refers to high pressure die casting as a shrinkage dispersion process as opposed to shrinkage feeding process such as gravity, sand, or low pressure casting. He states that it is not possible to feed shrinkage over a distance of more than twenty times the representative casting thickness regardless of the application of high pressure intensification. Whether this is correct is open to discussion. Some results indicate the amount of metal feeding occurring after die filling may be minimal while in other cases [31] pressure measurements in the cavity indicate that feeding during intensification is occurring. Others [16, 12] discuss the possibility of localised shrinkage feeding due to pressurisation of entrapped air during intensification. Different results such as this are due to the non standard nature of most die casting experiments. Casting designs and setups change from paper to paper, making it nigh on impossible to develop a definitive model.

A major difficulty in determining whether feeding is occurring or not is that the effect of solidification and feeding under pressure on the casting microstructure is unknown. Work by Arnberg et al [32] indicates that in gravity casting applied pressure may cause a collapse of the dendritic network during solidification. Such a regime of shrinkage feeding will lead to a significantly different casting structure than would otherwise occur. In the case of high pressure die casting we cannot detect whether such a mechanism may be occurring because for the most part we don’t know enough about the solidification process within the die and the microstructures that are likely to result.

Nonetheless, it is likely that developing directional solidification using a hot gate and cold casting extremities will, at the very least, not have a detrimental effect on casting quality.

Irrespective of whether feeding is possible after the die has filled, it is reasonable to assume that it will be possible to feed solidifying metal that has not yet passed through the casting gate. Garber and Draper [33] noted that a decrease in the metal holding temperature of 55˚C resulted in a reduction in the size of individual shrinkage defects. This may be due to solidification beginning earlier, allowing feeding to occur as the metal fills the cavity. Using lower metal pouring temperatures to lessen the amount of shrinkage in high pressure die castings is also mentioned by Herman [9] and LaVelle [1]. A reduction in the pouring temperature will also reduce the total amount of shrinkage due to metal cooling that the alloy undergoes. This effect was observed in gravity casting by Micks and Zabek [34].

Strategies for Reducing the Formation of Leakers Due to the Presence of Shrinkage Porosity

As discussed, the state of knowledge on the formation of shrinkage porosity is such that accurate recommendations in this area are difficult to make. Nonetheless, the following approaches are quite likely to have some beneficial effect on casting quality.

- **Designing dies to avoid the occurrence of thick sections fed by thin sections and placing critical regions of the casting near the gate** will maximise any metal feeding that may occur during solidification.
- **Designing dies to remove heat slowly near the gate region and rapidly at the casting extremities** will cause directional solidification, improving the chances of metal feeding during solidification.
- **Lowering the metal injection temperature** will reduce the total amount of shrinkage voids due to earlier start of solidification and slightly less total volumetric shrinkage.
- **Increasing the intensification pressure** will increase the likelihood of metal feeding during solidification.
- **Use of a near eutectic alloy** will reduce the alloy freezing range leading to large isolated shrinkage pores that are less likely to cause leakage than evenly distributed interdendritic porosity.

2.3.9 Soldering

Mechanisms of Leaker Formation due to the Presence of Soldering

Chu et al [35] state that soldering results in damage to the casting surface and may lead to defects such as drag marks. This surface damage may provide a path for leakage through the casting surface.

Mechanisms Governing the Formation of Soldering

Soldering is a chemical reaction that occurs when molten aluminium comes into contact with bare die steel. In order for this to occur the iron oxide layers left on the die steel after heat treatment and die running-in must be removed by erosion due to molten aluminium impingement at high die temperatures [2]. This will occur when the die design is such that metal streams impact directly onto die cavity surfaces.

The chemical content of the alloy will have a significant effect on the likelihood of the die soldering reaction occurring once the oxide layer has been removed. As the iron content of the alloy drops the propensity for soldering increases. An iron content of less than 0.8 weight % will lead to excessive soldering [3].

Strategies for Reducing the Formation of Leakers Due to the Presence of Soldering

- **Designing casting dies to reduce the angle and/or velocity of impingement of molten alloy onto the cavity surface** will limit erosion of the protective iron oxide layer.
- **Avoiding local hot spots in the die,** using spot cooling if necessary, will slow the chemical reaction leading to soldering.
- **Maintaining alloy iron contents at greater than 0.8 weight %** will reduce the driving force of the soldering reaction.
- **Reducing metal injection temperatures** will slow the soldering reaction due to the alloy temperature reduction and a corresponding drop in die temperatures.
- **Reducing the metal injection velocity** will slow the erosion of the protective oxide layer.
- **Appropriate use of casting lubricant** will help protect the die from damage due to metal injection and casting ejection.

2.3.10Surface Cracks

Mechanisms of Leaker Formation due to the Presence of Surface Cracks

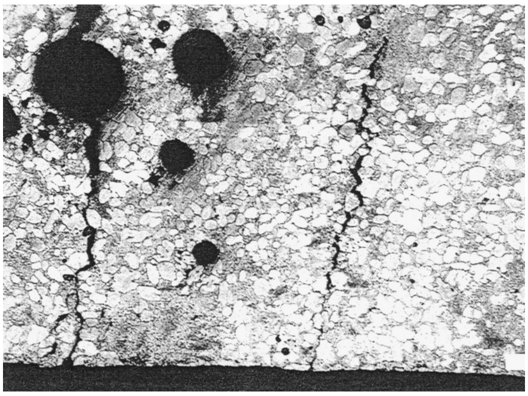

Figure 2.17 Surface Cracking in a Zinc Casting [2].

Any crack present in the surface of the casting will provide a path for leakage. Figure 2.17 shows a case where surface cracks link with gas pores in the casting centre.

Mechanisms Governing the Formation of Surface Cracks

Cracks in the casting are the result of the casting being locally stressed beyond its tensile limit after solidification. The most commonly discussed mechanism for stressing the casting is stress generated by the volumetric shrinkage of the casting as it cools after solidification. When a long section of casting is dimensionally restrained between two or more points, the stress developed as the casting tries to shrink may be sufficient to lead to cracking, [4]. Sharp corners and angles will act as points for stress concentration, accentuating the problem, [3]. The likelihood of the casting cracking increases the longer it is restrained during cooling [3].

Stresses may also occur during ejection of the casting. This will be the case if the casting resists ejection due to insufficient draft angle, undercuts, soldering, broken ejector pins etc. [3]

In order for cracking to occur these stresses must exceed the tensile strength of the alloy. Assuming that no defects such as cold shuts that will lower the effective strength of the casting are present, the alloy strength will be purely a function of the casting alloy and its temperature. The hot strength will be determined by the composition of the alloy. Iron levels below 0.8 weight %, zinc levels above 4 weight %, magnesium levels above 0.3 weight %, and low silicon levels will all reduce the hot strength of the casting alloy, [2]. The likelihood of cracking the casting during ejection is raised by increased ejection temperatures due to the lower alloy strength at these temperatures. Higher ejection temperatures will occur when the die holding time is reduced [3].

Strategies for Reducing the Formation of Leakers Due to the Presence of Surface Cracks

- **Reduce stresses during solidification** by avoiding constrained sections, sharp corners, and excessive holding times.
- **Reduce stresses during ejection** by allowing plenty of draft angle and even ejection.
- **Maximise alloy strength** by maintaining high iron and silicon and low magnesium and zinc levels as well as allowing the casting to cool sufficiently before ejection.
- **Eliminate casting defects** that will reduce the effective tensile strength.

2.4 Summary: Tracing the Route from Leaker to Cause

We now have a concise knowledge of the most common causes of leakers published in the literature. Figure 2.18 uses the concept of a “Fault Tree” to summarise this information. The use of Fault Trees to systematically analyse complex problems is discussed in [36]. The method uses logic to break a fault into root causes that can then be remedied.

When a specific casting is produced with an unacceptably high percentage of leakers, Figure 2.18 can be used to suggest a possible root cause. With the root cause known a solution can be implemented. To do this at least three crucial decisions need to be made:

- ✶ Selection of optimum strategy to reduce leakage:
- ✶ Prevent the formation of a leakage path through the centre of the casting .
- ✶ Concentrate on maintaining a sound surface layer as a defense against leakers.
- ✶ Determination of the most likely primary mechanism for the formation of such a path. This stage requires observation of the actual castings and the process used. Experience gathered in similar cases will also prove useful.
- ✶ Determination of appropriate root cause. Correct judgment at this stage requires experience and a willingness to experiment with a range of options.

During this chapter an understanding of the mechanisms of leaker formation has been developed, however, it is apparent that the problem is complicated and does not lend itself to easy or rapid solutions. The use of Figure 2.18 oversimplifies the problem and thus it is important to use common sense when applying this method.

Over the remaining chapters we demonstrate the use of observation of both casting and process to allow the above decisions to be made in the specific case of the water inlet casting.

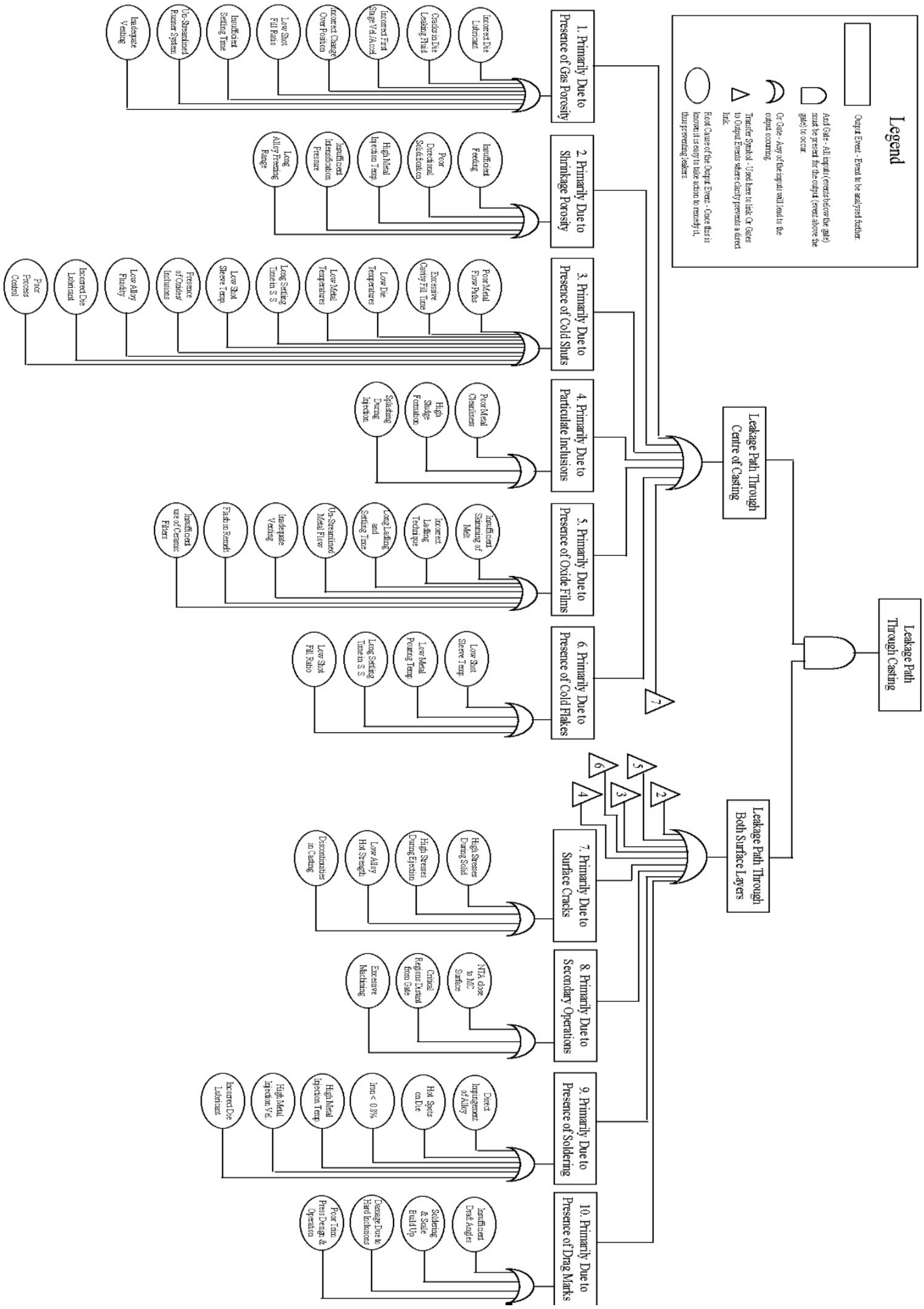

Figure 2.18 Fault Tree Summarising the Major Causes of Leakers Based Upon Published Literature.