University of Queensland

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Mechanisms of Leaker Formation in Aluminium High Pressure Die Casting

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Declaration

This thesis contains no material that has been accepted for the award of any degree or diploma in any university and to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference is made.

Stephen Thompson.

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Abstract

Within this report an understanding of the mechanisms of leaker formation, both in general and in a specific aluminium high pressure die casting, is developed. This understanding is developed through several stages.

A review of previously published work determines casting defects that may contribute to the formation of leakers in high pressure die casting. Further review of the literature concentrates on understanding each of these defects and their effect on casting pressure tightness. The defects reviewed are, cold flakes, cold shuts, drag marks, gas porosity, oxide films, particulate inclusions, secondary operations that remove or damage the surface layer, shrinkage porosity, soldering, and surface cracks. This information is then compiled to form a “Fault Tree” that will assist in the determination of the “Root Causes” of leakers in a specific casting.

Observation of an automotive water inlet casting is then used to determine the likely root causes of leakers in a specific example. Defects found that may be root causes of leakers were cold shuts, gas porosity, shrinkage porosity, surface porosity due to volatilised fluids, drag marks, and surface cracks. The machining of critical areas of the casting also appeared to increase the likelihood of leaker formation.

Of these defects cold shuts appeared to be the most critical root cause of leakers. To analyse the effect process parameters on the occurrence of cold shuts and leakers a structured trial was carried out in which the die and metal temperatures were manipulated to increase the occurrence of leakers. The results show a strong link between the occurrence and extent of cold shuts and the occurrence of leakers. Furthermore, the results demonstrate a link between die temperatures and the occurrence of leakers.

Finally, a number of strategies to reduce the occurrence of leakers in the automotive water inlet casting are proposed and suggestions are made as to possible further investigation.

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Chapter 1

An Introduction

1.1Molten Metal Forming

A vast range of complex components can be manufactured by containing solidification of molten metal within a shaped mould. However, metal cast in this way is subject to a wide range of defects due to the constraints placed upon solidification by the process and mould. The occurrence of these defects will depend upon the specifics of the casting process.

Amongst the most basic casting processes is sand casting. From this basic casting process a range of other processes have evolved over time, all with their characteristic strengths and weaknesses. Amongst these is high pressure die casting.

1.1.1High Pressure Die Casting

One of the most common reasons for selecting high pressure die casting over other processes is the low cost per casting and very large production rates and volumes that the process is capable of. However, when the process is used to its full potential it is capable of casting very complicated castings with thinner wall sections and higher dimensional accuracy than most other casting processes. However, when used in this manner, the centre of the casting section will be quite porous leading to lower mechanical strengths than could be achieved otherwise.

In most cases, practical constraints prevent the process from being used to its full potential. When this occurs a large number of defects may occur. A defect is regarded as any casting feature which falls outside limits set by the customer. In the case of a casting that must contain or channel a fluid, a feature that leads to a leak forming under a given pressure will be called a “Leaker”. Castings containing such a defect must either be rejected or impregnated with a polymeric sealing agent.

Due to the great diversity of castings made by the high pressure die casting process we cannot discuss a “typical” scenario for the formation of a leaker. Within this thesis we examine the example of an automotive water inlet casting.

1.2Leakers in a Water Inlet Casting

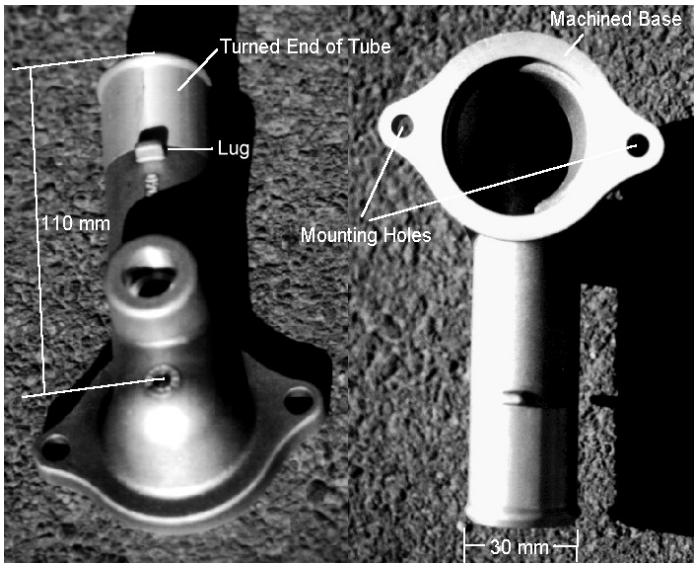


Figure 1.1 Automotive Water Inlet Casting.

Figure 1.1 shows a water inlet casting manufactured primarily using high pressure die casting. The component is subject to range of possible defects. These include out of tolerance dimensions, exposed porosity on the machined areas, and a lack of pressure tightness, ie. leakers.

While the bulk of the metal forming is performed by the high pressure die casting, the part is produced by a process stretching from the arrival of ingots of alloy at the foundry to the pressure testing of the final parts. Figure 1 .2 lists the various processes the part goes through during manufacture. Further details of the most critical steps in the process are contained in Appendix A.

We note that pressure testing occurs late in the process. This ensures that no leaking castings are delivered to the customer. However, it also means that all of the processes occurring before pressure testing will influence the pressure tightness of the casting. When the part is finished it is irrelevant whether it was sound in the “as-cast” condition. The only measure of part pressure tightness that matters is the condition of the part after the “secondary operations” have been performed and the casting is in it salable state. For this example the mechanisms of leaker formation are therefore complicated by the presence of factors outside of the high pressure die casting process. However, while all the stages present in the process will have an effect on the pressure tightness of the completed casting, it is likely that the defining step will be the casting stage. The reason for this is the high degree of uncertainty produced during this stage.

The potential for variation in the output of the high pressure die casting process is much greater than that for other critical steps such as machining and shot blasting. So while processes such as shot blasting and machining are likely to have a significant

effect on the overall rate of leakers produced, they are unlikely to have a defining influence on whether a specific part leaks.

This assumption is proven in the results of this study. Results of observations presented in Chapter 3 indicate that machining of the tube end has a large effect on the number of leakers formed. However, in Chapter 4 an ability to predict the rate of leaker formation given only a selection of parameters from the high pressure die casting process is demonstrated. This indicates that it is the high pressure die casting process that determines the occurrence of leakers.

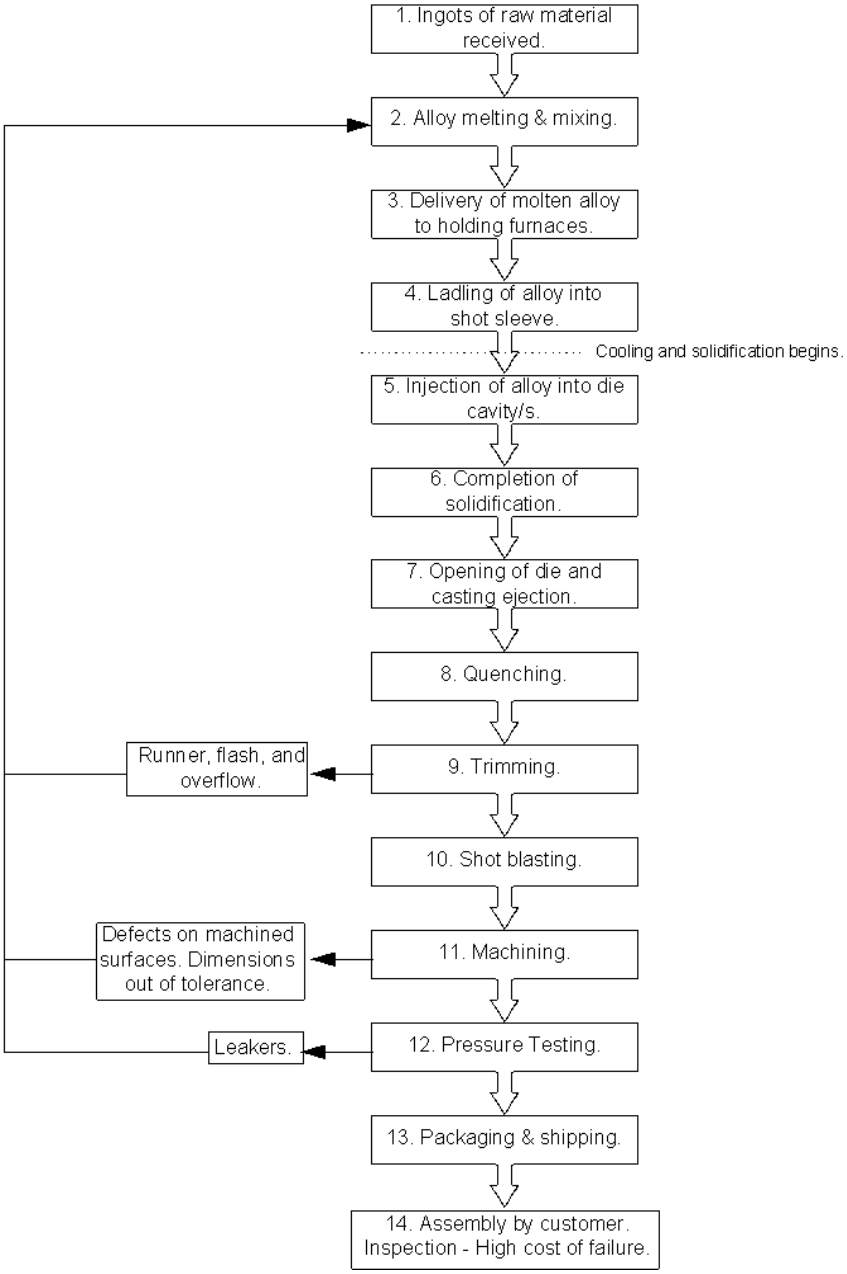


Figure 1.2 Flow Chart of Part Manufacture.

1.2.1Understanding the Formation of Leakers in High Pressure Die Casting

A review of previously published literature revealed that leakers in high pressure die casting are not a widely studied phenomenon. The main reason for this is that although the term leaker is often used in practice to describe this class of defect, the formation of leakers is in fact due to combinations of other casting defects that form a path through the casting. Further to this, in most cases there is little information on the formation of these contributing defects in high pressure die casting.

With this in mind, this study has the following aims:

I. Compile existing published research to determine common mechanisms in the formation of leakers.
II. Use observations of the process and casting to determine likely mechanisms of leaker formation in the water inlet casting.
III. Propose parameters, based upon the published literature, that are likely to have an important effect on the formation of leakers in the water inlet casting.
IV. Confirm the importance of the mechanisms determine in Step *II* and the important parameters proposed in Step *III* using a controlled experiment.
V. Using published knowledge and experience gathered propose strategies that may be used to reduce the occurrence of leakers in the water inlet casting.

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.

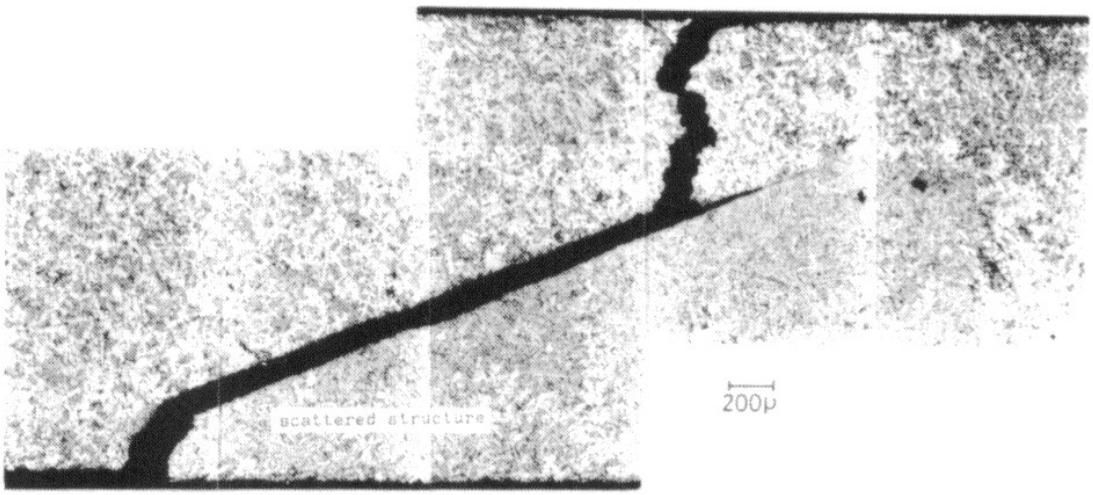


Figure 2.1 Fracture Along the Face of a Cold Flake [6]

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.

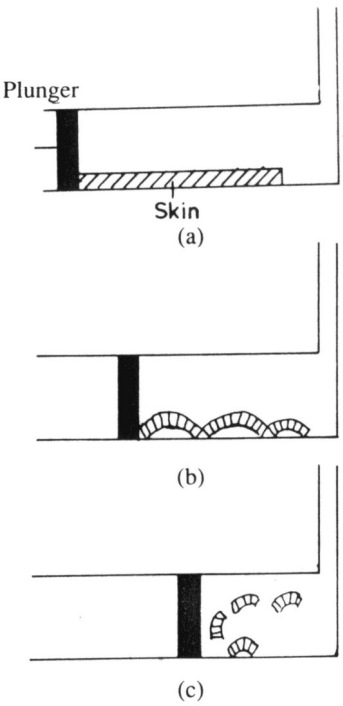


Figure 2.2 Mechanism of Cold Flake Formation [7]

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 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.

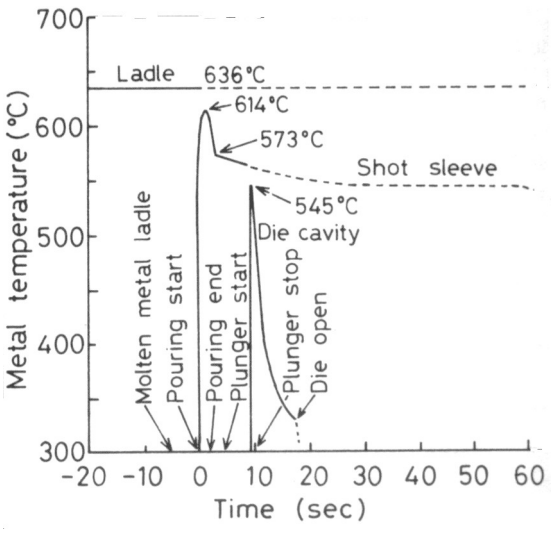


Figure 2.3 Heat Losses From Alloy During Casting Cycle [6]

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.

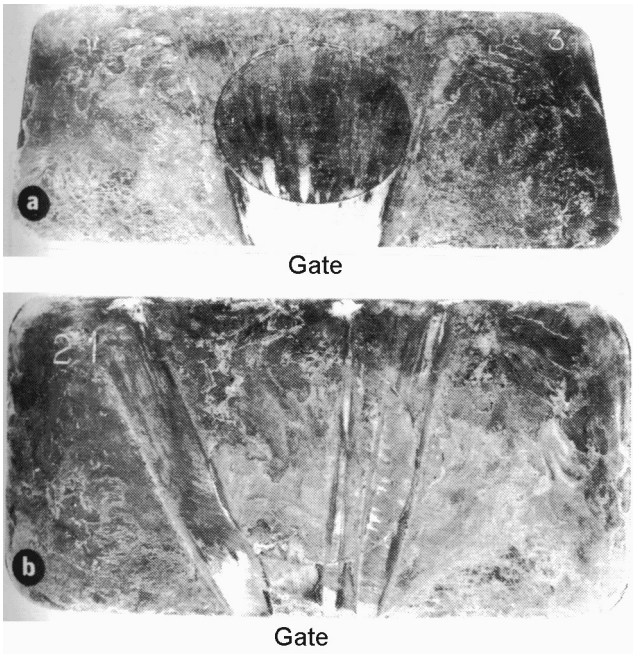


Figure 2.4 Flow Lines on Flat Plate Castings Showing Difference Between Casting Filled by Full Width of Fan Gate (a) and Casting Filled by Partially Blocked Gate (b). [5]

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.

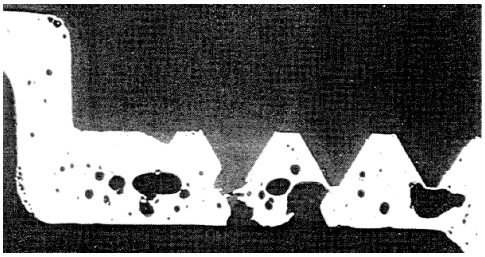


Figure 2.5 "Large Gate Pores ... Exposed by Machining to Create a Leaker." [2]

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.

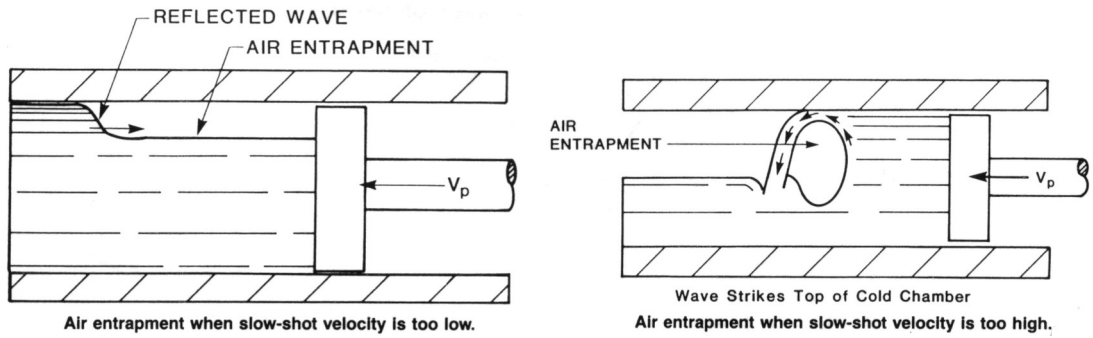


Figure 2.6 Air Entrapment at too Low and too High a First Stage Velocity. [17]

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.

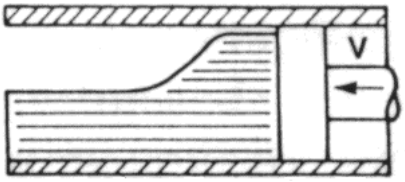


Figure 2.7 Wave Formed at Critical First Stage Plunger Speed. [17]

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.

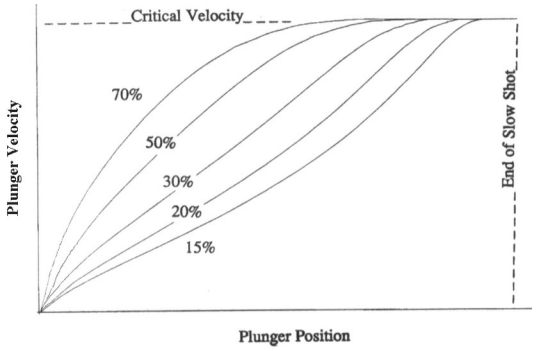


Figure 2.8 Optimum Acceleration Profiles For Different Shot Fill Ratios. Each Plot is Scaled to its Critical Velocity and Plunger Position at Shot Sleeve Full Point. [18]

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.

$$v = C\left(\frac{100-f}{100}\right)\sqrt{\frac{D}{25.4}}$$ **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;

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

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.

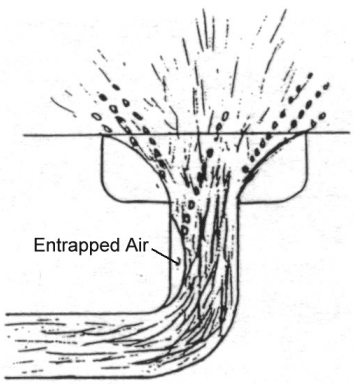


Figure 2.9 Air Entrapment in a Poorly Designed Runner. [2]

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.

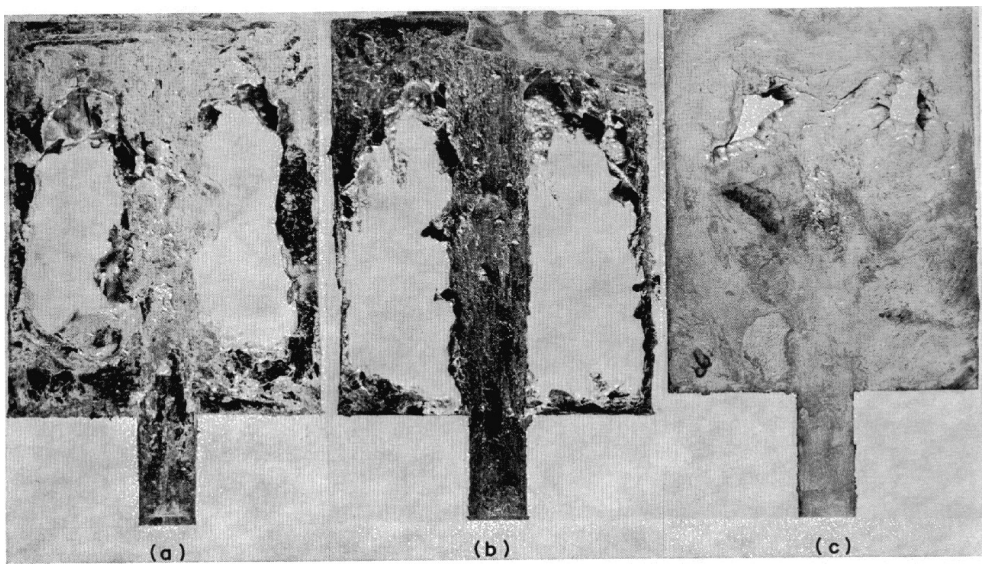


Figure 2.10 Short Shots in Zinc and Aluminium Alloys Showing How Gas Entrapment Can Occur in the Cavity. Shots A, B, and C Differ in the Amount of Metal Ladled. [12]

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]

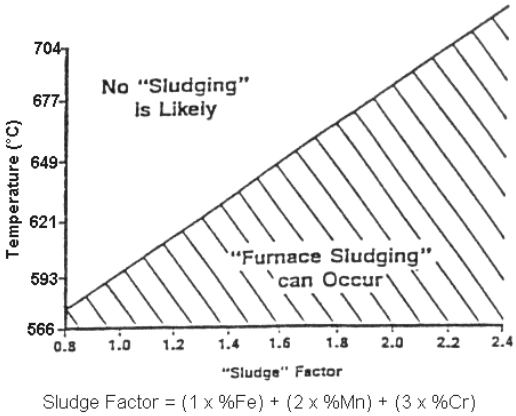


Figure 2.12 Tendency for Sludge Formation as a Function of Temperature and Sludge Factor [13].

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.

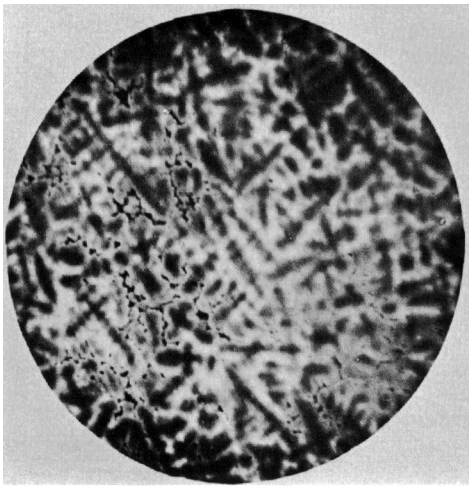


Figure 2.13 Interdendritic Shrinkage in Sand Cast Gun Metal Casting (Approximately 40 × Magnification) [23]

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.

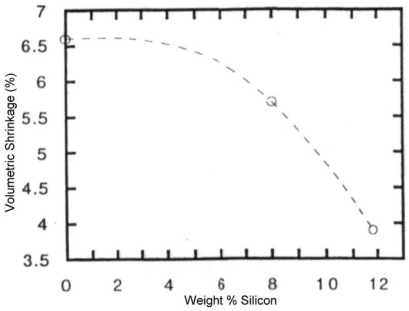


Figure 2.14 Solidification Shrinkage in Aluminium Silicon Alloys [24].

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%).

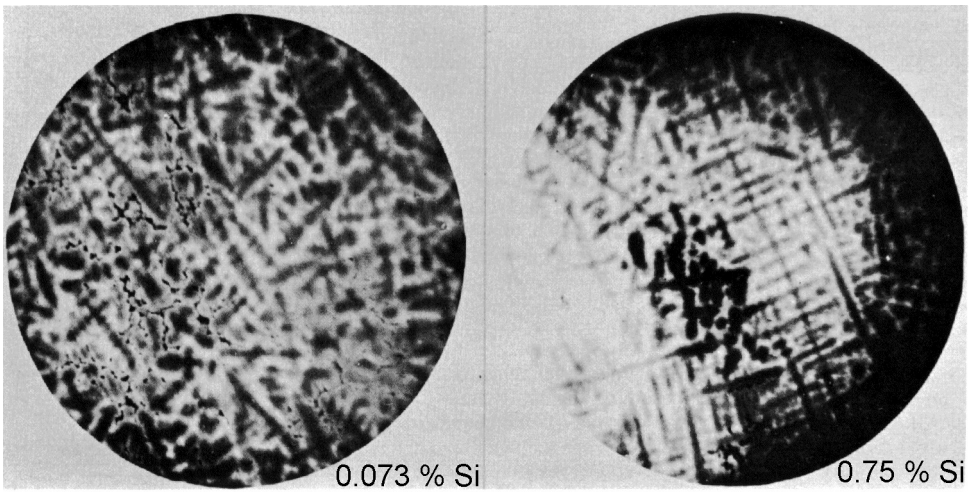


Figure 2.15 Shrinkage Porosity Distributions at Different Alloy Compositions. (Both Micrographs at Approximately 40 × Magnification) [23].

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

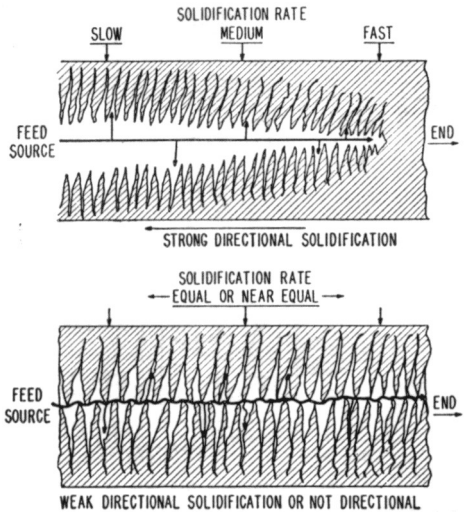


Figure 2.16 Shrinkage Feeding Using Directional Solidification. [15]

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

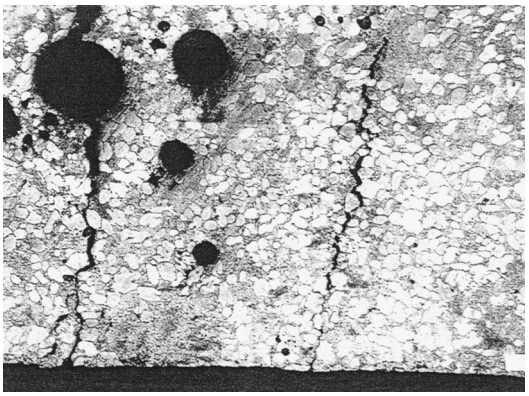


Figure 2.17 Surface Cracking in a Zinc Casting [2].

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.

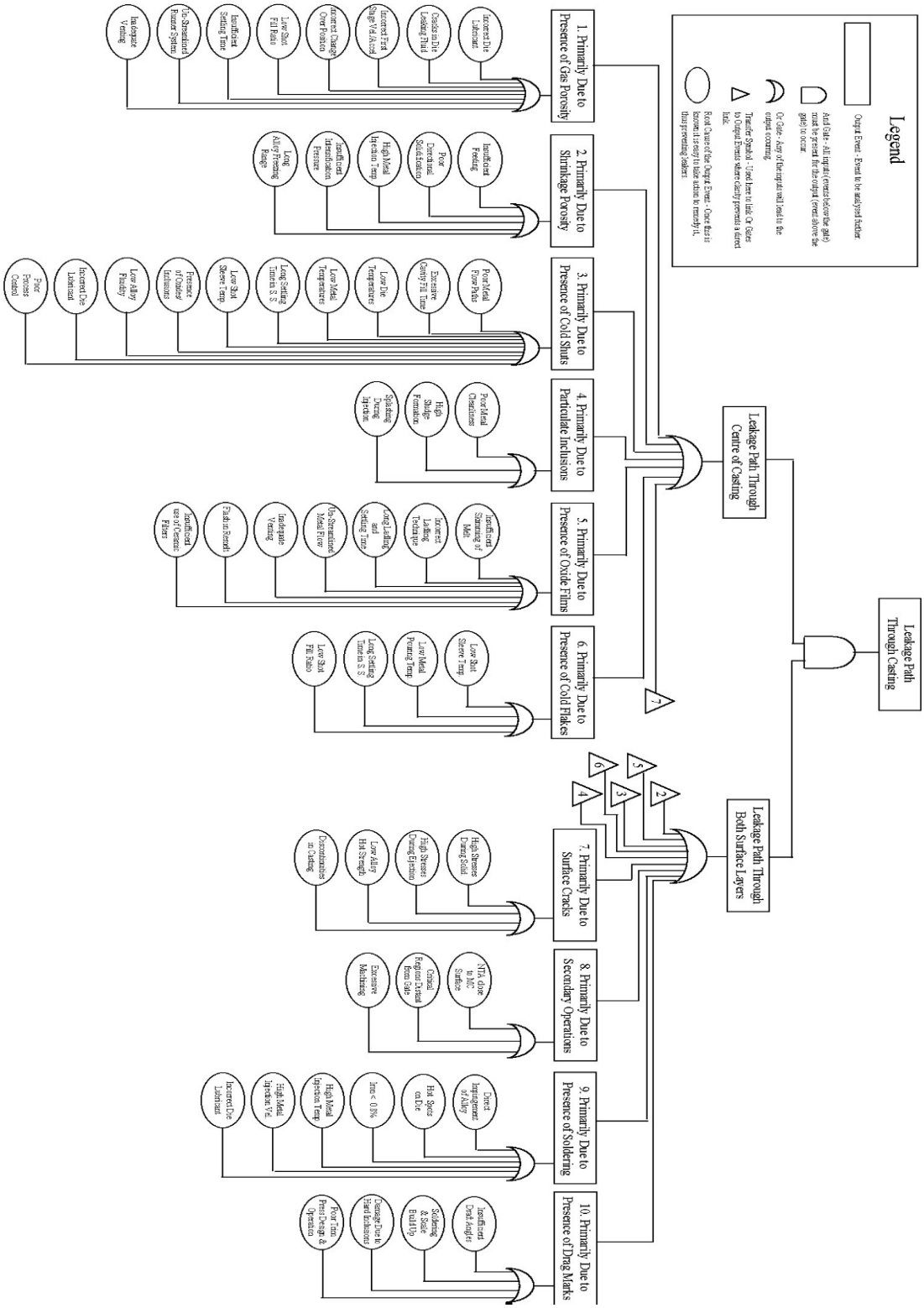


Figure 2.18 Fault Tree Summarising the Major Causes of Leakers Based Upon Published Literature.

Chapter 3

Observations of the Casting Process and the Occurrence of Leakers in the Water Inlet Casting

3.1Introduction

Information in the literature highlighted the fact that describing a defect as a leaker may succinctly state the problem but is of little use in finding a solution. In order to do this the cause of the leaker needs to be defined. Although in most cases a leak path cannot be followed through the casting due to its complicated nature, the casting can be expected and other defects present noted. Depending upon the location and extent of these other defects an informed judgment can be made about the most likely causes of the leaker.

3.2 Common Locations of Leakers

The first clue as to the mechanism of leaker formation is their location. In the case of the water inlet the location of leakers is fairly consistent. Most leakers occur on or near the machined end of the tube. The majority of these leakers occur on or near the parting line of the casting. However, leakers can occur at any point on the circumference of the machined area. A smaller number of leakers occur near the bases of the lugs on the top and bottom of the tube. In this case the leak may occur through the shot blasted surface rather than the machined surface. Figure 3 .1 shows these areas.

Figure 3.1 Photograph of Water Inlet Casting Showing Common Sites of Leakers.

3.2.1Possible Factors Leading to Leakers on the Machined Surface

Material Removal Due to Machining

Literature suggests that most high pressure die castings possess a relatively sound surface layer underlain by a more porous inner region. The action of machining the casting will remove part or all of the sound surface layer. This will expose shrinkage and/or gas porosity within the casting centre providing a ready path for leakage.

The tendency for many leakers to occur near the parting line may be explained by the presence of the gate to the overflows which provides an area where the internal porosity will be shifted towards the area to be machined. Figure 3 .2 shows the likely effect of machining at the tube end. Under certain conditions and within certain regions the process of machining the tube will expose internal porosity. This provides a leak path through the outside surface of the tube.

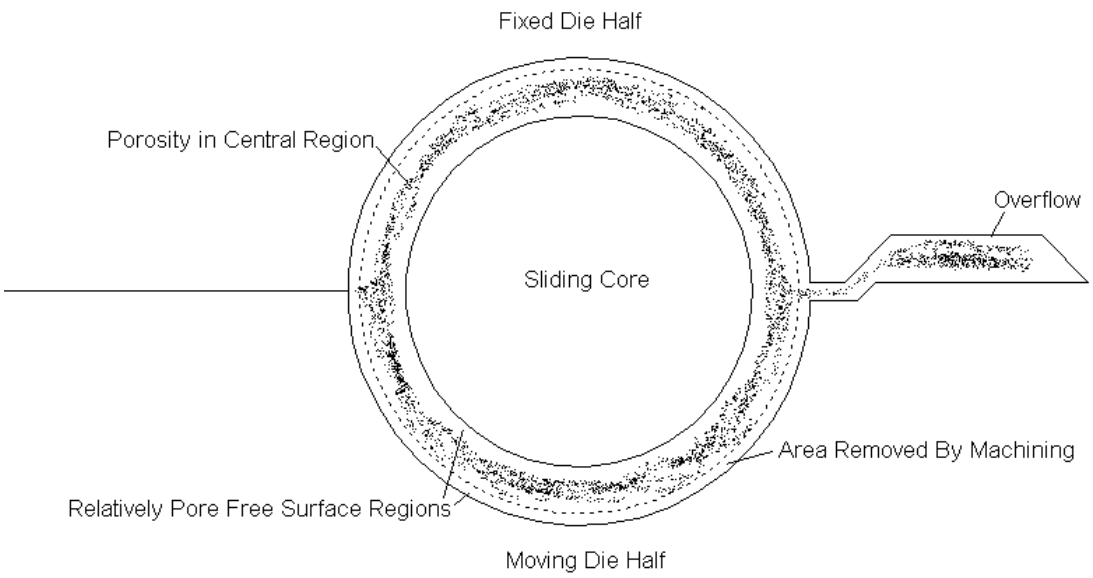


Figure 3.2 Likely Porosity Distribution at Tube End, Showing Effect of Overflows and Machining.

This raises the question of whether a strong correlation exists between the location of overflow gates and the location of leakers. Figure 3.3 shows the location of overflows and the corresponding gates. Gates are present on each side of the tube end. In a small number of cases leakers occurred at locations exactly corresponding to these gates, but in the majority of cases the location of leakers did not match the location of the gates to the overflows.

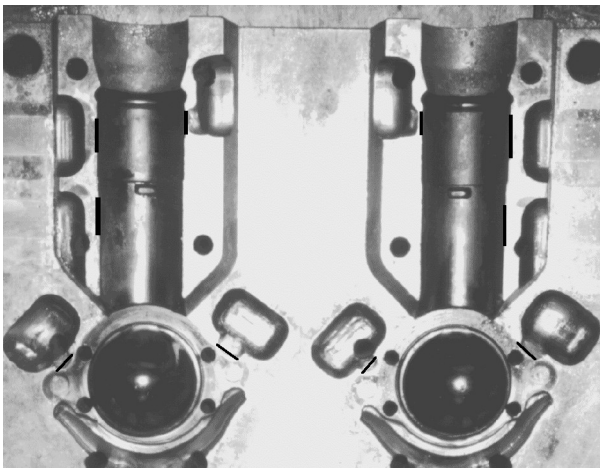


Figure 3.3 Water Inlet Die Cavity Showing Location of Overflows. The Gates to the Overflows are Marked in Black.

In one case a large leak was observed through a "break-under" defect occurring at an overflow gate on the tube but away from the machined area. Break-under refers to a defect that occurs during trimming of the casting when material is removed from the casting behind the gate due to the shearing action of trimming, see Sections 2.3.5 and 2.3.7. This defect will be exacerbated by the presence of shrinkage porosity or other defects present in or around the gate. The occurrence of such a defect during trimming may also lead to a larger number of leakers occurring around the die parting line. Break-under on the machined surface will be masked by the machining process, making it harder to identify after leak testing.

Fill Pattern of Die.

The end of the tube is located at the part of the cavity most remote from the gate. Metal reaching this area will have traversed the rest of the cavity, losing heat along the way. Due to the shape of the cavity and the way it fills this area is also subject to a number of converging flow streams. This flow pattern is confirmed by examination of short shots, see Figure 3 .4. Here we see that two flow paths are in the process of coming together at the end of the tube. This makes this area susceptible to the formation of cold shuts when the heat lost by the flowing metal is sufficient to cause premature solidification. We would expect cold shuts to form in some locations at the tube end in preference to others.

Lack of Intensification.

Due to this area's remoteness from the gate it is likely that the application of high intensification pressure will have less beneficial effect on this region of the casting. We expect that the internal region of the casting at the tube end will be less dense than regions nearer the gate.

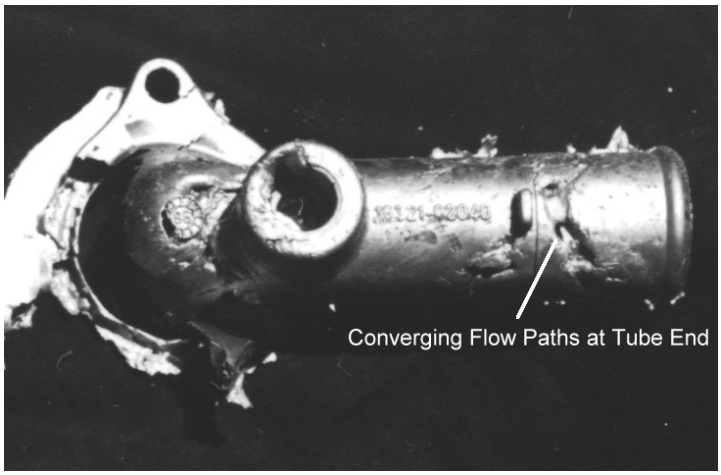


Figure 3.4 Short Shot Showing Last Areas to Fill.

3.2.2 Possible Factors Leading to Leakage Around the Lugs

The occurrence of leakers around the lugs will be affected by the distance from the gate, ie. the occurrence of cold shuts and the lesser effect of intensification pressure. To this, the presence of the lugs will add a couple of other factors that may lead to leakers occurring.

Stresses Induced By Restriction to Shrinkage

The lugs provide a restriction to the shrinking of the casting. Thus there will be stress applied to the base of the lug as the casting shrinks during cooling. Figure 3 .5 shows the locations at the base of the lug where stresses induced by volumetric contraction of the casting during cooling will occur.

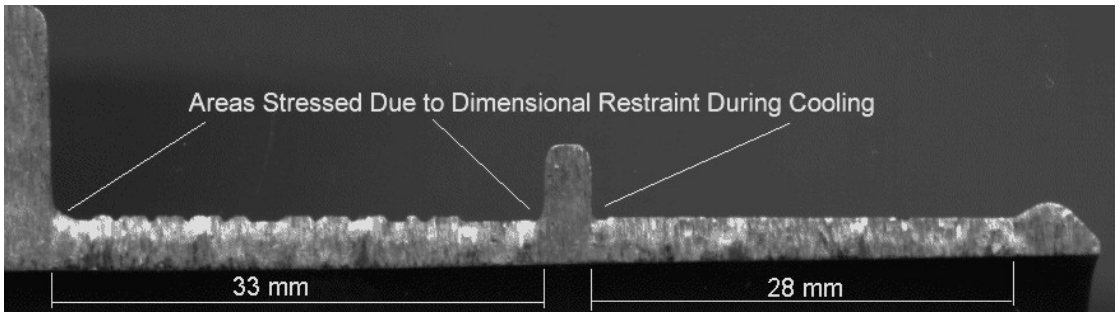


Figure 3.5 Restrained Sections Near Tube End.

We can determine, very roughly, the strain caused by the contraction of the casting and thus the stresses induced. The “Metals Handbook” [37] gives a range of properties for 380.0 alloy, a United States designated alloy that is very similar to 313 alloy, amongst these is the coefficient of thermal expansion.

$$\text{Coefficient of Linear Thermal Expansion } (20\text{-}200\ ^\circ C) \approx 22 \times 10^{-6}\ \text{m/m}.k \qquad [37]$$

The temperature at which the alloy is completely solid is 540 ˚C [37]. Observation using a thermal imaging camera indicates that ejection occurs when the alloy is at around 300 - 400˚C. Thus we can calculate the strain caused as the casting cools between these temperatures using the formula:

$$\text{Strain} = \text{Coefficient of Thermal Expansion}(\text{m/m}.k) \times DT$$

$$\text{Strain} = 22 \times 10^{-6} \times (540 - 300) = 0.0053\ \text{m/m}$$

If we use a value of 71 GPa from [37] for the modulus of elasticity we can find an approximate stress value using:

$$\text{Stress}\ (\text{Pa}) = \text{Modulus of Elasticity} \times \text{Strain}$$

$$\text{Stress} = 71 \times 10^{9} \times 0.0053 = 375 \times 10^{6}\ \text{Pa}$$

Comparing this value with a yield strength of 165 MPa and a ultimate tensile strength of 330 MPa [37] we see that yielding and indeed fracture is likely. However, due to the small distances involved, about 30 mm (see Figure 3 .5), the amount of yielding necessary to relax the stresses involved will be small. For a strain of 0.0053 m/m over a distance of 0.03 m, the displacement caused by yielding will be:

$$\text{Displacement Due to Strain} = 0.0053 \times 0.03 = 0.00016\ \text{m}$$

These calculations are very approximate as they use material properties based on room temperature conditions which will not be the case during casting. Nonetheless, they show that cracking due to solidification stresses is possible, but that due to the small restrained distance, any cracking will be of very small size. Nonetheless, it is possible that the action of solidification stresses will worsen any defects present such as cold shuts and gas porosity.

Flow Irregularities Induced by Lugs

The holes in the die cavity that form the lugs will act as a disturbance to smooth metal flow within this region, contributing to the occurrence of cold shuts.

3.2.3 Summary of Possible Causes of Leakers

From observation of the location of common leakers we can conclude that the following defects may be the cause of leakage in this casting.

- Porosity in the central region of the casting, caused by shrinkage and/or the presence of gas.
- Shrinkage and gas porosity near the external surface of the tube at the gates to the overflows and the occurrence of break-under during casting trimming.
- Cold shuts on internal and/or external faces of the tube.
- Expansion of defects near the lugs due to the influence of stresses induced by casting shrinkage during solidification.

The machining of the tube end will contribute to the formation of leakers by removing any sound as-cast surface layer.

3.3 Examination of Observed Leakers

Visual examination of castings generally confirms the information gleaned from the location of the leakers. The following defects were noted on leaking castings.

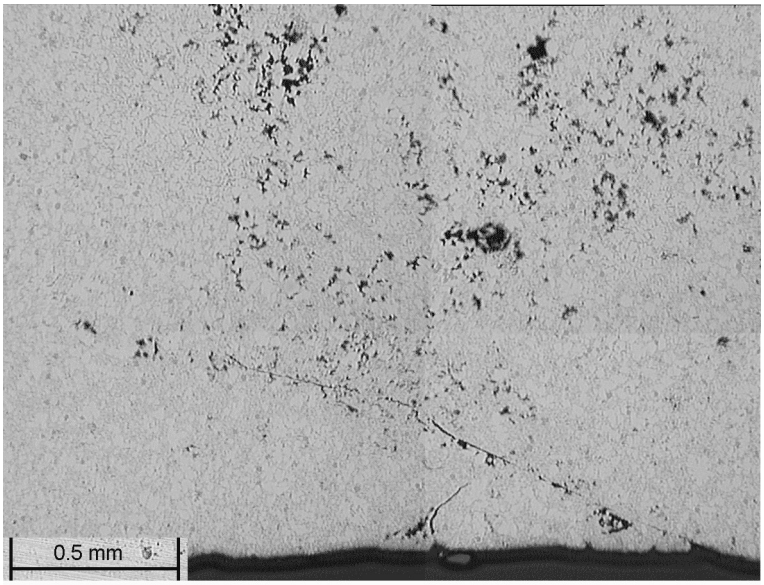
- Cold shuts in various locations and of various sizes on the internal face of tube.
- Exposed gas/shrinkage porosity on machined surfaces.
- Surface porosity on the internal surface of the cylinder.
- Drag marks on the internal surface of the cylinder.
- Small cracks associated with other defects around the base of lugs.

Some of these defects were often noted on sound castings as well as leaking castings, while others seemed to be more common on leaking castings than on sound ones. The following discussion expands upon this using information gathered from the examination of large numbers of leaking castings to determine which types of defects commonly lead to leakers.

3.3.1Cold Shuts on the Internal Face of Tube

These defects were commonly found on leaking castings. Occasionally they were also noted on sound castings. From the literature we already have a good idea of the causes of cold shuts and the manner in which they lead to leakage, see Section 2.3.2. Applying this knowledge to the situation at hand, we can make the following points:

- The cold shuts observed on the internal face of the tube allow a path through the otherwise sound surface layer into the central regions of the casting. This concept is well illustrated by Figure 3.6.



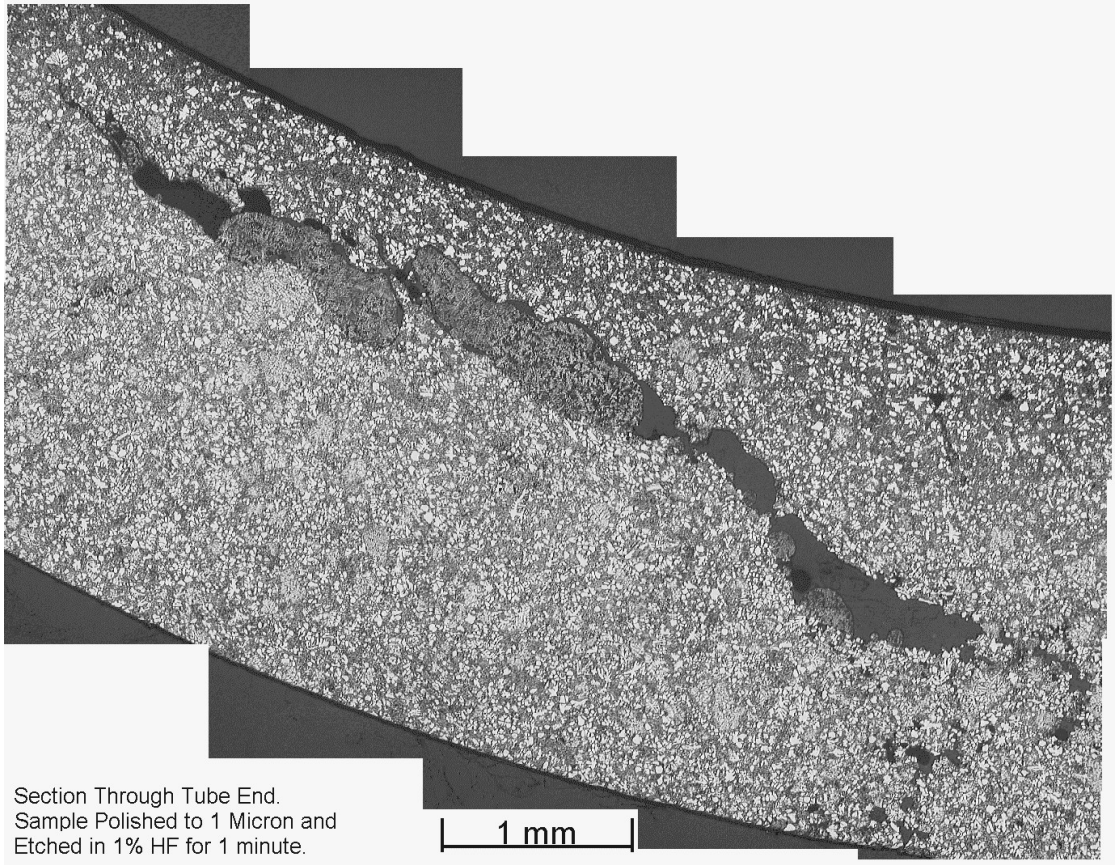
Cross Section Through Surface Cold Shut. Polished to 1 micron, Unetched.

Figure 3.6 Cold Shut at Surface of Leaking Casting Leading to Porous Inner Region.

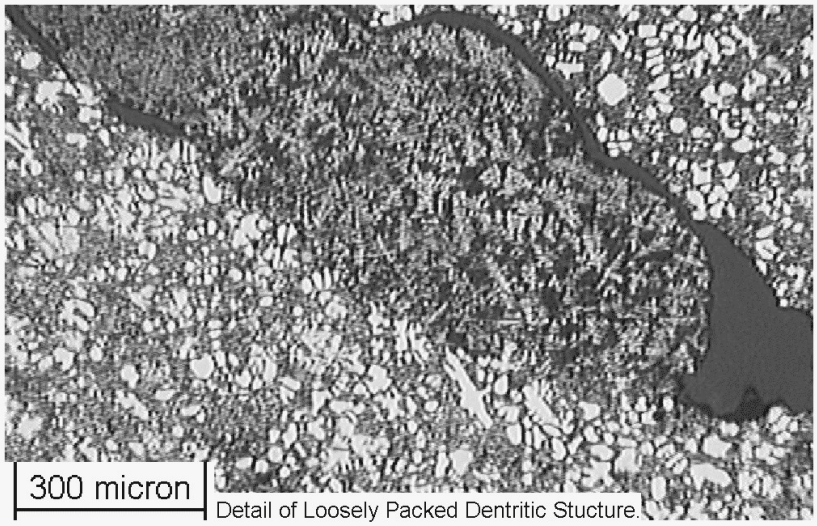
- In some cases the cold shuts visible on the surface are indicative of larger defects present within the casting. Such larger defects may provide a leakage path through the body of the casting. Such a case is illustrated in Figure 3 .7. In this case a number of small cold shuts were visible on the casting as well as porosity on the external tube face. Sectioning revealed a very large void associated with a cold shut. Figure 3 .7 shows an overall view of the cold shut defect as well as an expansion of an interesting microstructure found within the cold shut.
- The consistent position of cold shuts suggests that they are caused by poor flow patterns within the die coupled with an excessive fill time.

Comparison of actual fill times with calculated ideal fill times shows that the actual fill times are generally less that the calculated maximum fill times, see Appendix B. This suggests that this casting is especially prone to cold shutting due to poor

fill patterns. As such the fill times need to be considerably shorter than the values suggested by calculation. Such fill times are generally achieved in practice as the majority of castings are free from cold shuts. In cases where cold shuts have occurred it is likely that the maximum allowable fill times have been reduced by changes in the heat transfer rate between the metal and die. It is unlikely that the actual fill times would vary significantly.



Section Through Tube End.
Sample Polished to 1 Micron and
Etched in 1% HF for 1 minute.



Detail of Loosely Packed Dentritic Stucture.

Figure 3.7 Large Cold Shut Leaving Void Through Casting Centre.

3.3.2 Exposed Gas/Shrinkage Porosity on the Machined Surfaces.

Many castings display visible defects on the machined surfaces. The majority of these display the classical rounded and shiny characteristics of gas porosity. Others present a more complicated appearance that could represent either shrinkage porosity exposed by machining or cold shuts. There does not appear to be a strong link between the appearance of this exposed porosity and the occurrence of leakers. Many castings that exhibit excessive surface porosity on the external surface appear sound under pressure testing. Similarly not all leakers exhibit such exposed porosity.

Furthermore, the nature of the pressure testing method, see Appendix A.4, allows the external exit point of the leaker to be determined accurately. This allows us to make the interesting observation that in many cases where porosity exposed by machining is present, the leak path does not exit through the obvious pore. In most cases the exit point of the leak appears defect free to the naked eye.

Nonetheless, in many cases exposed pores are noted on leakers. In cases where these exposed pores are due to shrinkage porosity or cold shuts it is easy to conceive how they may be linked to internal paths for leakage. However, this will only occur in the minority of cases. In the majority of cases the exposed pores appear to be the result of gas porosity. In these cases the potential still exists for an interconnected leak path to extend from a gas pore. Figure 3 .8 shows a section through a leaking casting that displayed significant exposed porosity on the machined surface. The expansion of Area 2 shows the manner in which an exposed gas pore can be very nearly linked through smaller pores to other pores.[1] As the casting carries on either way in the dimension perpendicular to the page, it is likely that linkage of the pores will occur in this third dimension as well. With this in mind it is apparent that in some cases links may occur further through the casting. This exposed porosity may therefore be linked to the formation of leakers.

In a similar manner, Area 1 shows porosity near the inner surface of the tube. The pores get very close to, but do not actually break the surface. Remembering that the

[1] Interestingly we see what appears to be inter-linked shrinkage porosity in close proximity to the gas pores. Referring to Sections 2.3.4 and 2.3.8 of the literature review we recall the uncertainty surrounding the interaction between gas and shrinkage porosity. Figure 3 .8 suggests that the presence of gas porosity may retard shrinkage feeding.

casting continues on in three dimensions it is possible that breakage of the surface occurs in a parallel plane due to small shrinkage porosity or small cold shuts.

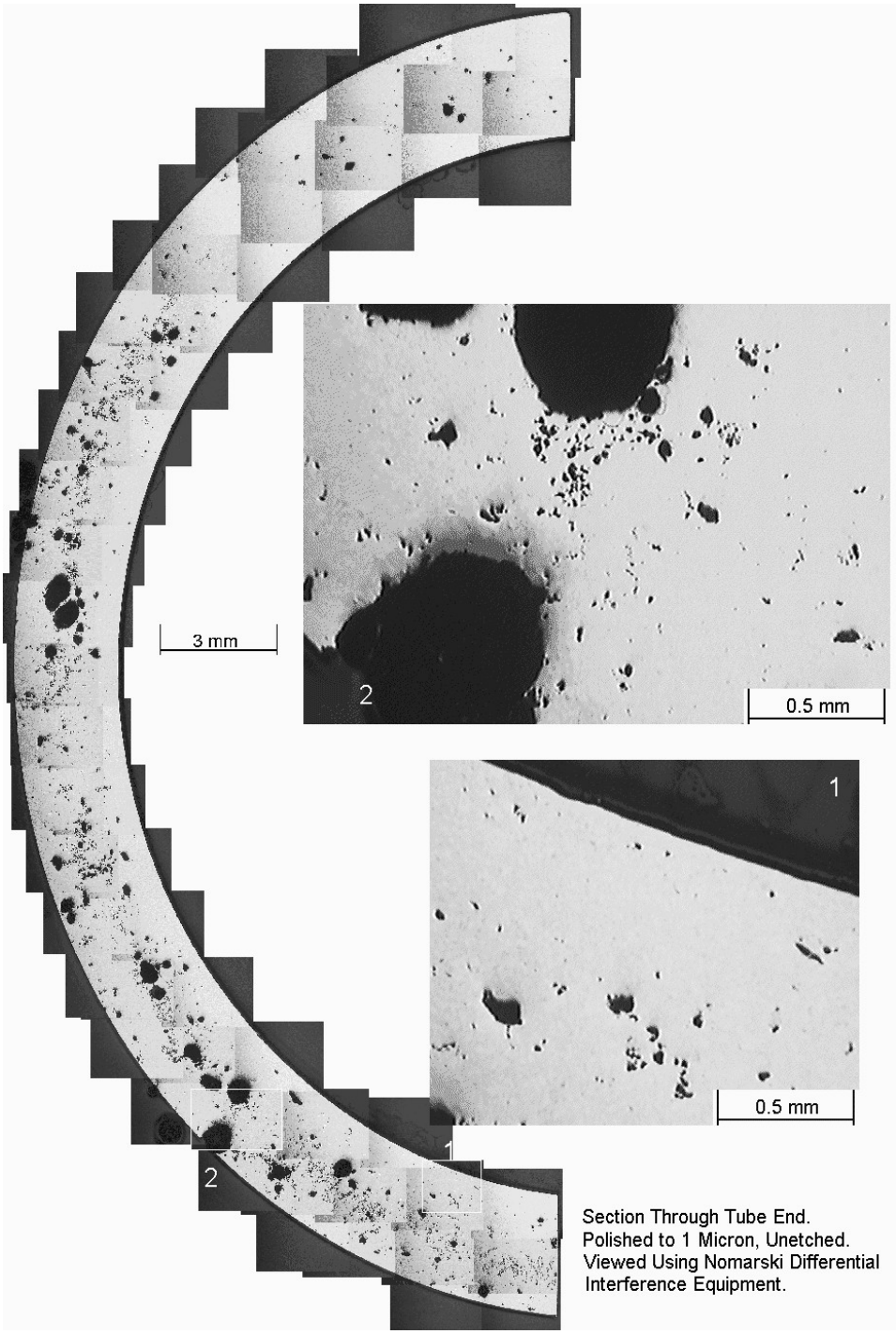


Figure 3.8 Extensive Gas Porosity Found Through Section of Tube End.[2]

[2] Nomarski Differential Interference refers to a method of illumination that can be used to highlight differences of height within the sample. When used on an un-etched polished sample the only significant height difference will be due to the porosity. Thus this approach can be used to highlight the various voids in the casting, limiting the distraction of other features of the microstructure. The "Metals Handbook" [38] gives a detailed description of the workings and use of this technique.

Looking at situations in which this porosity has been caused by the presence of gas in the casting, it is easy to isolate its major causes. Referring to the shot timing as recorded by the shot traces and to the design of the runner system itself we find two major causes of excessive gas porosity within the castings.

Entrained Air Due to Wave Formation in the Shot Sleeve

In the review of the literature we discussed the importance of the first stage velocity and acceleration in terms of minimising the formation of waves in the shot sleeve and thus gas entrapment. If we use the most basic approaches outlined by [9] we find that while the velocities and accelerations used are near the theoretical optimal values, the change-over from the first to second stage occurs significantly earlier than would be expected, see Appendix C. The plunger accelerates to the high velocity second stage while the remaining shot sleeve volume is only 70% full of alloy. The result of this is that a very large proportion of air will be entrained by the molten alloy as the plunger accelerates to second stage velocity. Figure 3.9 shows an actual shot trace with the "shot-sleeve full" point marked. We can see that the plunger has begun acceleration well before this point.

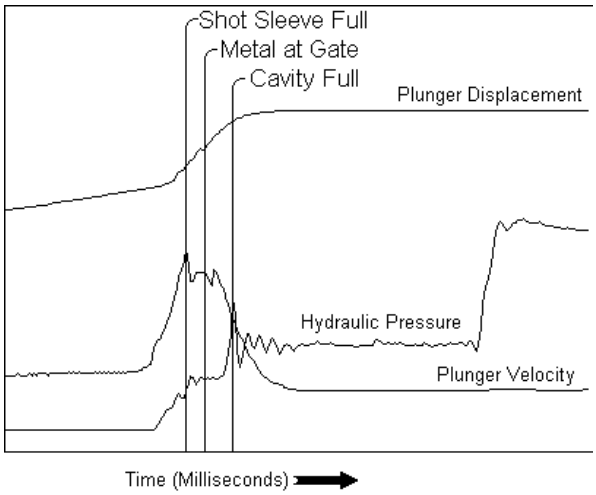


Figure 3.9 Shot Timing for Water Inlet Casting.

Gas Entrapment Due to Lack of Streamlining in Runner System Examination of the runner system indicates that there is a section at which the runner rapidly diverges. This is highlighted in Figure 3.10. Such a section will mean that the rapidly advancing metal front will separate at this point allowing further gas entrapment. Short shots indicate that at this point the momentum of the molten metal causes the metal flow to maintain a reasonably straight trajectory, flowing up and through the outside gate. This effect is shown in Figure

Figure 3.10 Diverging Runner Section of Water Inlet Casting.

3 .11. This results in large areas that will remain unfilled after the die vents have been sealed off. Air in these unfilled areas will remain trapped within the casting.

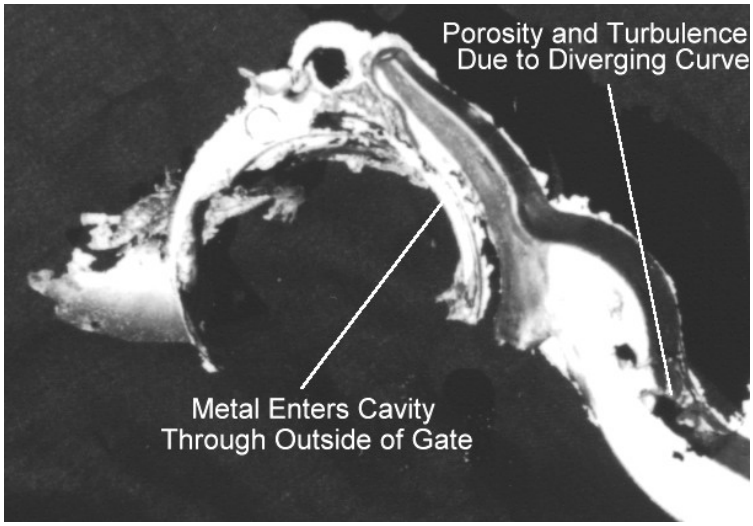


Figure 3.11 Short Shot Showing Flow Through Runner.

Total Level of Gas Entrapment Within the Casting

Both these causes of gas entrapment are design features of the die. Their effect will not differ greatly from shot to shot. We can expect a high level of gas porosity in every casting due to this. Unless there are significant changes in the shot timing between different shots and/or different production runs, this mechanism of gas porosity formation does not explain differences in leaker rate between different production runs or different shifts etc. If we were to modify the shot timing to begin acceleration to second stage velocity while the molten metal front was somewhere along the runner system and/or redesign the runner system to improve streamlining we would expect that the overall level of castings rejected due to leakers as well as exposed porosity would drop. However, as already discussed the high number of sound castings displaying excessive gas porosity and the number of leakers that appear to have less gas porosity suggests that while gas porosity assists the formation of leakers, it is not the most direct cause of leakers in this case.

3.3.3Surface Porosity on Internal Surface of Cylinder

This defect was infrequently observed on the internal surface of leaking castings. Usually its appearance is coupled with excessive cold shutting. Figure 3 .12 shows an example of this defect.

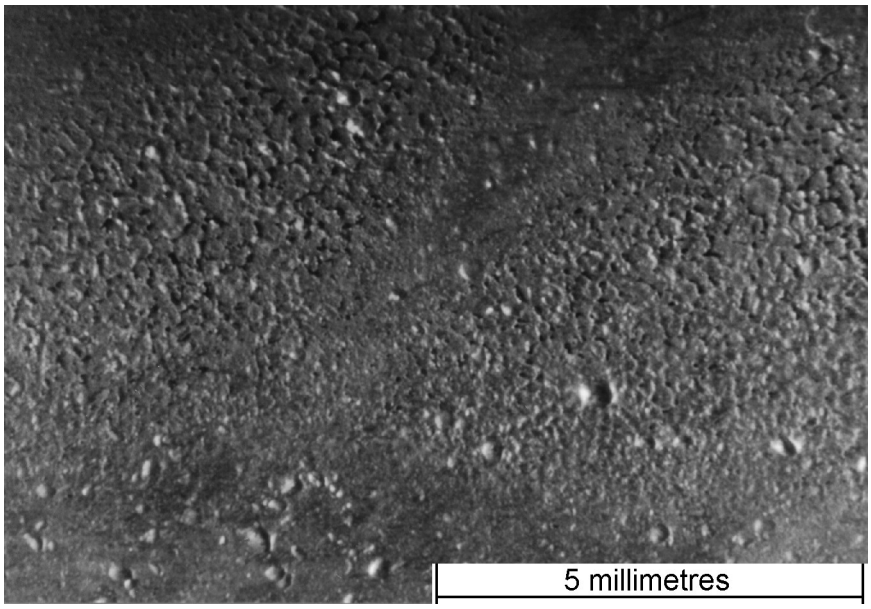
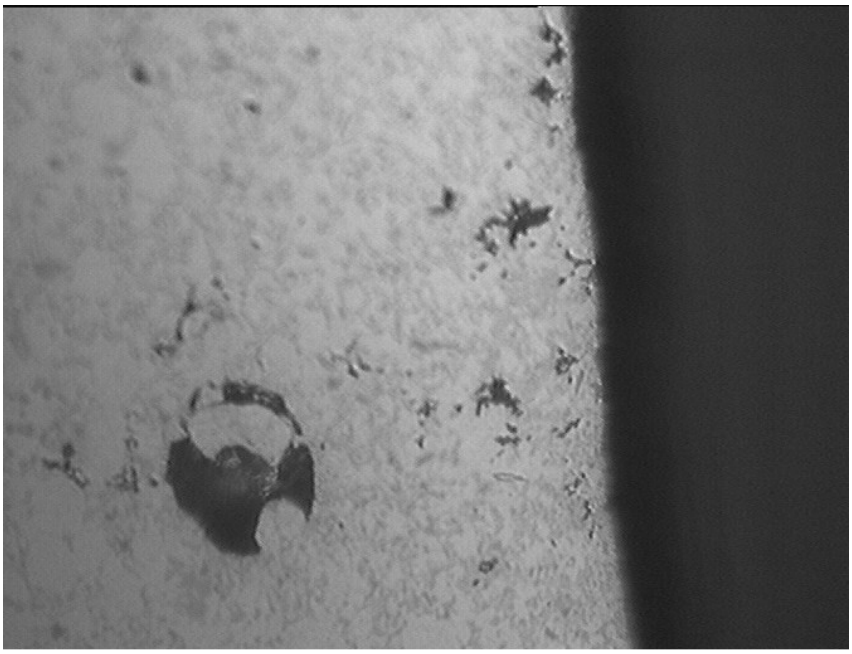


Figure 3.12 Surface Porosity on Internal Face of Tube.

The pores' discoloured appearance and pattern of occurrence suggests that they are caused by the volatilisation of die lubricant. As well as the application of die spray every shot there is a periodic application of thick, waxy lubricant to the die. The application of this lubricant slows the cycle slightly allowing the die to cool momentarily. This will increase the likelihood of cold shutting.

We would expect that the presence of these surface pores would provide a path for leakage through the inner wall of the tube. Sectioning through such defects reveals that this is the case in some examples while in others the surface porosity appears more superficial.

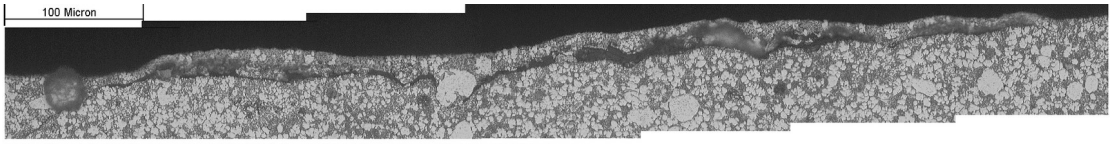
Figure 3 .13 shows a case where sectioning through the visible surface porosity revealed a series of interconnected pores leading into the centre of the casting. Figure 3 .14, however, shows a case where sectioning through apparently similar surface porosity revealed large pores running parallel to the surface of the casting but failing to lead into the centre of the casting.



Section Through Surface Porosity on Internal Tube Wall.
Sample Polished to 1 micron, Unetched.
Viewed Using Nomarski Differential Interference Equipment.

50 Micron

Figure 3.13 Section Through Surface Porosity on Internal Face of Tube Leading to Interconnected Pores Within the Casting.



Section Through Surface Porosity on Internal Tube Wall. Sample Polished to 1 micron and Etched in 1% HF for 1 minute.

Figure 3.14 Section Through Surface Porosity on Internal Face of Tube that Appears to be Isolated from Porosity Within the Casting.

The evidence points to this surface porosity allowing a leakage path through the inner surface of the tube in a small number of cases. In others cases castings made in a cold die immediately after the application of die lubricant will exhibit both surface porosity and extensive cold shutting. In these cases it is impossible to say whether the leakage path through the internal wall of the casting will be provided by the cold shut or the surface porosity. Judging by the strong link between cold shuts and leakage it is likely that in most cases it will be the cold shut that allows leakage. Thus it may be that a correlation between leakers and this surface porosity may be due more to this link between cold shuts and the die lubricant than to a genuine strong link between the formation of leakers and the appearance of this surface porosity.

3.3.4 Drag Marks on Internal Surface of Cylinder

As the sliding core retracts after solidification some sticking occurs leaving drag marks on the internal walls of the tube. Figure 3 .15 shows an example of drag marks on this surface.

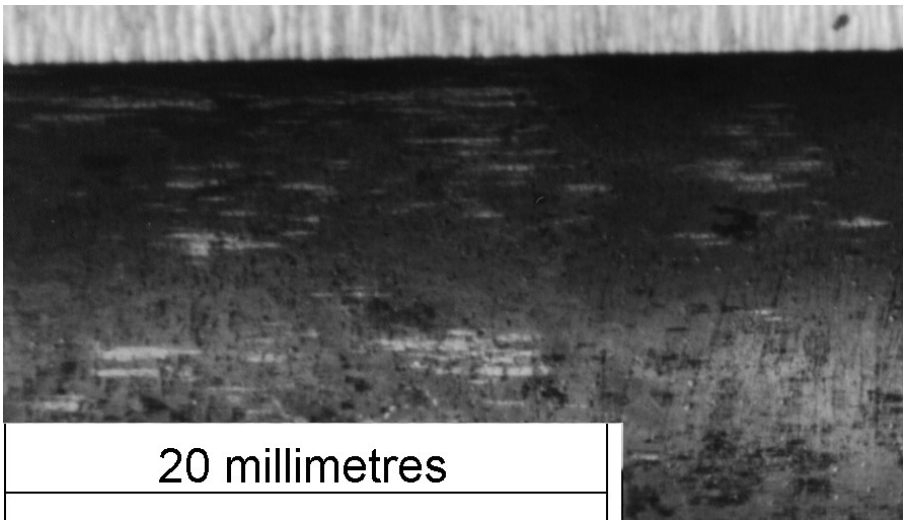


Figure 3.15 Drag Marks on Internal Wall of Tube.

These are most severe towards the end of the sliding core, ie. towards the base of the tube. This area is well away from the machined end of the tube where nearly all leakers occur. This coupled with the fact that drag marks are found on nearly all castings, regardless of other defects including leakers, indicates that they are not a major cause of leakers in this case.

3.3.5 Small Cracks Around Base of Lugs

In a small number of cases leakers were observed around the base of the lugs on the top and bottom of the tube. In these cases small cracks were sometimes observed in these areas. Figure 3 .16 and Figure 3 .17 show two sections through cracks near the lugs.

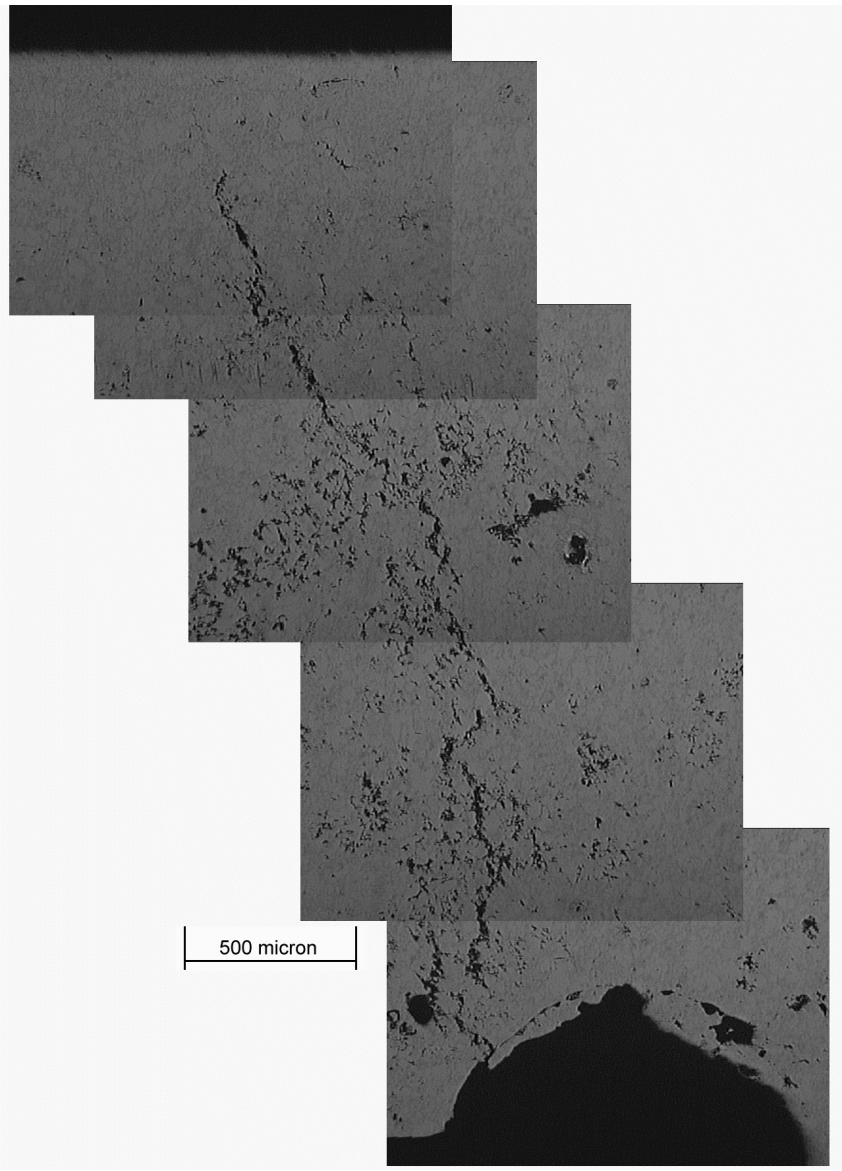


Figure 3.16 Small Crack Running Through Casting Near Base of Lug.

The cracks shown in both Figure 3 .16 and Figure 3 .17 are very small in width. This is consistent with the calculations in Section . In Figure 3 .16 a crack has occurred in a region weakened by shrinkage porosity. Figure 3 .17 shows small cracks between the outer surface of the tube and large gas pores present below the surface. It is likely that the cracks are present mainly due to the occurrence of these other defects. It is reasonable to conclude that cracking due to stresses applied after solidification may help cause leakers in some cases, but is unlikely to be the root cause of a leak. In most cases where leakage was observed around the lugs, although cracking was observed around the lugs, other defects such as cold shuts or excessive porosity were also noted on the casting.

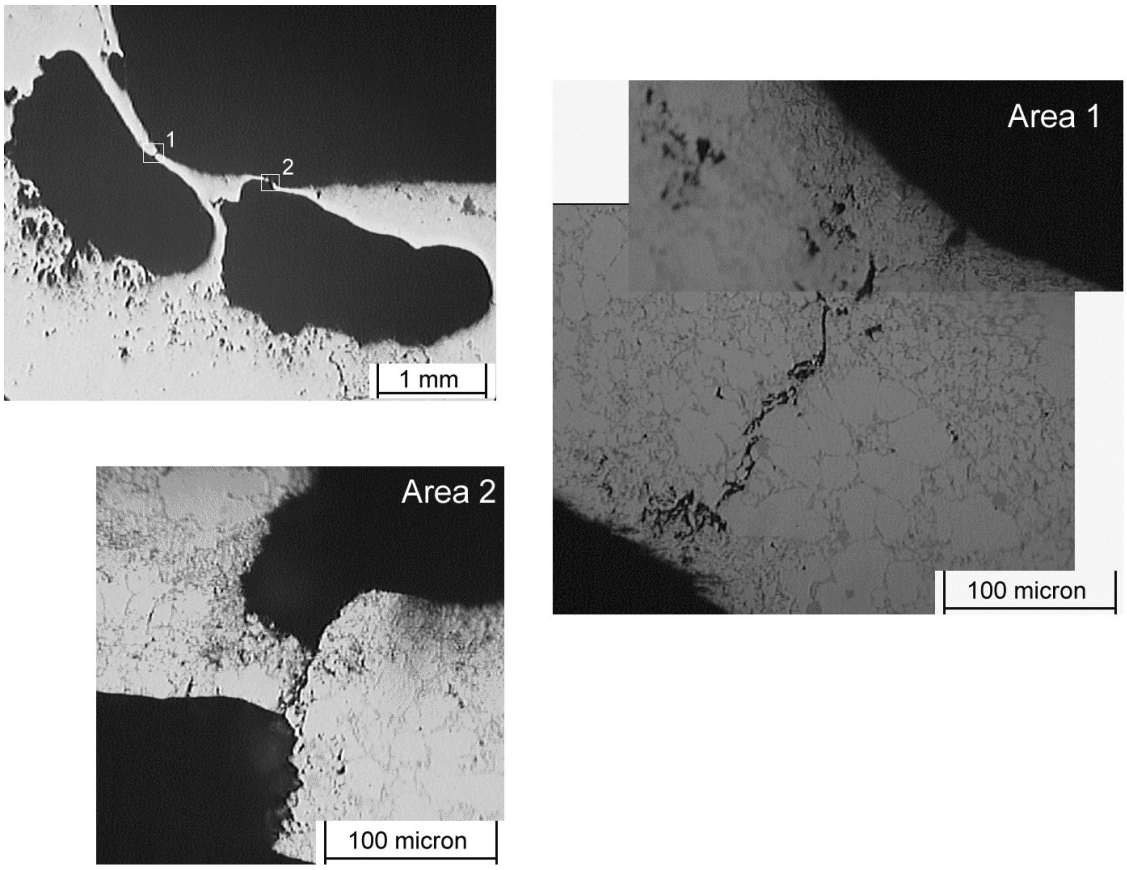


Figure 3.17 Cracks Associated With Large Gas Pores Near Base of Lug.

3.3.6Summary of Causes of Leakers

The above observations indicate that there are a number of contributing factors to the formation of leakers. Of these exposed gas/shrinkage porosity and drag marks are present to some extent in most castings whether they leak or not. Thus while they may influence the mean number of leakers occurring over time it is unlikely that they provide a direct mechanism for leaker formation. Surface porosity on the inside of the tube and small cracks around the lugs were found in association with leakers but usually also in the presence of cold shuts. Cold shuts were the only defect type that showed a strong likelihood of being directly linked to the formation of leakers.

3.3.7Correlation Between Cold Shuts and the Occurrence of Leakers

To test whether the perceived link between cold shuts and the occurrence of leakers was real or imagined a simple test was performed. From the results of the experiment discussed in the following Chapter, 65 castings that were rejected either due to leakage or visible defects were examined. Visible defects ranged from porosity visible

on the machined surfaces to large external cold shuts as well as defects that occurred during machining.

Castings were cut down the centreline, allowing easy visual examination of the internal surface of the tube. Each casting was visually examined and the size and number of any cold shuts recorded using a scale of 0 to 4. 0 represents no visible cold shuts while 4 represents severe cold shuts. A visual description of each level of cold shutting is given in Appendix D.

Table 3 .1 lists the number of leakers occurring at each level of cold shutting. It is apparent that there is a significant correlation between the level of cold shutting recorded and the occurrence of leakers. The significance of this correlation was confirmed using a χ^2 test, see Appendix E. This suggests two theories, either these cold shuts lead directly to leakers in some cases or the mechanisms that lead to cold shuts are closely related to those which lead to leakers.

Level of Cold Shutting	None	Small	Moderate	Extensive	Severe
Number of Castings	24	15	13	9	4
Number of Leakers	2	4	6	6	4
Leaking Castings/Castings	0.083	0.27	0.46	0.67	1

Table 3.1 Relationship Between Extent of Cold Shutting and Leakers.

Observations of castings made during normal production and in trials where the cycle was not extensively interrupted suggest that under normal conditions the level of cold shutting would generally vary from 0 to 2. Levels 3 to 4 would only occur when the die is colder than usual.

Although there is a strong correlation between the formation of leakers and the occurrence of cold shuts, in two cases leakers occurred where no cold shuts were visible. This indicates that although visible cold shuts are usually related to leakers, cold shuts are unlikely to be the sole cause of leakers in this casting.

3.4Summary

Observation and examination of leaking and sound castings indicates a strong relationship between the occurrence of leakers and the occurrence of cold shuts. The location and pattern of occurrence of these leakers indicates that they occur at locations large distances from the gate where the in-flowing metal has suffered large heat losses as it traverses the cavity. This suggests that the time taken to fill the cavity is excessive.

If we use the calculations in [9] to calculate an “ideal” fill time and compare this with the fill time achieved in practice we find that the actual fill times do not appear to be excessive. It is likely that the high degree of gas entrapment and the very broken and swirling cavity fill pattern that would be caused by the shot timing and diverging runner means that this casting is particularly prone to cold shuts. Nonetheless if the die were sufficiently hot at the time of casting we should still be able to make castings without cold shuts. This is confirmed by the fact that the vast majority of castings are free from cold shuts and do not leak. Given that the injection conditions will be reasonably constant during production it would be expected that the controlling influence on cold shut formation will be the heat transfer rate to the die. This heat transfer rate will be determined by the temperatures of the die and the metal. In order to test this relationship an experiment during which the heat transfer rates were manipulated was executed. The next chapter discusses the results of this experiment.

Chapter 4

Determination of Effect of Die and Metal Temperature on Casting Quality

4.1 Aims of Experiment

Having established in the previous chapter that the formation of cold shuts near the casting extremity appears to be the major reason for the formation of leakers, this trial is aimed at changing the casting conditions to encourage the formation of cold shuts and examining the effect of these changes on the proportion of leakers produced.

To encourage the formation of cold shuts the rate at which the solidifying alloy gives up its heat can be increased and/or the amount of heat the alloy has to give up before it fails to flow can be decreased. These can be controlled directly by using fluid cooling of the die and by varying the metal temperature.

4.2 Description of Trial

4.2.1 Control of Heat Removed Using Cooling Channels

The design of the die allows cooling to be applied independently to a number of different regions. This feature can be used to cool one cavity while the other remains at relatively normal conditions. Figure 4 .1 shows how this can be done.

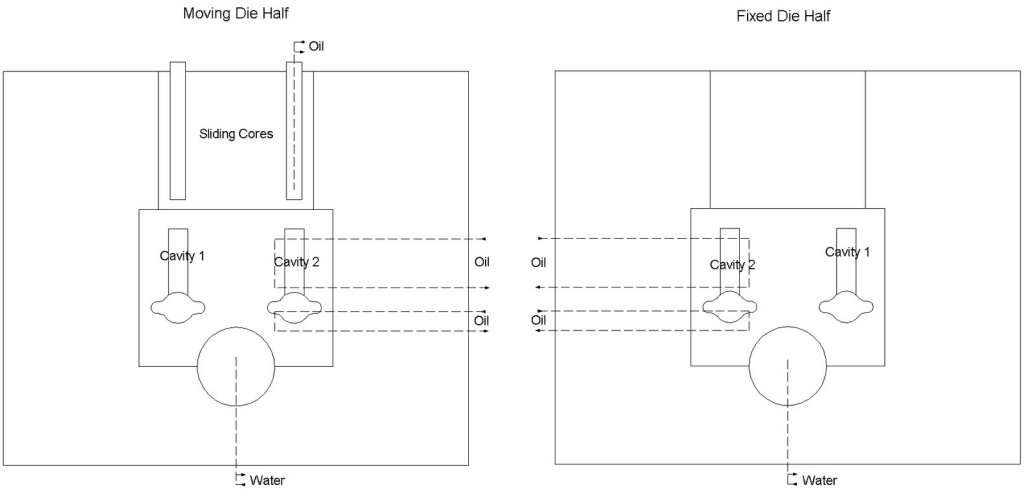


Figure 4.1 Diagram of Cooling Line Setup During Trial.

Oil is pumped through the marked lines to remove or add heat to the cavity depending on the relative temperatures of the die and the oil. The use of oil as a heat transfer medium allows greater control of the input temperature and the flow rate using a standard oil heater/cooler unit, when compared to water pumped directly from the mains supply. Water is pumped through cooling lines within the sprue post on the moving die half and through a sleeve around the shot sleeve on the fixed die half. This

maximises cooling of the biscuit, reducing the cycle time of the die. This approach to cooling around the biscuit is standard practice during production of this casting.

The oil input temperatures used were selected based on knowledge of the usual operating conditions of the die. 180 °C was used for the "Low" oil cooling level. This oil temperature is commonly used to warm the die before the first shot and to keep the die running at reasonable temperatures during interrupted production. When used in such a manner the oil is usually run through channels further from the cavity surface than the channels used during this trial. This results in a bulk heating of the die rather than the more localised control used in this trial. 100 °C was used for the "High" oil cooling level. This oil temperature should simulate a cold die without cooling it to a point where it becomes inoperable.

Referring to Figure 4 .1 we note that only cavity 2 is directly cooled by the oil. Leaving cavity 1 un-cooled gives us an extra "Zero" oil cooling level. To compare this directly with the castings made in cavity 2 we need to make the assumption that under equivalent thermal conditions the two cavities would produce equal numbers of leakers. Common sense suggests that this would be the case, but previous observations and experiments have yielded insufficient numbers of leakers to confirm this assumption.

4.2.2 Control of Casting Alloy Temperature

The temperature of the molten alloy prior to casting can be readily controlled using the metal holding furnace control system. This allows the metal temperature to be set over a wide operating range. The normal operating temperature for the casting in question is 680 °C. This value was selected as a "high" operating point, while a value 20 °C below this, 660 °C, was used as a "low" operating point.

Lowering the alloy temperature would be expected to reduce the amount of heat the alloy can surrender before it fails to fill the cavity, ie. it will reduce the solidification time of the alloy. By changing the thermal state of the die it will also impact upon the heat transfer rate and the observed die temperatures.

4.2.3 Summary of Experiment Design and Expected Effects

We have proposed the use of three levels of die cavity cooling and two levels of alloy temperature. Such a design lends itself to the use of a six point experiment. Figure

4 .2 summarises this experimental design and the expected effects of varying parameters in this way.

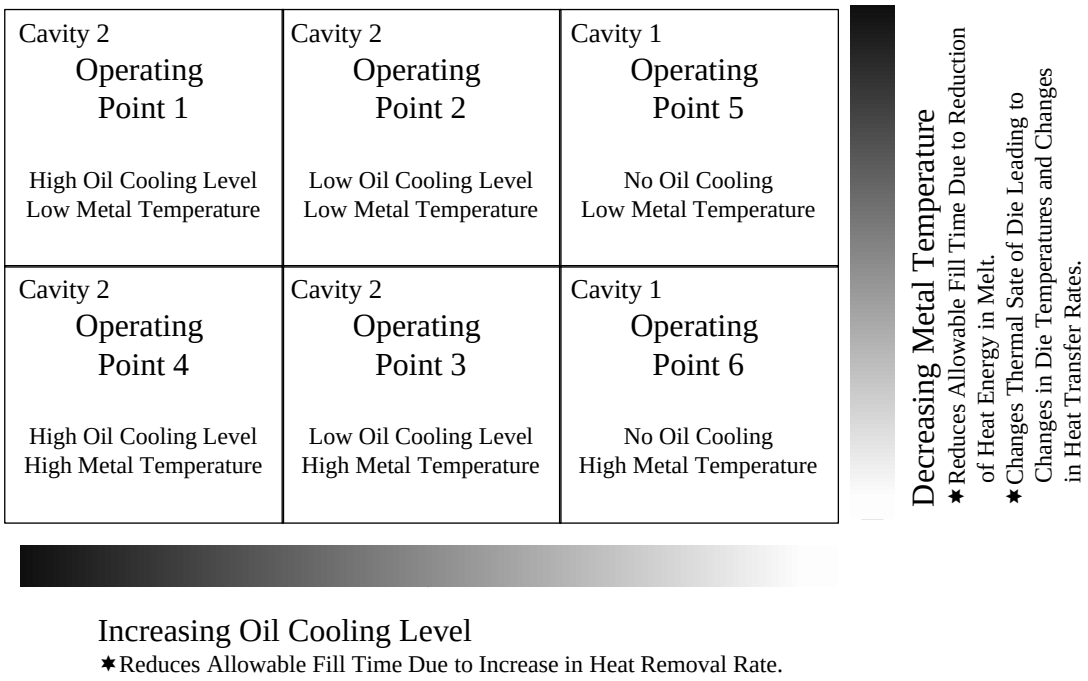


Figure 4.2 Summary of Experimental Design and Expected Effects.

By producing castings at each of these six points we will be able to test the effects of each control input on the castings.

We wish to produce as many castings at each operating point as possible to maximise the accuracy of the results. The number of castings that can be made practically will be limited by the amount of time we have access to the machine. In this case a target of 30 to 40 castings representative of steady production conditions at each operating point was judged to be reasonable. To achieve this a target of 50 castings per operating point was set. Due to the use of a 2 cavity die and the experimental design, twice as many castings will be made at operating points 5 and 6, ie.

✶ Operating Points 1 - 4 : 50 Castings Each

✶ Operating Points 5 - 6 : 100 Castings Each.

Of the 50 castings a number will be removed. Castings removed will include those made at the start of the operating condition when the die temperature is much lower than that encountered during steady production. This accounts for “warm up” shots which are usually discarded as standard production practice. Any other castings that

show up as anomalies will also be removed if justified. Most of these were castings where the shot numbering on the casting appeared unreliable, making it hard to match these castings with the shot monitoring data.

4.3 Measurement of Casting Parameters

In order to correlate the occurrence of leakers with the condition of the casting machine and die at the time of casting, it is necessary to measure selected parameters to quantify the machine condition.

The high pressure die casting machine used in the trial is equipped with transducers that measure the displacement of the plunger throughout the shot and the hydraulic system pressure. These transducers are connected to data acquisition and analysis software that allows the data to be converted into series of parameters that represent the state of the machine shot end. Table 4 .1 lists these parameters.

Machine Shot End Parameters
Casting Cycle Time
Plunger Displacement During First Stage Injection
Plunger Displacement During Second Stage Injection
Average Plunger Speed During First Stage Injection
Average Plunger Speed During Second Stage Injection
Maximum Plunger Speed During Second Stage Injection
Delay Between End of Second Stage Injection and Application of Intensification Pressure
Maximum Hydraulic Pressure During First Stage Injection
Maximum Hydraulic Pressure During Second Stage Injection
Plunger Displacement at End of Injection Cycle

Table 4.1 Shot End Data Recorded During Trial.

We also need to quantify the thermal condition of the die. This can be done by measuring the cavity temperature in a number of locations. As the cavity temperature will vary throughout the casting cycle it is necessary to measure the temperature at the same point of time in each cycle to compare shots. The temperature in each cavity was measured in four representative locations. Figure 4.3 shows the location of these points.

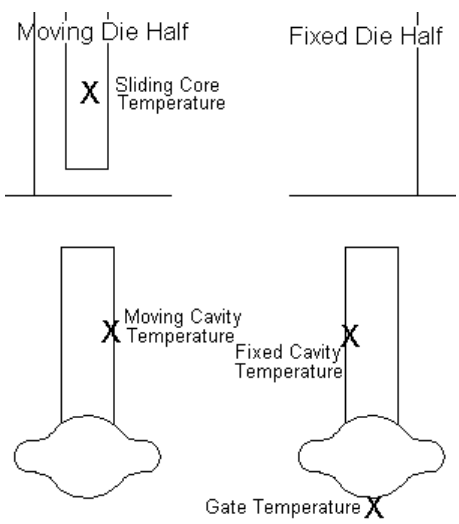


Figure 4.3 Locations of Temperature Measurements in Cavity.

During the trial these temperatures were measured every 10 shots using a hand held surface probe and recorded on paper as cavity 1 temperatures and cavity 2 temperatures. Measurements were taken immediately after the die opened, before the application of die spray, to minimise effects of any inconsistencies in die spray application. The order of measurement was controlled to ensure that measurements in each spot were taken at a consistent point in time during each cycle. After the trial these temperatures were linearly interpolated to give an approximate temperature for each location for every shot. For each casting made we therefore have a measure of the die surface temperature. The molten metal temperature was also measured every 10 shots and interpolated for each casting. This gives a more accurate reading of this important variable than the set metal temperature. Table 4 .2 lists the temperature related parameters for each casting.

Temperature Parameters for Every Casting
Casting Cavity Sliding Core Temperature
Casting Cavity Moving Cavity Temperature
Casting Cavity Gate Temperature
Casting Cavity Fixed Cavity Temperature
Measured Metal Temperature

Table 4.2 Temperature Parameters for Every Casting.

The variables in Table 4 .1 and Table 4 .2 can be regarded as casting inputs. The output variable is whether the casting leaks or not. As the test used in production is a pass/fail test it is of little value to complicate the results by scaling the amount of leakage per casting. The production leak test, see Appendix A.4, was used to assign a pass/fail output variable to each casting.

4.4 Results of Trial

The trial produced roughly 220 shots, ie. 440 castings, of which about 80 shots, ie. 160 castings, were discarded, leaving a final sample of 133 shots, ie. 266 castings. Most of the castings removed were warm-up shots. Analysis of the data indicated that removal of the first 10 shots for each condition would be appropriate. It was apparent

that the stoppages occurring every 10 shots to measure the die temperatures had a significant effect, thus 2 shots after each such stoppage were removed from the data. A handful of other castings were removed from the data due to problems with identification. In these cases the shot number was either illegible or suspicious in relation to other castings.

The number of castings made and the number of leakers made at each operating point are summarised in Table 4 .3.

	Op. Point 1	Op. Point 2	Op. Point 3	Op. Point 4	Op. Point 5	Op. Point 6
Cast	33	34	35	31	67	66
Leak	7	3	1	6	5	1

Table 4.3 Summary of Casting Results.

We can now analyse the results of the trial. The most direct approach to take is the use of statistics to see if there is a correlation between the control inputs, (the set metal temperature and the oil cooling level), and the occurrence of leakers. Following on from this we can test for correlation between the production of leakers and the measured input variables, (Table 4 .1 and Table 4 .2).

4.4.1 Correlation Between Oil Cooling Level and Leaking Castings

We can break the data into three groups depending on the oil cooling present during casting. These are;

- ✶ Castings made at operating points 1 and 4 ➢ High Oil Cooling Level.
- ✶ Castings made at operating points 2 and 3 ➢ Low Oil Cooling Level.
- ✶ Castings made at operating points 5 and 6 ➢ No Oil Cooling.

Table 4 .4 shows the data divided into these groups. The term Leaker Rate refers to the number of leakers made divided by the number of castings made at that condition.

	No Oil	Low Oil Cooling Level	High Oil Cooling Level
Number of Castings	133	69	64
Number of Leakers	5	4	13
Leaker Rate	0.03759	0.06250	0.1884

Table 4.4 Number of Leakers at Differing Oil Cooling Levels.

We can see that the maximum number of leakers per casting is produced at conditions of maximum cooling via the oil while the smallest number of leakers per casting is produced under conditions without oil cooling. We need to test whether this trend is likely to be due to a real difference in the probability of a leaker occurring between each level of cooling or whether such a result is likely in a sample where the

probability of a leaker at each oil cooling level is equal. We can test this using a statistical approach known as the χ^2 test.

To carry out a χ^2 test on our sample we use the following approach.

The value of χ^2 for our data and hypothesis can be found from Equation 4 .1.

$$c^2=\sum_{i=1}^{k}\frac{(o_i-e_i)^2}{e_i}$$ **Equation 4.1 [39]**

The terms o_i and e_i represent the observed and expected frequencies for the *i*th cell. The term *k* represents the number of groups of data. The observed values are found from the actual data, in our case the number of leakers at each operating point. The expected value refers to the value we would expect to occur if a given hypothesis is true. In our case we wish to test the hypothesis that there is no difference in leaker rates between each condition, referred to as the "null hypothesis". So the expected value for each condition can be found by finding an overall leaker rate, ie. total number of leakers divided by the total number of castings, and multiplying this by the number of castings at each condition. Table 4 .5 shows the expected frequency for each condition as well as the corresponding observed frequency.

	No Oil	Low Oil Cooling Level	High Oil Cooling Level
Expected Value (e_i)	11	5.707	5.293
Observed Value (o_i)	5	4	13

Table 4.5 Observed and Expected Frequencies for Different Oil Cooling Levels.

Thus the value of χ^2 can be found.

$$c^2=\frac{(5-11)^2}{11}+\frac{(13-5.293)^2}{5.293}+\frac{(4-5.707)^2}{5.707}=15.09$$

We can now compare this value with statistical tables which state the probability of a χ^2 value of this magnitude or greater occurring if the assumed hypothesis were true.

From pg 706 [39] we see that the probability of χ^2 exceeding 13.815 for 2 degrees of freedom[1] is 0.1%. This indicates that were the null hypothesis true, the probability of

[1] The number of degrees of freedom is defined as the number of classes whose frequencies may be arbitrarily assigned [41] without changing the overall frequency. In this case it is given by *k*-1 = 2.

the observed distribution of leakers occurring is less than 0.1%. This effectively disproves the null hypothesis. Therefore we can say that the use and magnitude of oil cooling has a significant impact on the probability of producing a leaker.

4.4.2 Correlation Between Metal Temperature and Casting Leakers

We can also break the data into groups depending on the temperature of the metal at which the casting was made. These are;

- ✶ Castings made at operating points 1, 2, and 5 ➢ Low Metal Temperature.
- ✶ Castings made at operating points 3, 4, and 6 ➢ High Metal Temperature.

Table 4.6 shows the data divided into these groupings.

	Low Metal Temperature	High Metal Temperature
Number of Castings Made	134	132
Number of Leakers Made	14	8
Leaker Rate	0.1045	0.06061

Table 4.6 Number of Leakers Made at Different Metal Temperatures.

We can see from Table 4.6 that there is an increase in the rate of leakers being formed as the metal temperature is reduced. We can test to see if this difference is likely to have occurred by chance if there were no difference in the probability of forming a leaker at the different metal temperatures (the null hypothesis). Table 4.7 shows the expected and observed frequencies for this data and hypothesis.

	Low Metal Temperature	High Metal Temperature
Expected Value (e_i)	11.08	10.92
Observed Value (o_i)	14	8

Table 4.7 Expected and Observed Frequencies at Different Metal Temperatures.

As this situation has only one degree of freedom, the accuracy of the result will be improved if we use a function known as Yates' Correction [40] when determining the appropriate χ^2 value. Yates' correction involves subtracting 0.5 from the absolute value of each (o_i - e_i) term in Equation 4.1 prior to squaring. Solving Equation 4.1 with this correction;

$$c^2 = \frac{(|14-11.08|-0.5)^2}{11.08} + \frac{(|8-10.92|-0.5)^2}{10.92} = 1.063$$

From pg 706 [39] we see that the probability of this value of $\chi 2$ being exceeded if the null hypothesis applies is greater than 30%. A probability this high means we cannot

If we arbitrarily assign the number of leakers in two of the groups in Table 4.4 then the number of leakers in the third group is determined by the fact that there must be 22 leakers overall.

discount the null hypothesis. On the basis of this data we cannot claim that the temperature of the metal has a significant effect on the probability of a leaker being formed.

4.5 Use of Trial Results to Predict Casting Output

Having shown a strong link between the use of cooling oil in this trial and the occurrence of leakers we now seek to quantify this relationship. Following on from this we will use the values of the measured parameters, Table 4.1 and Table 4.2, to try and predict the formation of leakers during our trial. Such an analysis will provide a powerful tool for the prediction of leakers during production.

To look for relationships between input parameters and the formation of leakers we will use the method of least squares to fit linear regressions between the casting quality output variable, (y), and the selected input variables, (x_i). The general form of such an equation is given in Equation 4.2. Descriptions of how to use the method of least squares can be found in Chapters 11 and 12 of [39].

$$y = m_1 x_1 + m_2 x_2 + \cdot\cdot + m_k x_k + b \qquad \textbf{Equation 4.2}$$

4.5.1 Relationship Between Control Variables and Casting Output

Using the method of least squares we can fit a linear regression that predicts the casting output from the controlled inputs, oil cooling level and set metal temperature. To fit such a curve it is necessary to assign a value to each of the possible input and output states. The values used are shown in Table 4.8. For the oil lines the variable we are changing is the rate of heat transfer from the cavity. At present we have no physical measure of this rate. Given this lack of knowledge it is appropriate to use the simplest possible method of differentiating between the levels, ie. 0, 1, and 2. For the metal temperature the choice of values is unimportant as with only two levels the linear regression will account for any changes.

Oil Cooling Level	No Oil	Oil at 180 ˚C	Oil at 100 ˚C
Value of x_1	0	1	2
Set Metal Temperature	660 ˚C	680 ˚C	
Value of x_2	0	1	
Casting Output	Casting Sound	Casting Leaks	
Value of y	0	1	

Table 4.8 Values of Equation Parameters for Different Conditions.

Using the method of least squares to fit the most accurate linear regression possible for this data results in Equation 4.3.

$$y = 0.07635\,x_1 - 0.04300\,x_2 + 0.04750 \qquad \textbf{Equation 4.3}$$

If we divide the data into the six operating points defined in Section 4.2.3 we see that for each operating point the value of y will be constant. Therefore Equation 4.3 will be of limited use in predicting the occurrence of an individual leaker, but may be of some use in predicting the proportion of leaking casting produced under given operating conditions. Figure 4.4 is a plot of the output of Equation 4.3 versus trial shot number, with the observed rate of leaker formation overlaid.

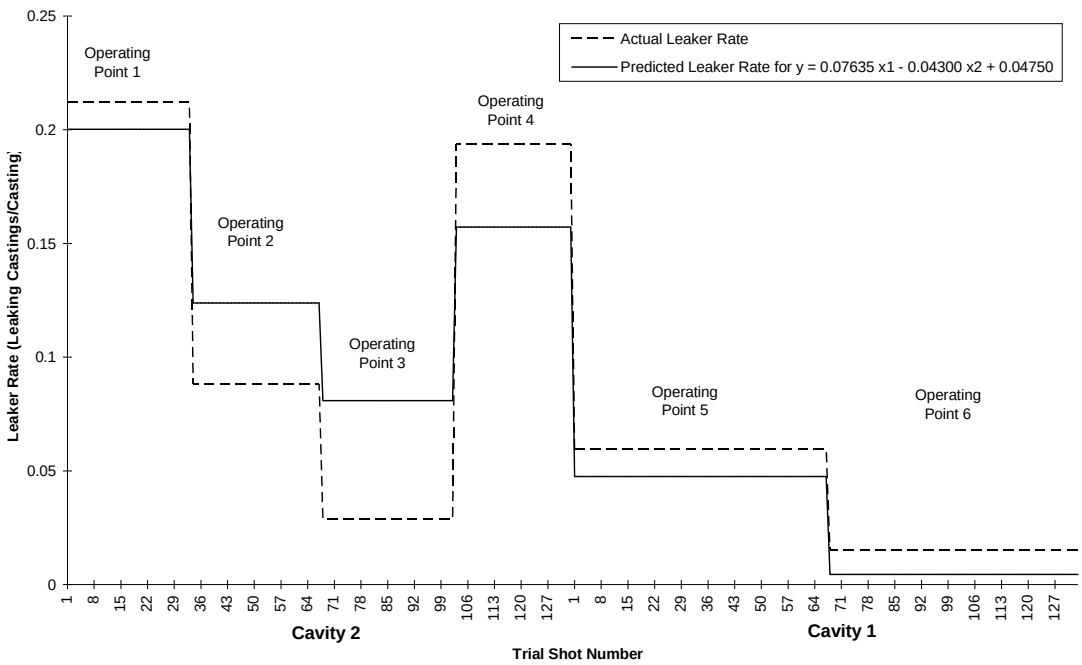


Figure 4.4 Plot of Predicted Leaker Rate, Using Equation 4.3, Versus Shot Number.

The trial shot number does not correspond to the shot number recorded for each casting during the trial. This is due to the fact that a number of castings were removed from the data, such as warm up shots, etc. Table 4.9 lists groups of trial shot numbers and the corresponding groups of castings. Within each group the shot numbers are in chronological order, though due to the removal of some castings from the data, consecutive shot numbers do not necessarily represent consecutive castings.

Shot Number	Corresponding Casting
1 to 33	Castings Made in Cavity 2 During Operating Point 1
34 to 67	Castings Made in Cavity 2 During Operating Point 2
68 to 102	Castings Made in Cavity 2 During Operating Point 3
103 to 133	Castings Made in Cavity 2 During Operating Point 4
1 to 67	Castings Made in Cavity 1 During Operating Point 5
68 to 133	Castings Made in Cavity 1 During Operating Point 6

Table 4.9 Groupings of Castings Numbers.

An examination of Figure 4 .4 shows that the formula is reasonably successful in predicting the rate of leaker formation for a given operating point. The effect of metal temperature differences appears well predicted, however our prediction of effects due to the oil cooling level could be improved. Operating points 1 and 4 are underestimated while 2 and 3 are overestimated. This is due to the difference in leaker rates between low oil cooling level and high oil cooling level being greater than the difference in leaker rates between no oil and low oil cooling level, ie. the relationship between oil cooling level and leaker rates is non-linear. This suggests that the fit of the regression curve could be improved by introducing a non linear term into the regression equation. If we introduce an x_1^2 term and use the method of least squares to fit a new regression we get;

$$y = -0.04083\,x_1 + 0.06167\,x_1^2 - 0.4222\,x_2 + 0.05855 \qquad \textbf{Equation 4.4}$$

where y, x_1, and x_2 are as defined in Table 4 .8. This relationship is plotted alongside the observed leaker rate in Figure 4 .5.

Figure 4 .5 displays a considerably better fit than that shown in Figure 4 .4. The good fit shown by Figure 4 .5 indicates that the results of our trial can be readily explained by variation in the controlled parameters.

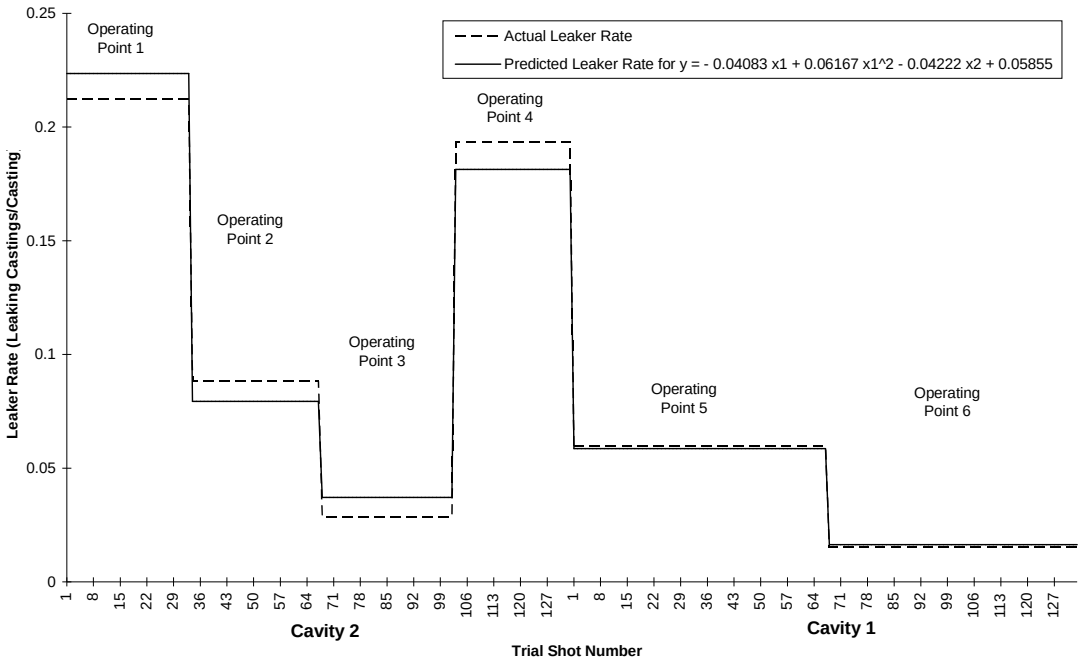


Figure 4.5 Plot of Predicted Leaker Rate, Using Equation 4 .4, Versus Shot Number.

4.5.2 Relationship Between Measured Variables and Casting Output

While the relationships developed in Section 4.5.1 are of use in judging the effects of the control inputs in this trial, it will be of more use in practice if we can relate the occurrence of leakers to measured die temperatures, measured metal temperatures and shot end parameters, Table 4 .1 and Table 4 .2. While we know that the formation of leakers will not be governed by variation of a single parameter, it should be possible to observe trends that occur between leaker rates and individual parameters. There are two ways of doing this. The first is to plot the given parameter versus casting number and observe its variation over the course of the trial, overlaying the observed leakers. This will highlight any obvious correlation. Fitting linear regressions between each parameter and the occurrence of leakers will allow us to assess the strength of any possible linear relations that may exist.

In order to test the strength of a linear regression we require a measure of the accuracy of the regression. A commonly used statistic to assess the accuracy of a linear regression is the “Coefficient of Determination”. This assesses what proportion of the variation in the y output is explained by the regression. It is given by the formula;

$$R^2 = \frac{\sum_{i=1}^{n} \left(\text{Predicted } y_i \text{ Value - Mean Observed y Value}\right)^2}{\sum_{i=1}^{n} \left(\text{Observed } y_i \text{ Value - Mean Observed y Value}\right)^2}$$ **Equation 4.5**

This is detailed on Page 434 of "Probability and Statistics for Engineers and Scientists" [39]. The value of this statistic will vary between 0 and 1. A value close to zero indicates that the variation in the y values is not explained well by the regression, while a value close to 1 suggests a good match between the observed y values and those predicted by the regression equation.

Linear regressions were fitted for each parameter and the coefficient of determination found. The results are ranked in Table 4 .10. The slope value refers to the slope of the regression curve. A positive slope indicates that an increase in the value of a given parameter will increase the chances of a leaker occurring, while a negative slope indicates that an increase in the value of the parameter will reduce the chances of a leaker occurring.

Parameter	Coefficient of Determination	Slope
Casting Cavity Gate Temperature	0.089667	-ve
Casting Cavity Fixed Cavity Temperature	0.085314	-ve
Casting Cavity Moving Cavity Temperature	0.08222	-ve
Casting Cavity Sliding Core Temperature	0.043636	-ve
Plunger Displacement at End of Injection Cycle	0.031863	+ve
Maximum Hydraulic Pressure During First Stage Injection	0.01667	-ve
Maximum Hydraulic Pressure During Second Stage Injection	0.013227	-ve
Average Plunger Speed During Second Stage Injection	0.012056	+ve
Plunger Displacement During Second Stage Injection	0.00947	+ve
Measured Metal Temperature	0.006643	-ve
Maximum Plunger Speed During Second Stage Injection	0.005686	+ve
Delay Between End of Injection and Intensification Pressure	0.002428	-ve
Plunger Displacement During First Stage Injection	0.00039	-ve
Average Plunger Speed During First Stage Injection	0.000174	+ve
Casting Cycle Time	4.86E-05	-ve

Table 4.10 Coefficients of Determination for Measured Inputs.

To understand what the values mean it is helpful to plot curves of the value of the relevant regression equation against the trial shot number with the observed leakers overlaid. Such plots are included in Appendix F. Note that as the regression value is a linear transformation of the parameter value the shape of the regression curve is identical to the that of a plot of the parameters, only the magnitude and direction may change. For this reason plots of the parameters have not been included.

The parameters can be grouped depending on their coefficient of determination.

Coefficient of Determination < 0.01

In these cases there appears to be very little correlation between the input and output. Within the limits of this trial we can safely discount the effects of these inputs. An interesting member of this group is the measured metal temperature. This parameter is plotted in Figure 4 .6.

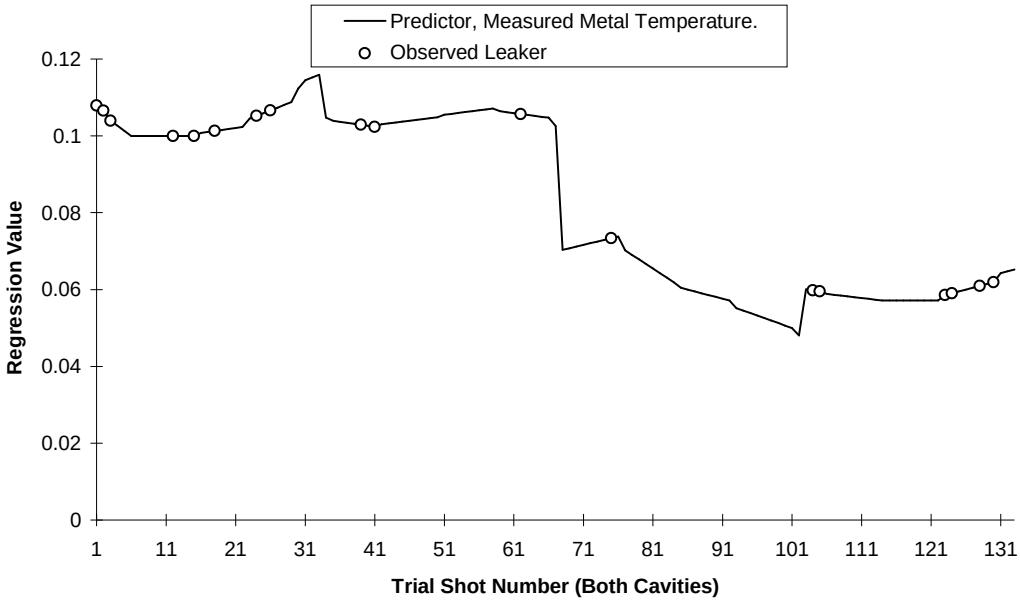


Figure 4.6 Plot of the Value of Linear Regression Based on Measured Metal Temperature Versus Trial Shot Number.

We can see that although the increase in metal temperature corresponds to a drop in the number of leakers from 14 to 8, within each group there appears to be no relation between the measured metal temperature and the occurrence of leakers. Thus a relatively steady input leads to an unpredictable output, hence the low coefficient of determination.

0.01 < Coefficient of Determination < 0.02

In these cases significant variation of the parameters occurs and a number of leakers occur on peaks of the predictor curve. However, a similar number of leakers occur in troughs or in areas where the curve is at a ‘normal level’ This indicates that in some cases an exceptional value of this parameter may be linked to the formation of a leaking casting, but that in a great many other cases there appears to be no relation. Thus these parameters are of very little use in predicting leaker formation.

Plunger Displacement at End of Injection

This parameter displays a few peaks where leakers occur. It is likely that a relationship between the total plunger displacement and the formation of leakers does exist and that the variation within this parameter within the trial was enough to witness this relationship. The presence of such a relationship would be due to the fact that the plunger displacement at the end of injection is directly related to of the amount of alloy ladled into the shot sleeve. This will affect the amount of heat entering the die and shot sleeve, the formation of waves and thus gas entrapment within the shot sleeve as well as the points at which the cavity begins to fill.

Coefficient of Determination > 0.04, Casting Cavity Temperatures

In these cases we begin to see reasonably good correlation between temperatures and leaking castings. The sliding core temperature appears to be largely influenced by the temperature of the oil flowing through it. Of the four temperatures this is the most stable from shot to shot. This explains its lower coefficient of determination. Its variation somewhat shadows the actual leaker rates shown in Figure 4 .5. Figure 4 .7 shows the regression line using this temperature.

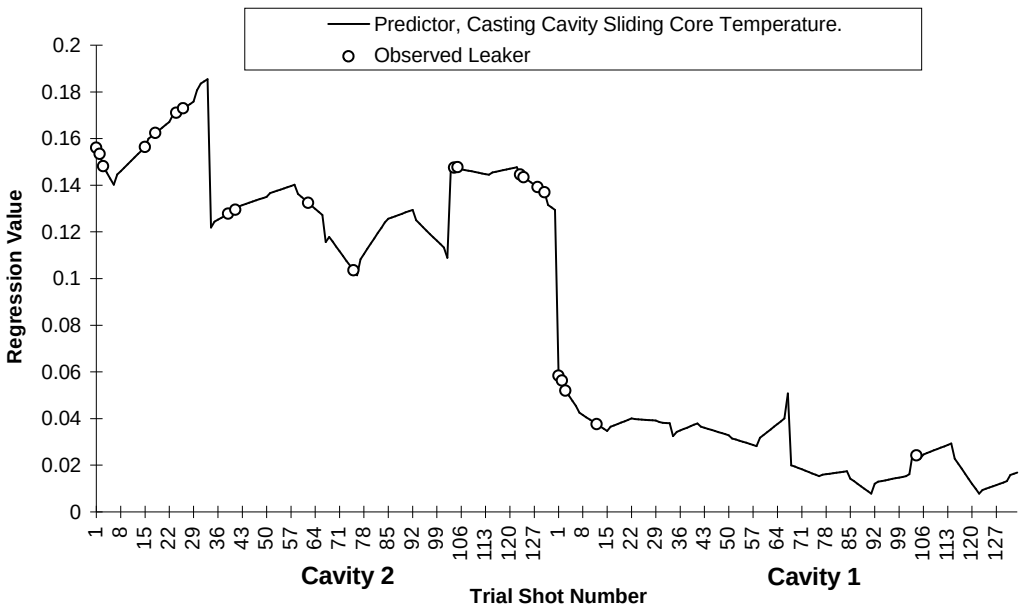


Figure 4.7 Plot of the Value of Linear Regression Based on Sliding Core Temperature Versus Trial Shot Number

It is, however, less successful in predicting individual leakers than the other temperatures. This appears likely to be due to the temperature in the other locations

being more readily affected by the stop/start nature of the trial. So while the temperature of the sliding core reflects the state of oil through the die the other in-cavity temperatures are mainly controlled by heat added by the molten alloy and rapidly lost through normal conduction through the die. The reasons for this are discussed later. Figure 4 .8 shows the regression line for the moving cavity temperature.

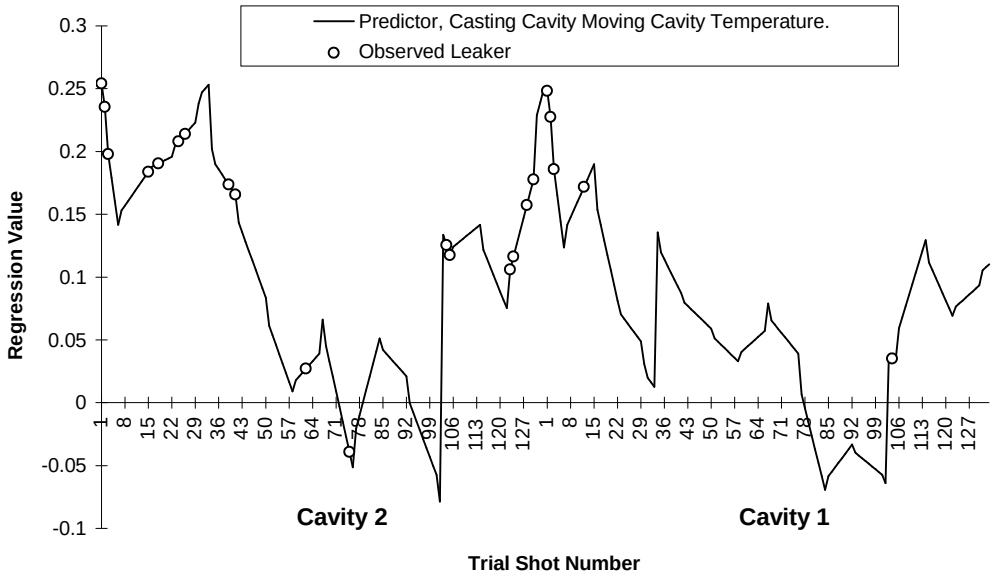


Figure 4.8 Plot of the Value of Linear Regression Based on Moving Cavity Temperature Versus Trial Shot Number

Increasing the Accuracy of the Linear Predictors

By using a combination of input parameters we can improve the accuracy of the linear regression. In this case we could use the four in-cavity temperatures and the plunger displacement at the end of injection. As discussed each of these parameters appears to be related to a given aspect of leaker formation, so using a multiple linear regression taking into account each of these variables we should be able to a achieve a more accurate prediction of the occurrence of a leaker. Figure 4 .9 shows that this is indeed the case.

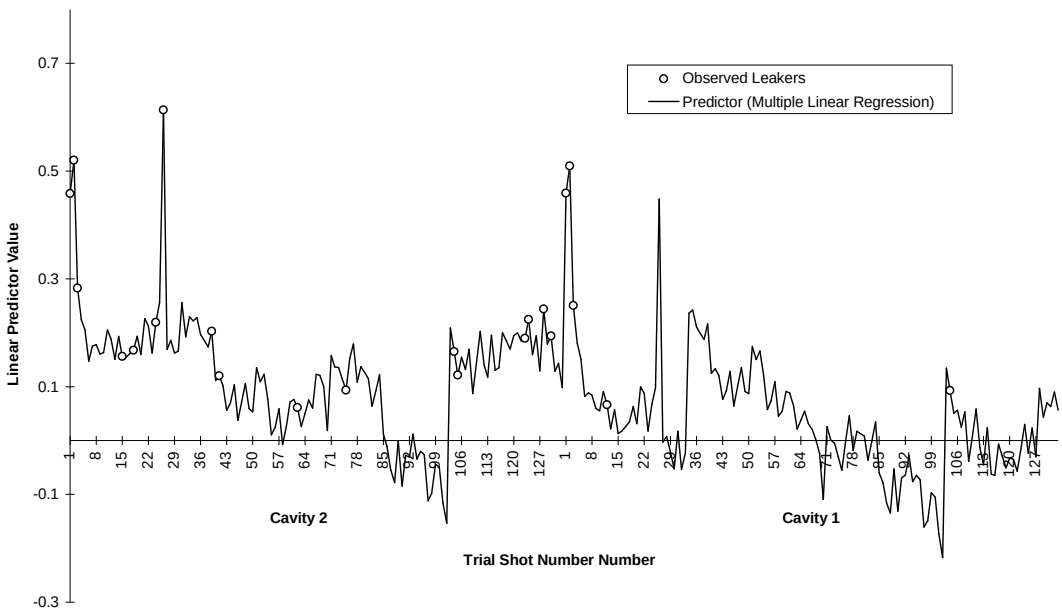


Figure 4.9 Prediction of Leakers Using Multiple Linear Regression.

The regression shown in Figure 4 .9 appears to predict the occurrence of leakers to a reasonable degree of accuracy. Most observed leakers occur at points high on the regression curve. There are no observed leakers occurring at low extremes of the regression. The regression is still unable to predict whether an individual casting will leak given the inputs, but it appears to be quite useful in predicting a general rate of production of leakers. In this respect it may be useful to compare the average value of this regression over each operating point with the observed leaker rates over each operating point. This is done in Figure 4 .10.

Figure 4 .10 shows a very good match between the predicted and observed leaker rates for the first three operating points. The other operating points are not as accurately predicted but the general shape of the curve is correct. Together, Figure 4 .9 and Figure 4 .10 indicate that measured casting parameters are useful in predicting leakers formed during the trial. In this case the parameters that have the greatest impact on the formation of leakers are the die temperature in different locations and the total plunger movement, which indicates the amount of metal cast per shot.

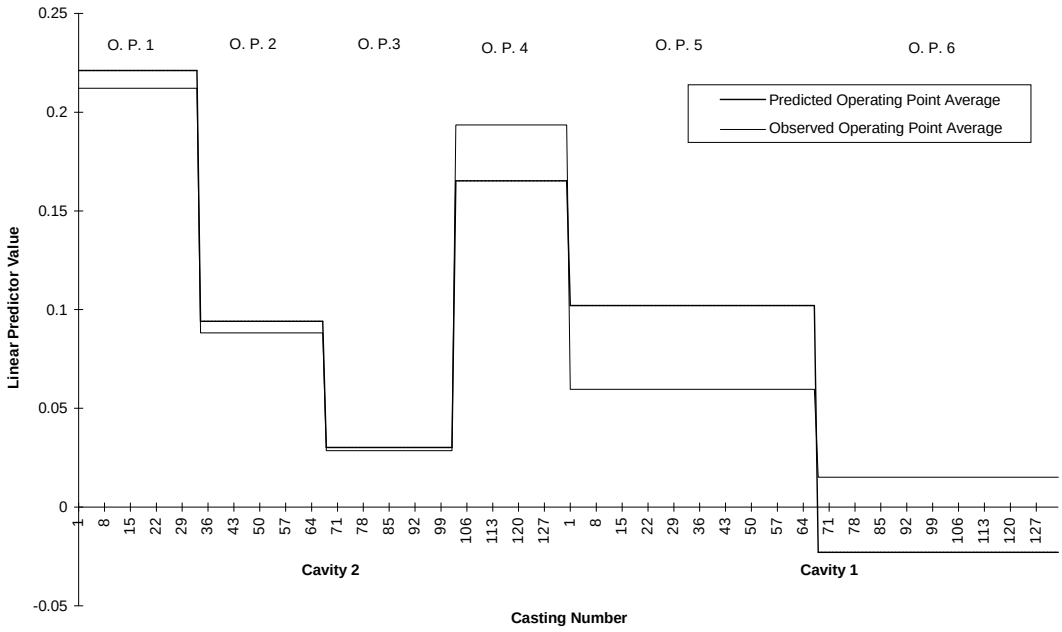


Figure 4.10 Average Values of Multiple Linear Regression.

4.6 Discussion

4.6.1 Quantifying the Thermal Condition of the Die

We have shown that the number of leakers formed over a given period is dependent on the rate of heat removal from the die, ie. the oil cooling level. Relating the formation of leakers to cavity surface temperatures allows us to broaden the result to cases where oil cooling is not used. Both the die temperatures and the rate of heat removal are related to the thermal condition of the die. The thermal condition of the die will be changed by the thermal forces acting upon it and is defined by the distribution of temperature throughout the die. In this case we have relative measures of two of the thermal forces acting upon the die, the oil cooling level and the metal temperature, and a measurement of the temperature in four locations in the cavity. Other major factors that will alter the thermal condition of the die will include;

- The amount of heat lost due to die spray.
- The cumulative heat in the die from previous shots, ie. a function of metal temperature, cycle time, and heat removed from the die after each shot.

To these we can add a great many variables that will have a minor, and for our purposes negligible, effect.

The point we want to make is that a simple measure of die temperature, such as we made, provides sufficient information about the thermal condition of the die to enable it to be used as a predictor of leakers. Figure 4 .10 suggests that within limits this is the case. Next we will examine the effects of the four main heat transfer effects acting on the thermal condition of the die and whether these effects were significant within this trial and if they can be accounted for using the die temperature measurements.

Relationship Between Oil Cooling Level and Die Cavity Temperature

A strong relationship was observed between the oil cooling level and the measured surface temperature of the sliding core. This is illustrated in Figure 4 .11.

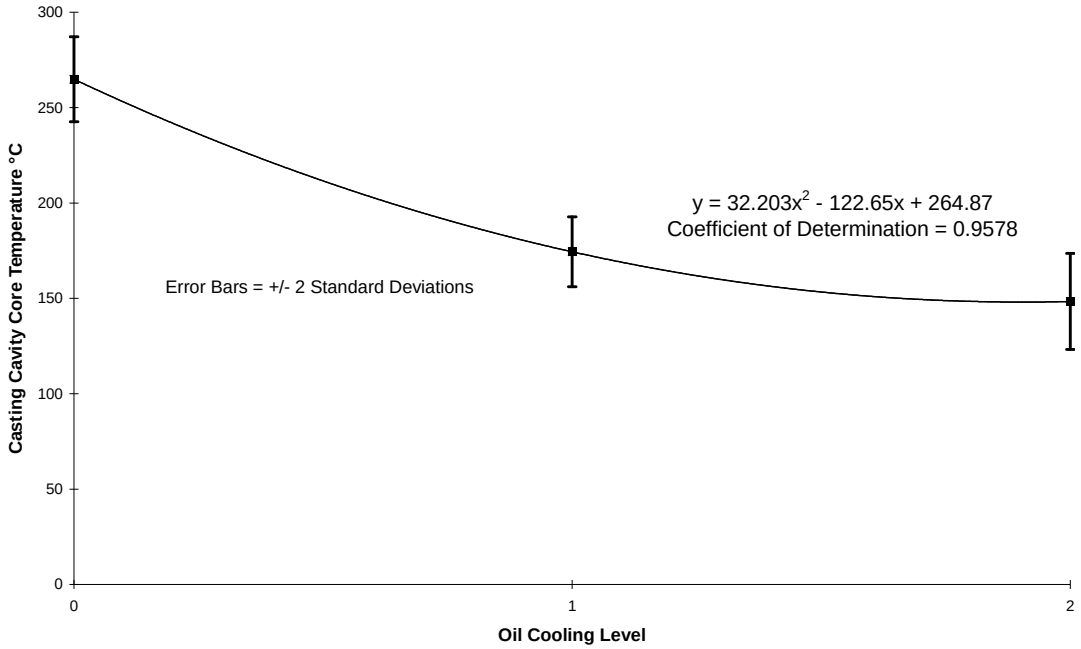


Figure 4.11 Relationship Between Casting Cavity Core Temperature and Oil Cooling Level.

The temperature in the other three in-cavity locations does not appear to be greatly influenced by the oil cooling level. Reasons for this include the distance of the oil lines from the cavity surface and the geometry of the die.

The oil line through the sliding core is located close to the cavity surface, and therefore its effect on the temperature of the cavity will be strong. The core is also thermally isolated from the rest of the cavity block. This means that there will not be a great deal of heat loss due to conduction through die steel. Most of the heat will be

removed by the cooling medium. Together these factors lead to a sliding core that heats up rapidly due to heat transfer from the molten alloy, but cools down slowly when no cooling fluid is present. When the oil is present it is effective in controlling the core temperature due its proximity to the surface.

The other sections of the die are all capable of losing heat rapidly due to conduction through the die block. The cooling lines are placed further from the surface which means that their effect will be less immediate. It is to be expected that within these areas the heat removed by conduction through the die block may be the dominant mechanism of heat removal from the cavity. The effect of the oil cooling may not be noticeable until the die attains steady operating conditions. Due to relatively frequent stoppages during this trial the die never fully attained consistent operating conditions. Therefore the effect of oil is less noticeable in these areas than upon the sliding core.

The result of these differences in oil line and die geometry is that within each cavity there are two distinct thermal zones. The relatively isolated sliding cores provide a strong correlation with the oil cooling level, while the other cavity temperatures fluctuate based upon the effects of the other variables.

Effect of Metal Temperature on Die Temperatures

Although the results of the trial were not statistically conclusive in terms of the effect of metal temperature on leakers, it is noticeable that more leakers were made at the lower metal temperatures than at the higher metal temperatures. Examination of Figure 4 .7 shows a slight drop in the sliding core temperature corresponding to the drop in metal temperature. The suggestion is that reducing the metal temperature by 20 ˚C leads to a relatively small drop in die temperatures and a corresponding small increase in leaker rate.

Direct examination of the relationship between metal temperature and the various die temperatures showed that in all locations the die temperatures increased as the metal temperature increased. In the case of the sliding core temperature the effect was masked by the effect of the oil cooling, ie. no effect was apparent until the data was broken up into the various oil cooling levels as well as the metal temperature level.

The most simple demonstration of the effect of metal temperature on die temperature is to take a die average of the temperatures. This involves averaging the temperature

over the four measured points in both cavities. This eight point average is less

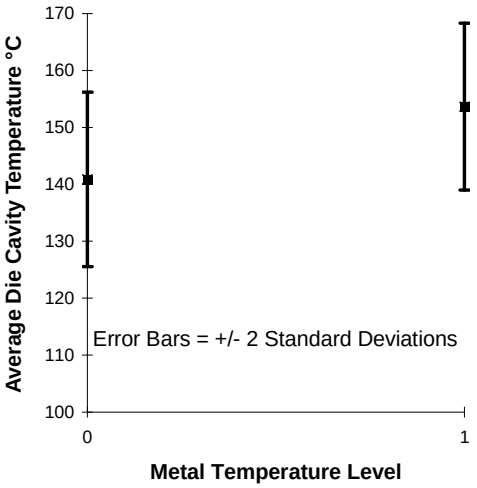


Figure 4.12 Effect of Metal Temperature on Average Die Temperature.

affected by the oil cooling level than the sliding core temperature. Figure 4.12 shows the relationship between metal temperature level and the average die temperature graphically. We see that the higher metal temperature produces higher die temperatures, although the effect is less than the effect of the oil cooling level on the sliding core. Due to the relatively small effect we should ask whether this observed trend may be due to the influence of chance in our sampling. ie. Is it likely that metal temperature actually has no effect on the die temperatures and that the trend we have observed could result from random sampling of a single population with the observed standard deviation? This hypothesis can be readily tested using a *t* distribution. To do this we determine a *t* value using Equation 4 .6.

$$t = \frac{\text{Difference in Means}}{\text{Standard Error of Mean}}$$ **Equation 4.6 [41]**

This value is then compared to a table of *t* values to give the probability that the observed difference in means would occur due to random sampling of a population with given standard deviation.

In our case;

Difference in Means = 12.78

and

$$\text{Standard Error of Mean}=\sqrt{\frac{n_1 s_1^2+n_2 s_2^2}{n_1+n_2-2}} \qquad \textbf{Equation 4.7 [41]}$$

where n_i indicates the number of observations in the given sample and s_i indicates the standard deviation of the sample. Thus;

$$\text{Standard Error of Mean}=\sqrt{\frac{67\acute{}7.664^2+66\acute{}7.328^2}{67+66-2}}=7.556$$

Solving Equation 4 .6 for *t* we get;

t = 1.692

from page 703 of [39] we find that the probability that this difference in sample means would occur by chance is slightly less than 5%. A probability this low indicates that in all likelihood the metal temperature has a measurable effect on the overall temperature of the die.

Effect of Die Spray on Measured Die Temperatures

In normal production a large amount of heat is removed due to the use of die spray. This is applied manually by the machine operator. Die spray removes heat rapidly from the surface of the die. When the spray ceases the die surface temperature will climb slowly due to the heat remaining in the die. There is no way of telling what the effect of die spray and changes in die spray will be from the result of the trial. However, we can say that it is likely that the effect of die spray did not vary greatly over the trial. Although the spray is applied manually and thus there is potential for large variation, this will not occur in the main. A single operator will vary their spray pattern slightly from shot to shot over the course of a shift, but we would expect that such variation would be fairly random around a given mean value, leading to no long term effect on the die temperature. A change in operator would most likely change the mean heat removal by die spray leading to a change in die thermal condition over time. For this reason an effort was made to complete the trial using the same operator. It is likely that the variation from shot to shot is also limited by the fact that in general the application of die spray is quite heavy. Die spray is most effective when it is first applied to the die. With time the die cools and the heat transfer rate drops rapidly, [9]. Therefore variation of the spray time of a heavy spray will have less effect than variation of the spray time where the spray time is shorter.

Regardless of these considerations it is likely that variations in the amount of heat removed have occurred during the trial. As the effect of a change in die spray will act immediately on the shot following its application, it is unlikely that our temperature measurements will account for it due to the fact that they were only taken every 10 shots. This may lead to leakers occurring that are not easily explained by the various measured parameters. When leaker rates are considered rather than the occurrence of individual leakers this effect should cancel itself out.

Effect of Casting History on Thermal Condition

Heat in the die accumulates over a number of shots. Thus it is not only the heat inputted during the current shot that affects the die's thermal condition but the history of the die. If the shots leading up to the present have been interrupted leading to longer than usual cycle times then there will be a noticeable effect on the die temperatures. These effects were masked in the trial due to the removal of warm up shots and two castings after stoppages to measure metal temperature. Observed fluctuations of the three in-cavity die temperatures are largely due to this effect.

Due to this cumulative effect on the die thermal condition small changes in machine parameters may lead to larger changes in die temperatures over time. A slightly longer than usual cycle time could lead to a decrease in the die temperature over time. No such effect was noted during the trial. Similarly a small but consistent change in the amount of alloy ladled into the shot sleeve will also lead to a change in the die thermal condition. During the trial there was significant variation in this parameter but there did not appear to be a trend that would lead to a change of die temperature over time.

Summary: Using Multiple Die Temperatures to Determine the Thermal Condition of the Die.

From the above we can see that although our information on the thermal condition of the die is far from complete, we still have a good representation of some critical aspects of the die. The sliding core temperature provides an indication of the heat removal due to the oil cooling level. Temperatures at other points of the cavity vary largely based on the recent thermal history of the die. All temperatures are slightly affected by the metal temperature. Other, more transient effects on the die thermal condition may not have been observed from the die temperature measurements but

their effects, being short term by nature, should not greatly influence the results of the trial.

As the three in-cavity temperatures are all affected by the same thermal inputs there is a degree of interrelation between them. This can be observed on the plots in Appendix F. It was noted that if one of the three was removed from the multiple linear regression to predict the occurrence of leakers, the remaining two, plus the core temperature and the plunger displacement, continued to predict the occurrence of leakers to a reasonable accuracy. So while their variation is by no means identical it is reasonable to say that they are closely linked. This indicates that it is not necessary to know the temperature at every point in the cavity, merely at some representative points.

In summary the above indicates the need for some sort of die temperature measurement in production if the occurrence of leakers over the long term is to be understood. Thermocouples embedded in the sliding cores and at least one location near the cavity would provide enough feedback on the die thermal condition to be of significant use during production. Such information would be of use for any high pressure die casting. A given die can be divided into discreet thermal zones within which the mechanisms affecting the thermal condition can be understood. Thermocouples placed within each of these thermal zones will then provide a useful record of the thermal condition of the die at a given time. This record could then be used to help predict the casting output.

4.6.2 Effect of other (Shot End) Parameters on leakers

We have established that the thermal condition of the die has a significant effect on the formation of leakers. During the trial we also measured a number of other parameters based on the injection system of the machine. Of these only the total plunger displacement during injection appeared to have an noticeable relationship with the formation of leakers. The reasons why this effect was observed are;

- ✶ Variation of plunger position beyond certain limits will affect the rate of leaker formation.
- ✶ These limits were exceeded during the trial.

The second of these two points is significant as it tells us that in the case of the other shot end parameters even if the first point is true, no relation between the parameter

and the occurrence of leakers may have been observed due to the given parameter remaining in controlled limits. The aim of the trial was to alter the thermal state of the die, ie. the die temperatures, and no other parameters were intentionally altered. Although the bulk of shot end parameters were recorded and shown to have little relation to the formation of leakers these results will only hold true within the limits used during this trial.

While the results of this trial show the importance of controlling the die temperatures, it also remains important to control the shot end parameters. As the total plunger displacement had a significant effect on the probability of forming a leaker we will briefly discuss its effects.

Effect of Variation in Total Plunger Displacement During Injection.

During the trial it was noted that there was a correlation between longer-than-usual plunger displacements and the occurrence of leakers. This situation represents a case where there is less metal ladled than usual, resulting in a thin biscuit. This will tend to reduce any benefits derived from the application of intensification pressure. As the parameter represents the amount of alloy in the system a long plunger displacement will also correspond to less metal in the shot sleeve, leading to different patterns of wave formation, different flow through the runner system and thus different filling of the cavity. Less metal ladled will also lead to less heat in the die and shot sleeve. In short it is not surprising that variation of this parameter leads to changes in reject rates. This highlights the importance of a good quality, well maintained, metal ladling system.

4.7Conclusions

The trial has successfully shown that the thermal condition of the die, quantified using die temperatures, has a critical effect on the formation of leakers in this casting. We have established the bottom limit of a temperature operating window. It appears desirable to keep the temperature of the sliding core over about 200 ˚C while the rest of the die should be kept over about 150 ˚C. Below these limits we will experience increases in the formation of leakers. We have not determined upper limits, though it is likely that such limits exist.

4.8Recommendations

Having highlighted the importance of thermal control of the die it would be useful to be able to monitor changes in this variable over time. The use of limited monitoring of die temperatures using thermocouples embedded in the cavity blocks is recommended. Information gained from this equipment would facilitate the assessment of the various causes of variation in die temperature and their effect on leaker formation.

4.9Further Work

While this trial has provided useful data, there are many areas where our knowledge of leaker formation could be improved through similar experiments looking at different variables.

A particularly useful experiment would be to attempt to establish an upper limit on the allowable die temperatures. This would involve the use of oil at 180 - 200 ˚C through the cavity lines but not through the sliding core. Running the die continuously in such a manner would result in an accumulation of heat in the die. Any changes in the leaker formation rate as the temperature increases could be observed.

As discussed earlier the comparison of oil cooling levels between the two cavities relies on the assumption that the two cavities would produce equal number of leakers if the thermal conditions were identical. This assumption could be tested by performing a similar trial with cavity 1 cooled and cavity 2 left un-cooled.

Chapter 5

Summary of Results and Conclusions

5.1Summary of Results

5.1.1Knowledge Compiled from Existing Literature

By drawing together several strands of knowledge from available published literature, a reasonably comprehensive overview of mechanisms thought to lead to the formation of leakers in aluminium high pressure die casting has been developed. The major causes of leaker formation are listed in Table 5 .1. Information gathered on each of these causes enabled links to be made between casting parameter and the formation of leakers.

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 5.1 Summary of Possible Causes of Leakers Found in Published Literature.

5.1.2 Results of Observation of the Casting Process and the Castings Produced

Through observation of the casting process and a range of leaking castings produced, a solid understanding of likely mechanisms for leaker formation in the specific case of the water inlet casting has been developed. As discussed at the commencement of Chapter 2, in order for leakage to occur in a high pressure die casting, a path must exist through three distinct areas of the casting. These are the two surface layers and the centre of the casting. Thus the discussion of leakage mechanisms presented here is broken into these three areas.

Leakage Through Outside Surface Layer

In Chapter 3 the predominance of leakers on the machined surface was noted, indicating that the main mechanism for leakage through the outside face of the tube is the removal of any sound surface layer by machining. Many castings leaked through what appeared to be sound surfaces suggesting that in these cases the porosity exposed consists of small, linked shrinkage porosity. However, leakage was also noted through larger pores that appeared to be due to gas porosity. In some cases cold

shuts through the casting section may also have been revealed by machining. Differentiating between cold shuts and shrinkage porosity on a machined surface is complicated by the machining which removes the characteristic flowing shape of the cold shut. Thus diagnosis of a casting leaking through a very small pore exposed on the machined face is complicated.

In a limited number of cases leakage was noted around the base of the lugs. Sectioning revealed the existence of small cracks in association with other defects, leading to a leak path through this region. These cracks will be caused by stresses induced by solidification shrinkage of the alloy coupled with the weakening effect of any casting defects present in the region.

Leakage Through Casting Centre

The majority of castings studied had extensive porosity within the casting centre. Some appeared to be largely due to entrapped air while others appeared to be due to shrinkage of the alloy during solidification. In many cases it was clear that the turbulent flow of the metal and converging flow paths had contributed significantly to this porosity. The extent of the porosity suggested that in most cases porosity would be connected allowing leakage through this section of the casting.

Leakage Through Inside Surface Layer

The final link in the leak path was found to be the occurrence of cold shuts on the internal surface of the tube. These discontinuities provide a gap through which fluid can pass, allowing entry through the porous inner region to the machined surface.

In a small number of cases porosity due to volatilised die lubricant and/or water was found on the internal face of the tube wall. This may also provide a path for leakage through this layer.

Summary of Mechanisms of Leaker Formation in Water Inlet Casting

Table 5 .2 summarises the above mechanisms of leaker formation present in the water inlet casting.

External Surface Layer	Centre Region	Internal Surface Layer
Porosity, due to Alloy Shrinkage, Entrapped Air, and/or Cold shuts, Exposed by Machining	Porosity Due to Entrapped Air	Discontinuities Due to Cold Shuts
Cracks in Casting Due to Shrinkage Stresses Coupled with Casting Defects	Porosity Due to Alloy Shrinkage	Porosity Due to Volatilised Fluids on Die Surface
	Discontinuities Due to Flow Defects	

Table 5.2 Mechanisms of Leaker Formation Through Casting Section.

Figure 5 .1 presents an example showing some of these mechanisms in action.

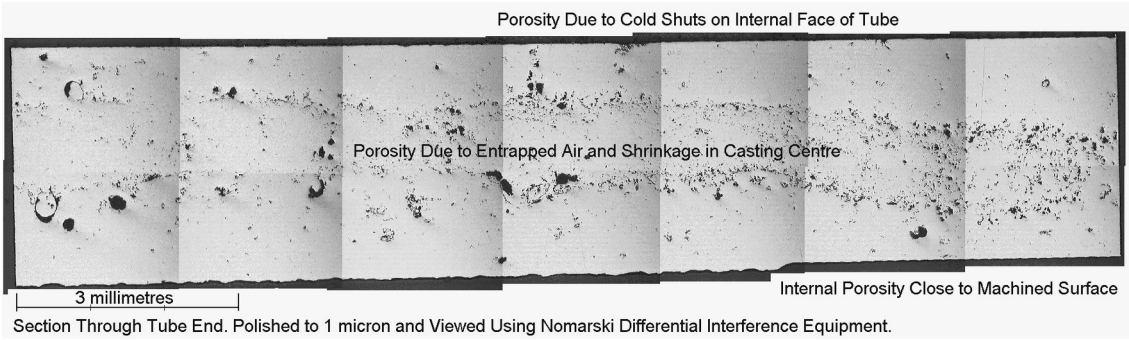


Figure 5.1 Cross Section Through Tube Wall Showing Cold Shuts, Internal Porosity, and Material Removal Combining to Provide a Path for Leakage.

5.1.3 Parameters Likely to Have a Critical Effect on the Formation of Leakers in the Water Inlet Casting

Summarising Table 5 .2, the major defects that may lead to leakage in the water inlet casting are:

- ✶ Cold shuts, both on casting surface and through centre of casting.
- ✶ Porosity due to entrapped air.
- ✶ Porosity due to shrinkage of alloy.
- ✶ Small cracks due to stresses applied after solidification.
- ✶ Surface porosity due to volatilised fluids on cavity surface.

Application of knowledge from the published literature, summarised in Figure 2.18, enables parameters that are likely to have a critical effect on the occurrence of each of the above defects in the water inlet casting to be determined. Table 5 .3 lists these parameters. Note that not every possible cause listed in Figure 2.18 is included in Table 5 .3. A judgment has been made on which parameters out of those listed in Figure 2.18 are most likely to be affected these defects in the case of the water inlet casting and only these have been listed in Table 5 .3.

Defect	Parameters Affecting Defect
Cold Shuts	• Metal Flow Paths - Design of Runner, Gate and Cavity. Plunger Injection Speeds and Change Over Position. • Heat Transfer Rate from Flowing Alloy - Die Temperatures and Metal Temperatures.
• Gas Porosity	• First Stage Injection Parameters - Velocity, Acceleration, and Location of Change over to Second Stage Velocity. • Shot Fill Ratio. • Design of Runner System. • Flow Paths in Cavity that May Block Vents Before Cavity Filling is Complete.
• Shrinkage Porosity	• Thermal Balance of Cavity - Degree of Directional Solidification Present. • Temperature of Alloy Prior to Injection. • Pressure Applied During Intensification. • Composition of Alloy.
• Stress Cracks	• Design of Casting Leading to Restrained Corners. • Presence of Other Defects in Area.
• Surface Porosity	• Choice and Application of Die Lubricant. • Temperature of Die Surface.

Table 5.3 Parameters Likely to Have a Critical Effect on the Formation of Defects Leading to Leakage.

All the parameters listed in Table 5 .3 may have a direct effect on the occurrence of leakers in this casting. Some, such as those relating to the design of the die, will remain constant, these will effect the overall numbers of leakers produced but will not be the cause of variation from casting to casting. Other parameters may fluctuate over long periods of time, ie. from one production run to another, and these may lead to changes in the number of leakers produced for a particular production run or even a production shift. These may include subtle changes in the alloy composition or shot end parameters. Finally some parameters have the potential to vary over short term periods or from one shot to another. This may lead to the production of individual leakers. These parameters will include the die temperatures and the application of die spray and lubricant.

5.1.4 Experimental Confirmation of Mechanisms of Leaker Formation

In order to determine whether the parameters presented in Table 5 .3 do actually affect the occurrence of leakers it is necessary to carry out an experiment where a given parameter is changed and the effect on the occurrence of leakers is examined. The temperature of the metal and the temperature of the die are two parameters that appear to affect a number of defects that may lead to leakage. This, together with the fact that die temperatures are likely to vary in practice, and the fact that both die temperatures and metal temperature were relatively easy to manipulate, meant that both were prime candidates for a structured experiment.

The experiment and its results showed that the temperature of the die has a large effect on the occurrence of leakers. Results from the experiment also confirmed that cold shuts on the internal surface of the tube are a critical cause of leakage. The occurrence of cold shuts and hence leakage defects was increased at reduced die temperatures.

The fact that the results managed to predict the rate of leaker formation reasonably accurately over a given operating point also indicates that the parameters recorded during the trial provide an adequate description of the entire manufacturing process, provided an acceptable level of control is in place in other parts of the process. When it is considered that after casting the part is quenched, trimmed shot blasted, and machined before pressure testing, it is testimony to the critical nature of the high pressure die casting process that a measure of die temperatures together with the amount of alloy ladled can provide a reasonable prediction of the occurrence of leakers, see Figures 4.9 and 4.10.

5.1.5 Strategies to Reduce the Occurrence of Leakers in the Water Inlet Casting

In order for leakage to occur a path must be present through all three regions of the casting. This indicates that one of the mechanisms in Table 5 .2 is likely to be a "critical" mechanism that determines whether a casting leaks while the other mechanisms may be present in most castings. Observation suggested that in this case cold shuts on the inner face of the tube were such a critical mechanism. This mechanism and the effect of die temperatures upon it were confirmed by experiment. It was demonstrated that the occurrence of cold shutting and thus the occurrence of leakers could be lessened by maintaining die temperatures at a high level. However, this is not the only method that can be used to reduce the occurrence of defects. Although the other mechanisms listed in Table 5 .2 may not be the determining mechanism in this case, control of their occurrence may still prove useful. Indeed, it is expected that a reduction in the amount of gas and shrinkage porosity in the casting centre or the elimination of the need to machine the tube end would prove a much more effective method of leaker reduction than control of the die temperatures.

Using Table 5 .3 as a guide and applying solutions based upon the literature we can propose a variety of useful approaches to reduce the occurrence of leakers in the water inlet casting. These are summarised in Table 5 .4.

Region	Defect	Strategies to Reduce Occurrence of Defect
External	Porosity Exposed by Machining	• Modify Die Thermal Design to Increase Heat Loss Through Outside of Tube. • Modify Casting Design to Eliminate Need for Machining. • Follow Suggestions for Centre Region to Reduce the Occurrence of Various Types of Porosity.
• Surface Layer	Small Cracks in Casting Due to Shrinkage Stresses	• Add Fillet to Tube Base Side of Lug. • Increase Casting Ejection Temperature. • Follow Suggestions for Centre Region to Reduce Occurrence of Other Defects in Area.
•	Porosity Due to Entrapped Air	• Change Shot Change Over Position. • Increase Shot Fill Ratio. • Re-Design and Modify Runner System to Provide Streamlined Flow.
• Centre Region	Porosity Due to Alloy Shrinkage	• Use Higher Silicon, Low Copper Casting Alloy. • Modify Die Thermal Design to Allow Directional Solidification.
•	Discontinuities Due to Cold Shuts	• See Suggestions for Cold Shuts on Internal Surface Layer.
• Internal Surface Layer	Discontinuities Due to Cold Shuts	• Maintain Cavity Temperatures During Stoppages Using Oil Heating and/or Electric Cartridge Heaters in Sliding Cores. • Re-Design Runner System to Provide Streamlined Flow. • Re-Position Gates to Locate Tube End Away From the End of the Flow Paths.
•	Porosity Due to Volatilised Fluids on Die Surface	• Avoid Spraying Die or Applying Lubricant While Die is Cold.

Table 5.4 Strategies to Reduce Occurrence of Leaker Mechanisms.

5.2 Conclusions

From the information presented in this study a number of important conclusions can be drawn.

- ✶ When analysing the occurrence of leakers, the casting can be divided into the surface regions and the casting centre. All of these must contain a leakage path for a leaker to occur. A logical procedure then exists for the diagnosis and reduction in the occurrence of leakage defects.
- ✶ The rate of heat transfer from the casting alloy to the die will have a critical effect on the occurrence of cold shuts in the water inlet casting.
- ✶ Cold shuts on the casting surface have a strong link with the occurrence of leakers in the water inlet casting.
- ✶ An ability to predict a critical casting output by analysis of the state of important casting inputs has been demonstrated. This indicates that through monitoring of the high pressure die casting process the occurrence of such critical casting outputs can be predicted and controlled in production.

5.3Suggestions for Future Work

5.3.1Reducing the Occurrence of Leakers in Water Inlet Casting

Structured implementation of the suggestions discussed in Section 5.1.5 should lead to a reduction in the occurrence of leakers in this casting. Using a structured trial and recording individual casting numbers, the effect of a given parameter on the casting quality can be determined. It is possible to complete similar trials on a wide range of parameters. In such a case it may be deemed unnecessary to number each casting as this step adds a significant amount of work to the process. Such a situation would greatly lessen the amount of information gained from the trial and would fail to guard against changes in un-monitored shot end parameters distorting the results. Nonetheless, in situations where such a level of error is acceptable, trials could be completed with relative ease.

5.3.2 Further Understanding the Mechanisms of Leaker Formation in Aluminium HPDC

Study of the literature revealed a great deal of confusion surrounding the mechanisms governing solidification within high pressure die casting. Due to the range of parameters that may be changed in the shot end system and the large range of casting designs that are made using high pressure die casting there does not exist a “typical” high pressure die casting.

As an example, a commonly used approach to filling a high pressure die casting is the use of “pre-fill”. This refers to the use of solid front filling of the cavity using slow speed injection. The high velocity second stage is activated after the cavity is partially filled. This approach is very different to the usual approach of trying to fill the cavity with an atomised jet of molten metal. It is expected that this would have a severe effect on the final microstructure but at present this effect can only be speculated upon. The use of this and other techniques all under the banner of high pressure die casting means that comparison of results between different castings is often meaningless.

In order to further understand the mechanisms leading to the formation of defects such as leakers, hence cold shuts, gas porosity, shrinkage porosity, etc. a structured, and published, knowledge of the basic die filling and solidification mechanisms likely to be encountered in high pressure casting must be made available. Such a data source must be presented such that it may be applied directly to a given casting, and should be based upon recorded experiment rather than speculation based upon observation. At present such a goal is un-imaginably difficult to achieve, but worth setting nonetheless.

A useful study that would work towards this goal while looking directly at the formation of leakers might take a similar form to previous studies looking at shrinkage porosity formation and pressure tightness in gravity and sand castings. [23, 15, 26, 27]. Casting a representative casting under controlled laboratory conditions, subjecting the casting to relevant secondary operations, e.g., trimming, machining, and/or shot blasting, and pressure testing using a rig that allows a degree of pressure tightness rather than a yes/no. Such a process has been done to some extent with work such as [30] where the effect of strontium addition on the pressure tightness of a flat plate casting was examined. However, such work lacks generality. It is very difficult

to compare such work with castings that are likely to be encountered in practice. As many castings with a requirement for pressure tightness have a cylindrical shape, be they automotive cooling system components or transmission extension housings, a more appropriate test casting may be cylindrical in shape. However, this would be less useful for castings with a pressure tightness requirement that have an oblong box shape, such as a gas meter or automotive rocker cover casting. Herein lies a difficulty in a lack of generality in shape of castings and not enough knowledge of the effect of casting shape on casting outputs. However, despite the ease with which a die to cast a flat plate may be designed and manufactured, very few foundries are in the practice of casting flat plates with a pressure tightness requirement. This makes results of studies such as that in [30] somewhat difficult to apply in practice. Once a suitable test die has been decided upon, an effort must be made to vary the multitude of parameters available within ranges that are used in production. Such a study may prove invaluable in understanding the formation of leakers and other defects in high pressure die casting.

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Appendices

Appendix A: Details of Casting Manufacture

A.1Details of Casting Alloy

Alloy designated CA313 is used to manufacture the water inlet casting. This is a general purpose aluminium die casting alloy. Table A .1 lists the amount of the most important constituents present in castings collected during this study. These values are based on analysis of eight castings. Three were taken from the trial discussed in Chapter 4, the remaining five were collected from three other trials performed during the term of this work, (between March 1996 and May 1997). By presenting the maximum, minimum, and mean values found an insight is gained into the amount of variation that occurred within the process over time. Note that when only castings from a single trial were analysed, eg. Chapter 4, the variation in alloy composition was significantly less, see Appendix F.

	Mean (Weight %)	Maximum (Weight %)	Minimum (Weight %)
Aluminium	Balance (85.44)	Balance (86.00)	Balance (84.55)
Silicon	8.92	9.37	8.34
Copper	3.17	3.35	3.05
Iron	0.96	1.06	0.86
Magnesium	0.20	0.27	0.09
Zinc	0.86	1.15	0.45
Lead	0.06	0.06	0.04
Chromium	0.03	0.04	0.03
Nickel	0.10	0.21	0.05
Manganese	0.23	0.29	0.2
Titanium	0.021	0.028	0.018
Tin	0.02	0.02	0.01
Strontium	<0.001	<0.001	<0.001
Zirconium	<0.005	0.005	<0.005

Table A.1 Casting Alloy Compositions Detected During Study.

In all cases the alloy composition fell within ADC's in-house limits.

No extraordinary processes such as degassing or filtering are used to prepare the alloy prior to deposition into the casting machine's shot sleeve.

A.2 Details of Casting Process

After a short settling period in the shot sleeve, metal injection begins. Figure A .1 and Figure A .2 show "Shot Profiles" of four castings. The shot profile is recorded by a displacement transducer mounted on the plunger and a pressure transducer in the machines hydraulic system. A trace of plunger displacement and machine hydraulic

pressure results. Differentiation of the displacement curve results in a plunger velocity curve.

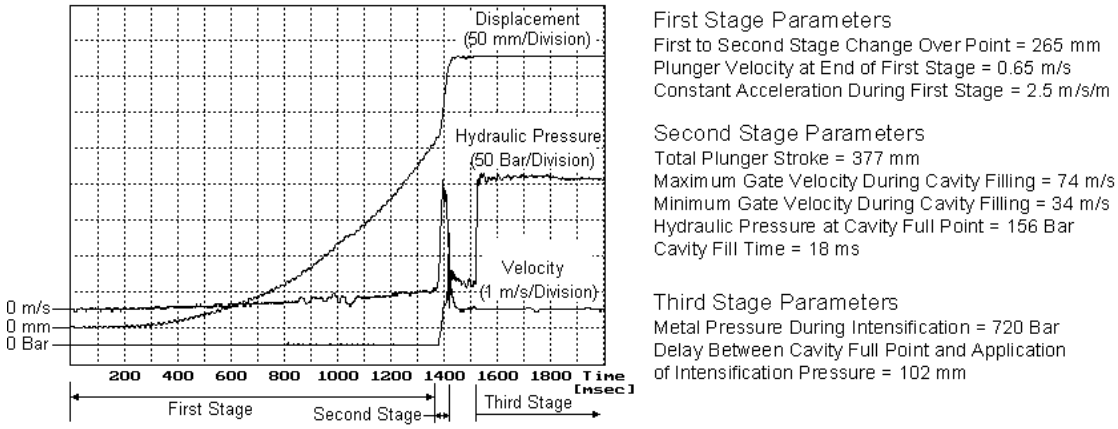
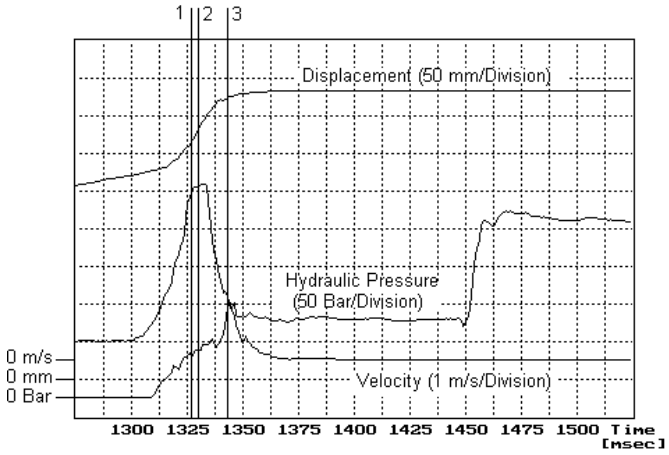


Figure A.1 Full Shot Trace for Water Inlet Casting.

Figure A .1 shows the full injection cycle. Figure A .2 zooms in on the cavity filling period for three different shots. To the right of each profile are a number of important injection parameters. Some of these parameters can be read directly off the shot trace while others are calculated from the shot profile data using a knowledge of the casting and machine dimensions. The listed parameters together with the shot profiles give a good description of the process used to manufacture these castings.

A detailed description of the die design is not included. Figure A .3 shows a dimensioned casting complete with runners and overflows. The machine used to make the castings was a Buhler H-250B, details of important machine dimensions were taken from the operating manual for this machine, [A1].

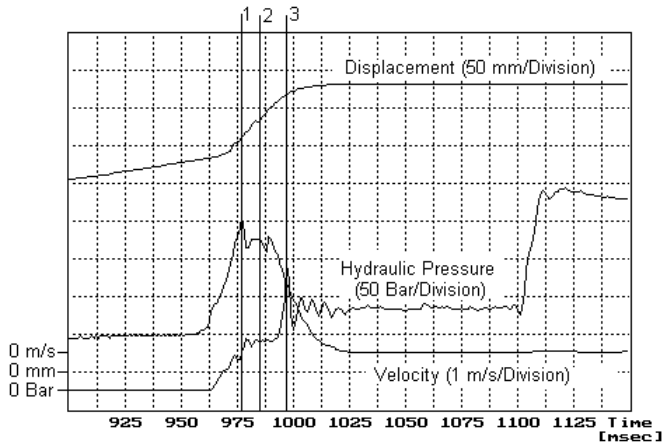


First Stage Parameters
First to Second Stage Change Over Point = 273 mm
Plunger Velocity at End of First Stage = 0.6 m/s
Constant Acceleration During First Stage = 2.2 m/s/m

Second Stage Parameters
Total Plunger Stroke = 385 mm
Maximum Gate Velocity During Cavity Filling = 90 m/s
Minimum Gate Velocity During Cavity Filling = 20 m/s
Hydraulic Pressure at Cavity Full Point = 130 Bar
Cavity Fill Time = 15 ms

Cavity Filling Points
1 - Shot Sleeve Full
2 - Metal at Cavity Gate
3 - Cavity Full

Third Stage Parameters
Metal Pressure During Intensification = 740 Bar
Delay Between Cavity Full Point and Application
of Intensification Pressure = 108 mm

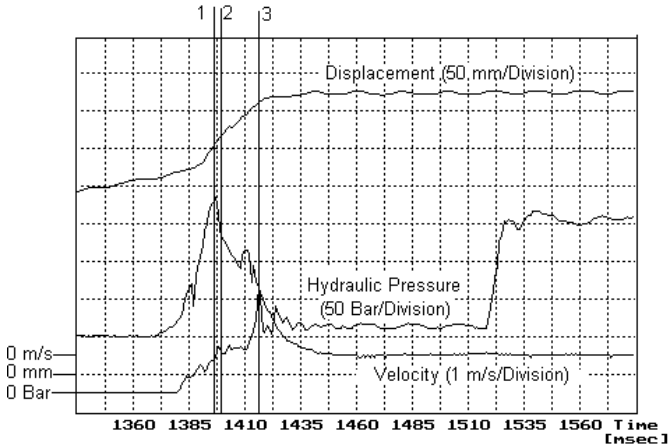


First Stage Parameters
First to Second Stage Change Over Point = 282 mm
Plunger Velocity at End of First Stage = 0.6 m/s
Constant Acceleration During First Stage = 2.1 m/s/m

Second Stage Parameters
Total Plunger Stroke = 382 mm
Maximum Gate Velocity During Cavity Filling = 74 m/s
Minimum Gate Velocity During Cavity Filling = 33 m/s
Hydraulic Pressure at Cavity Full Point = 168 Bar
Cavity Fill Time = 12 ms

Cavity Filling Points
1 - Shot Sleeve Full
2 - Metal at Cavity Gate
3 - Cavity Full

Third Stage Parameters
Metal Pressure During Intensification = 740 Bar
Delay Between Cavity Full Point and Application
of Intensification Pressure = 106 mm



First Stage Parameters
First to Second Stage Change Over Point = 268 mm
Plunger Velocity at End of First Stage = 0.6 m/s
Constant Acceleration During First Stage = 2.2 m/s/m

Second Stage Parameters
Total Plunger Stroke = 373 mm
Maximum Gate Velocity During Cavity Filling = 86 m/s
Minimum Gate Velocity During Cavity Filling = 37 m/s
Hydraulic Pressure at Cavity Full Point = 141 Bar
Cavity Fill Time = 17 ms

Cavity Filling Points
1 - Shot Sleeve Full
2 - Metal at Cavity Gate
3 - Cavity Full

Third Stage Parameters
Metal Pressure During Intensification = 740 Bar
Delay Between Cavity Full Point and Application
of Intensification Pressure = 104 mm

Figure A.2 Close Ups of Cavity Filling Period of Three Shot Traces.

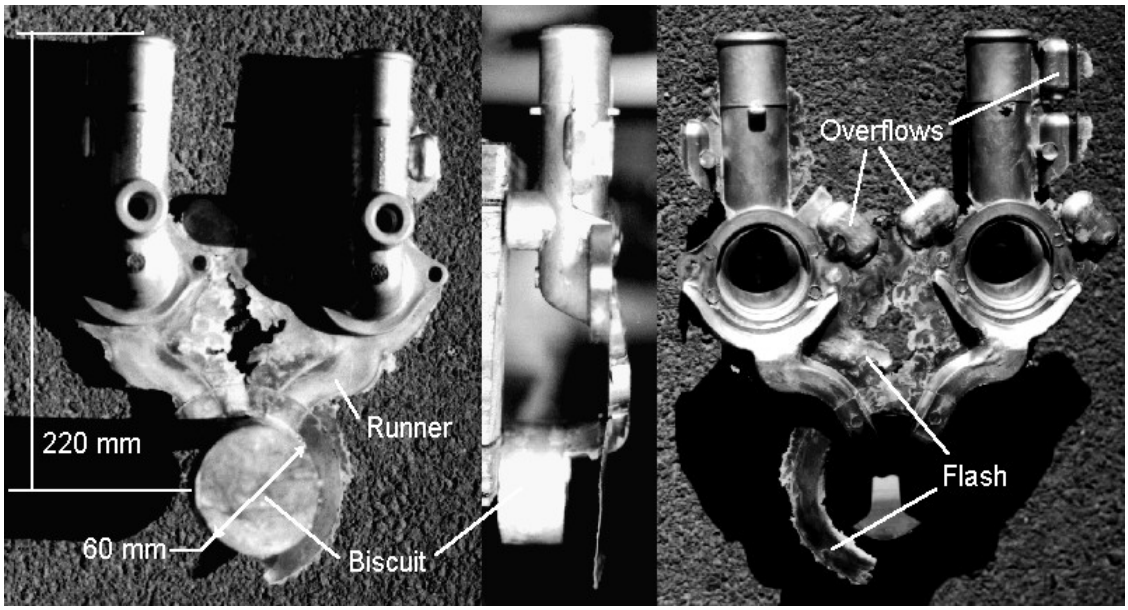


Figure A.3 Water Inlet Casting With Runners and Overflows.

A.3 Details of Secondary Operations

After removal from the die casting machine the castings are quenched in a water bath. From there they are placed in a trim press and the runners, overflows, and any casting flash are removed from the casting.

Castings are then shot blasted. This process removes any sharp edges and gives the castings a more salable surface finish. Any shallow surface blemishes on the outside face of the tube are removed, leaving a consistent dimpled surface. The effect on the inside surface of the tube is much more limited due to the fact that shot particles cannot impact directly onto the surface. The number and severity of impacts drops very rapidly as the distance from the open end of the tube increases. The small impacts left by shot particles are visible in the figures in Appendix D.

The casting is now machined in a number of areas. Machining of the base of the casting in performed to leave a smooth flat face for mounting onto the engine block. A thread is machined in the small tube at the top of the casting. The end of the tube is then machined. The purpose of this operation is to remove the raised seam formed along the parting line of the die. If this were not removed it would provide room for leakage between the casting and the hosing to be fitted onto the tube end.

A.4 Details of Pressure Tightness Testing Procedure

Castings are placed two at a time on a customised pressure testing rig. This blocks the three openings of the casting with rubber sealing surfaces. The casting is then filled with air, pumped through a hole in the rubber sealing face on the tube base, to a pressure of 300 Kpa. The casting is submerged in water and examined by an operator under strong lighting. Any bubbles forming on the outside of the tube result in casting rejection.

A.4.1 Limitations of Pressure Testing

- Due to the simultaneous testing of two castings, one side of each casting is slightly obscured from the operator. Detection of leakers on the obscured faces is often difficult. This can probably be overcome by operator experience.
- As well as support at the three sealing faces the casting is supported underneath the tube section. This support covers some of the machined surface of the tube. Figure A.4 shows this obscured area. It is unlikely that leakers occurring in this area will be detected during testing. As noted in Chapter 3, most leakers occur on the machined area of the tube around the die parting lines. Thus the obscured area is away from the main areas where leakers are found but is still on the machined surface. If it is essential to support the casting it may prove beneficial, in terms of reducing the number of leakers returned by the customer, to move the support back onto the non-machined area.

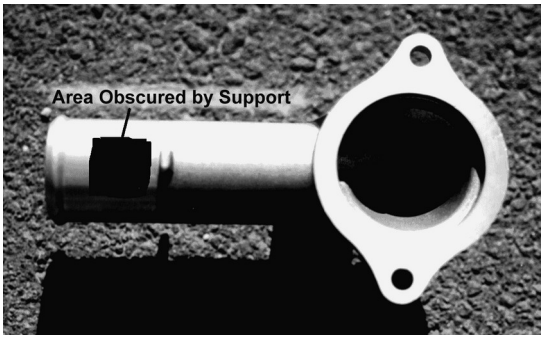


Figure A.4 Area of Casting Obscured by Support During Pressure Testing.

For the purposes of this study, the impact of a failure to detect what would be expected to be a very small number of leakers should be minimal, as long as the testing method remains consistent.

A.5References

A1 Buhler, *'Operating Manual for Buhler H250B-P Horizontal Cold Chamber Die Casting Machine'*, Buhler.

Appendix B - Calculation of Ideal and Actual Fill Times for Water Inlet Casting

B.1Calculation of Ideal Fill Times

The following formula can be used to calculate the ideal fill time for a given casting.

$$t = kT\left(\frac{T_i - T_f + SZ}{T_f - T_d}\right) \qquad \text{[B1]}$$

where;

t = Ideal filling time, seconds.

k = Empirically derived constant, s/mm.

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.

In order to solve the equation for fill time we must first determine suitable values for the other parameters. Herman [B1] has provided a list of suggested values for a range of alloy and die material combinations. A selection for aluminium alloys and H13 dies are given in Error: Reference source not found.

Casting Alloy	k, for H13 die (s/mm)	T_i (˚C)	T_f (˚C)	T_d (˚C)	Z (˚C/%)
Al 360, 380,384	0.0346	650	570	340	3.8
Al 390	0.0346	720	595	355	3.8

Table B.1 Suggested Values for Parameters in Fill Time Equation. [B1]

We shall now discuss the applicability of these values to our problem and suggest more appropriate values where possible.

***k*, s/mm,** is a function of, among other things, the heat transfer rate between the die and the molten alloy as the cavity fills. Its value will depend upon;

✶ the alloy being cast,

- the die material,
- the type and amount of lubricant, and
- the condition of the die surface.

This parameter has not been accurately determined for a range of conditions. The values supplied in the text only take into account the die material being used. The same value is used for almost all casting alloys from iron to magnesium. It is suggested that...

"The practical die caster may find it necessary to adjust the constant *k* as much as plus or minus 40% from the value recommended in [Error: Reference source not found] to get a good correlation with practice." [B1]

It is therefore the job of the die designer to assign a value to *k* based on experience with past dies. When one considers that varying *k* will have a direct effect on the fill time, ie. a 40% increase in *k* will cause a 40% increase in *t*, we can see the importance of correctly determining this parameter. If we can only guess at the value of *k* then much of the fill time calculation is meaningless.

In the current case we will calculate the fill times for a range of *k* values and present the results as a distribution.

***T_i*, °C,** represents the temperature of the molten metal when it reaches the gate. Herman [B1] suggests that the metal will usually lose 8 to 9 °C in the ladle and shot sleeve, so a value about 10 °C lower than the temperature in the holding furnace would be appropriate. This is contradicted by the work of Iwahori et al [B2] who demonstrated an alloy cooling from 640 °C in the holding furnace to around 570 °C by the time it reaches the gate of the cavity in an A384 alloy casting. This value of 570 °C is equal to the minimum flow temperature given in Error: Reference source not found. Clearly there also exists some confusion about what values are appropriate to be used here. The values determined by Iwahori et al [B2] seem to be more realistic and are backed up by sound experiments, for this reason we shall base the values we use upon them.

They represent a drop in holding furnace temperature to injection temperature of 70 °C. We know that for our castings the holding furnace temperature is usually 680 °C so we shall use a T_i value of 610 °C.

***T_f*, °C,** represents the temperature at which we would like the metal to travel through most of the cavity. Herman [B1] recommends a temperature of 570 °C. It is important that this temperature lies above the solidus temperature of the alloy, 540 °C for 380 alloy [B3]. Apart from this requirement it is difficult to see any reason to choose one value over another. With this in mind we shall use a value of 570 °C.

***T_d*, °C,** represents the die surface temperature that the molten metal encounters as it is injected. It is possible to get a fairly good idea of what this is by measuring the surface temperature of the die just before the die closes. In our case we have done this with a thermal imaging camera so we can use average values obtained from these images.

***S*, %,** represents the amount of solidified metal present in the flowing metal at the completion of cavity filling. In theory, for atomised flow, this solid component will consist of small isolated particles amongst the liquid flow. Such solidification will not hinder flow at low percentages. A high percentage solids factor should result in less overall shrinkage porosity in the final casting. However, if the factor is allowed to get too high the casting's surface finish will become worse. We shall use a range of values from 0 to 30 % in our calculations.

***Z*, °C/%,** is a function of the specific and latent heats of the alloy and as such is not subject to change. The value given in Error: Reference source not found will be used.

***T*, mm,** is the representative thickness of the casting. Very few castings have a uniform thickness throughout. In the case of the water inlet casting the thickness varies from 5 mm to 2 mm. We shall use a representative value of 3 mm. In a similar manner to the *k* parameter, this parameter will have a major effect on the resulting fill time so it is important to get it right. We can see that in this case if we used a value of 2 mm instead of 3 mm our ideal fill time would be reduced by 33%. This is another area in which experience must be used to determine an appropriate value.

B.1.1Calculation for Water Inlet Casting

Die temperature was determined by taking an average of the temperatures for the fixed and moving half and the sliding cores from a thermal image taken during experiments in the foundry. The resulting value used was 195 °C. The values of *k* and *s* were varied between high, medium, and low values. All other parameters were given

fixed values. The results are presented as a 3 × 3 matrix along with the maximum and minimum values. The average of the nine calculated values is also given.

1Parameter Values

k = 0.02076, 0.0346, 0.04844 s/mm.

T_i = 610 ˚C.

T_f = 570 ˚C.

T_d = 195 ˚C.

S = 0, 15, 30 %.

Z = 3.8 ˚C.

T = 3 mm.

2Results

		k (s/mm)		
		0.02076	0.0346	0.04844
	0	7	11	16
S(%)	15	16	27	38
	30	26	43	60

Table B.2 Fill Times in Milliseconds for Different *S* and *K* Values.

Maximum Value = 60 milliseconds

Minimum Value = 7 milliseconds

Average Value = 27 milliseconds

B.2Calculation of Actual Fill Times

The first step in the calculation of actual cavity fill times is the determination of the plunger position at the point when the molten alloy is at the gate of the casting. This is done by taking an actual casting and weighing the cavity, overflow, and runner

sections separately. The volume of each component can then be determined and thus the movement of the plunger required to fill any given part can be determined. This was done for two water inlet castings.

	Casting 1	Casting 2
Distance to fill Runner and Biscuit (mm)	50	53
Distance to fill Cavity (mm)	39	39
Distance to fill Overflow (mm)	9	9

Table B.3 Shot Displacements for Two Castings.

The point at which the metal is at the gate will occur a distance *X* before the cavity is full, where *X* = Distance to fill Cavity + Distance to fill Overflows.

The point at which the cavity and overflows are full is best determined by examining the shot trace for the given casting and looking for the pressure peak that will occur upon cavity filling. Once these two points are found the cavity fill time can be read off the time axis of the shot trace. This process is shown in Figure B .1.

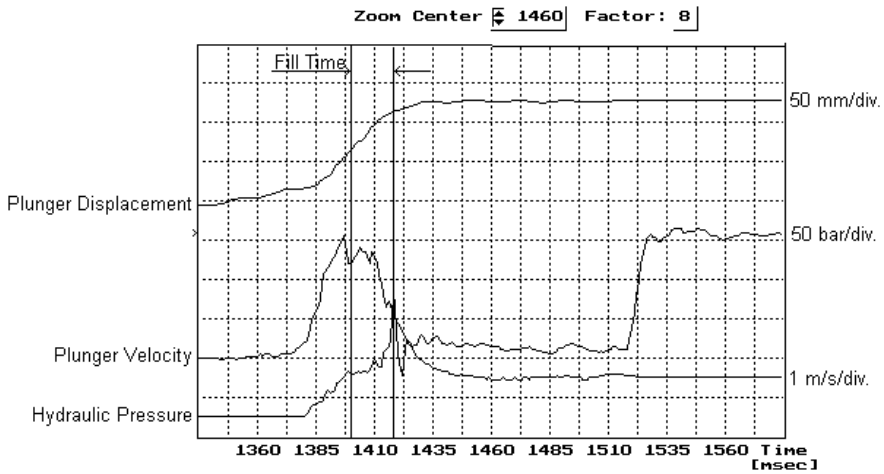


Figure B.1 Enlarged Shot Trace for Water Inlet Casting.

For both castings the actual fill times were determined to be 18 ms.

B.3 Comparison of Actual Fill Times with Ideal Fill Times

It can be seen that actual fill times for the water inlet are of the order of 20 ms. Values in the range of 7 to 60 ms with means around 30 ms were recommended by the ideal fill time equation.

The actual fill times are less than the average calculated fill times. This indicates that most castings will be free from flow defects such as cold shuts. There is room for variation in ideal and actual fill times and this will result in a number of castings that will have flow defects present. This variation may be due to changes in lubricant application, die temperatures, and metal temperature. It is likely that due to the poor fill pattern in the die a very low value of percentage solids is required to make good castings.

B.4References

B1 Herman, *'Die Casting Technology - Calculations'*, Die Casting Education Project RMIT University, 1995.

B2 Iwahori, Nakamura, Tozawa, Yamamoto, *'Metal Flowing Behavior in Die Castings and Defects in Aluminium Die Castings'*, 13th SDCE International Die Casting Congress and Exposition, 1985.

B3 ASM International, *'Metals Handbook - Volume 2, Properties and Selection: Nonferrous Alloys and Special-Purpose Materials, 10th Edition'*, ASM International, 1990.

Appendix C - Determination of Optimum Shot Profiles

C.1 Calculation of Optimum Shot Profiles

In order to determine optimum shot profiles we need to know the volumes of the various parts of the castings and the dimensions of the shot sleeve. We can convert masses to volumes using a density for aluminium 380 alloy of 2710 Kg/m^3 [C1]. Table C .1 gives the volumes of each casting part for the selected water inlet casting. The shot fill percentages are obtained by dividing the total casting volume by the shot sleeve volume, ie. plunger area $\times$ length.

Casting Volumes (m^3)			Shot Sleeve Dimensions		
Runners and Biscuit	Cavity and Overflows	Total Volume	Length (mm)	Diameter (mm)	Shot Fill Percentage
1.401×10^{-4}	1.331×10^{-4}	2.732×10^{-4}	413	59.5	23.79

Table C.1 Casting Data.

Using the above data we can determine the optimum first stage velocities and acceleration using the approximate formulae presented by Herman;

$$v = C\left(\frac{100 - f}{100}\right) \times \sqrt{\frac{D}{25.4}} \qquad \textbf{[C2]}$$

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;

$$\text{Acceleration}(\text{m/s/m}) = 1.75 + 0.01 \times \text{Plunger Diameter(mm)} \qquad \textbf{[C2]}$$

To determine the change over point we need to determine the point at which the shot sleeve is full and the point at which the metal is at the gate.

$$\text{"Shot Sleeve Full" Displacement} = \text{Shot Sleeve Length} - \frac{\text{Total Casting Volume}}{\text{Plunger Area}}$$

$$\text{"Metal at Gate" Displacement} = \text{Shot Sleeve Length} - \text{Biscuit Thickness} - \frac{\text{Volume of Cavity and Overflow}}{\text{Plunger Area}}$$

Here both plunger displacements are measured from the plunger position at the start of the shot.

A value between these two will be taken as the change-over position. If there is a large gap between the two points then a value 10 mm after the shot sleeve full point will be used to allow for variations in the amount of metal ladled.

The biscuit thickness for the selected casting is 37 mm.

Finally we will select a second stage velocity roughly equal to the existing second stage velocity which appears sufficient for this castings. Table C .2 shows the calculated optimal shot profile parameters for this casting.

First Stage Velocity (m/s)	Acceleration (m/s/m)	Shot sleeve full point (mm)	Metal at Gate Point (mm)	Change over Position (mm)	Second Stage Speed (m/s)
0.675	2.35	315	328	320	3.5

Table C.2 Optimum Shot Profile Parameters for Castings.

We can now compare this optimum shot profile with an actual shot profile.

C.2 Comparison with Actual Shot Profile

Comparisons between the actual and optimum shot profiles are presented in Table C .3, Figure C .1, and Figure C .2. A small starting velocity was used to begin the optimal shot. This was necessary due to the fact that initial velocity is proportional to displacement, so if both started at zero then no movement would occur. 0.05 m/s was chosen as a suitably small starting velocity based on actual shot data.

	First Stage Velocity (m/s)	Acceleration (m/s/m)	Change Over Position (mm)	Second Stage Speed (m/s)
Optimal Profile	0.675	2.35	320	3.5
Actual Profile	0.60	2.26	265	3.6

Table C.3 Comparison of Critical Values Between Optimal and Actual Shot Profiles.

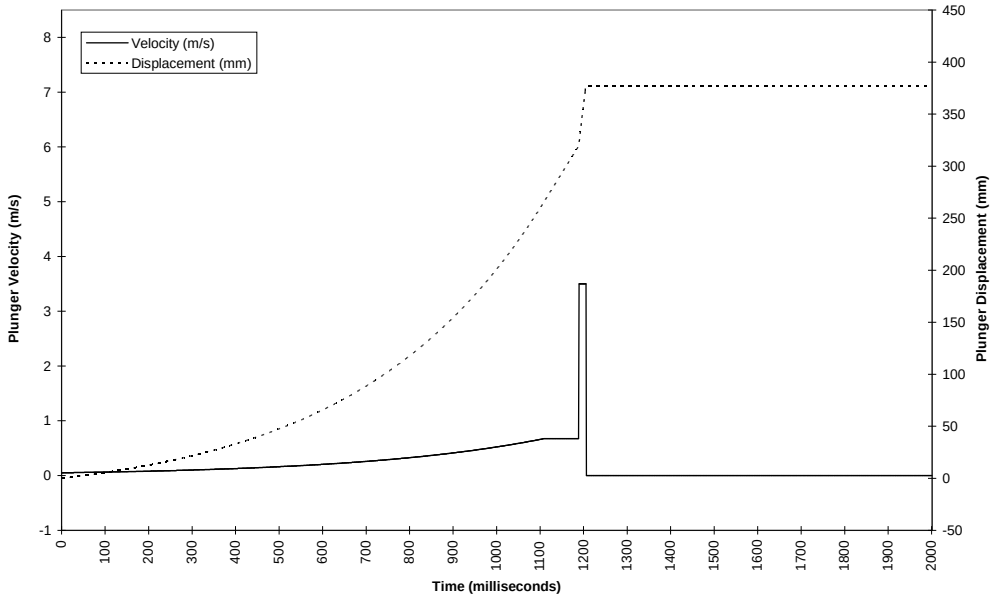


Figure C.1 Optimum Shot Profile for Water Inlet Casting.

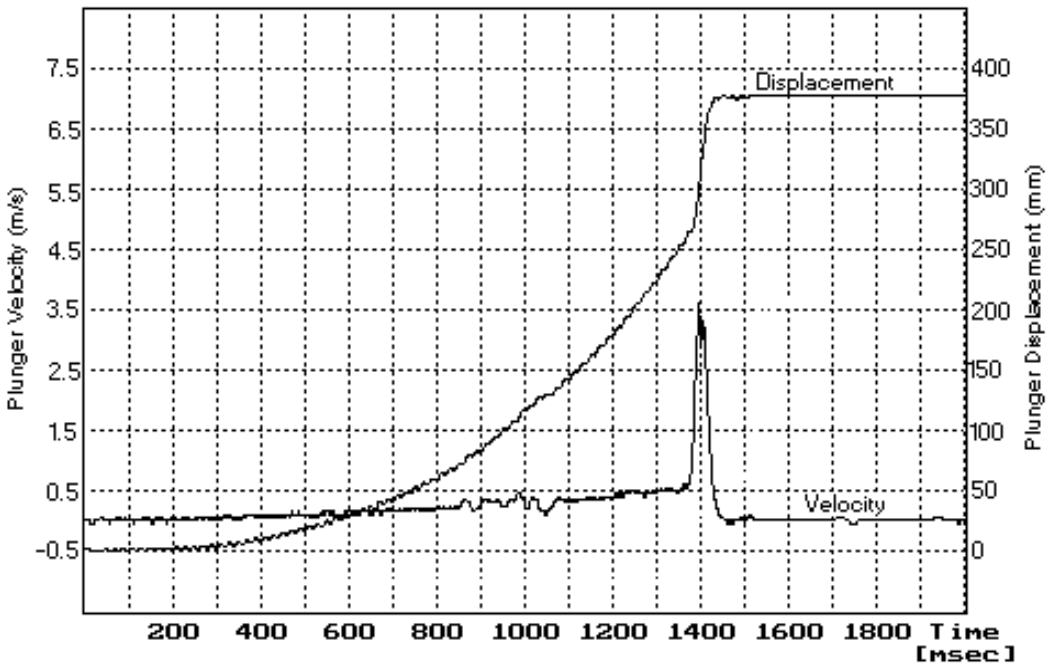


Figure C.2 Actual Shot Profile for Water Inlet Casting.

Both the initial acceleration and the first stage velocity are fairly close to what is considered optimum. The main difference is the change over position. The actual change over position occurs at a lesser plunger displacement than our calculations would suggest. Calculating the percent shot sleeve full when the plunger has moved 265 mm indicates that the shot sleeve is only about 70 % full when the high velocity second stage begins. So assuming that a minimum of air entrapment will occur during

the first stage due to the choice of velocities and accelerations used, when second stage starts 30 % of the remaining shot sleeve volume will be air and most of this will become entrapped in the casting.

C.3References

C1 ASM International, *'Metals Handbook - Volume 2, Properties and Selection: Nonferrous Alloys and Special-Purpose Materials, 10th Edition'*, ASM International, 1990.

C2 Herman, *'Die Casting Technology - Calculations'*, Die Casting Education Project RMIT University, 1995.

Appendix D - Cold Shut Levels

The amount of cold shutting present on each casting was subjectively quantified. The level assigned takes into account both the extent, location, and severity of cold shuts. The photographs presented provide an example of the cold shuts found at each level.

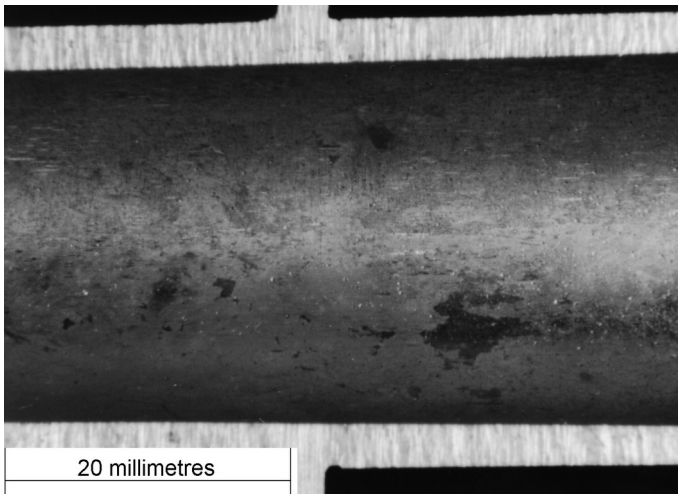


Figure D.1

Level 0 (No Cold Shuts)

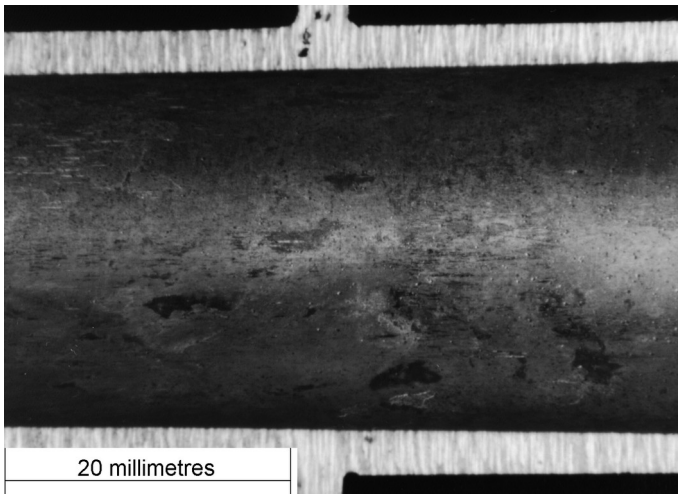


Figure D.2

Level 1 (Small Cold Shuts)

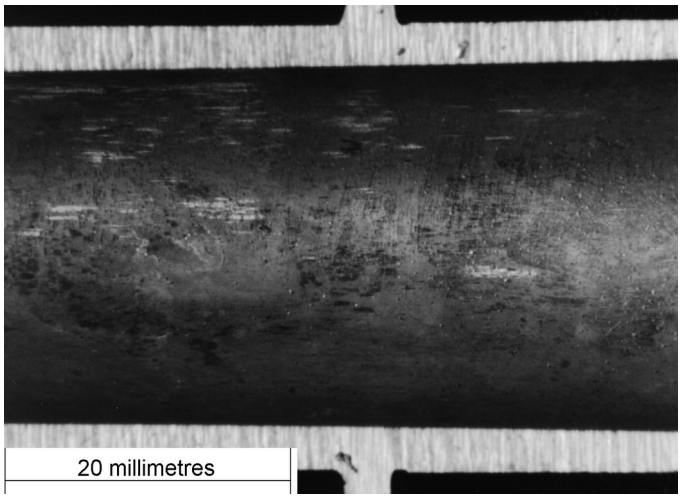


Figure D.3

Level 2 (Moderate Cold Shuts)

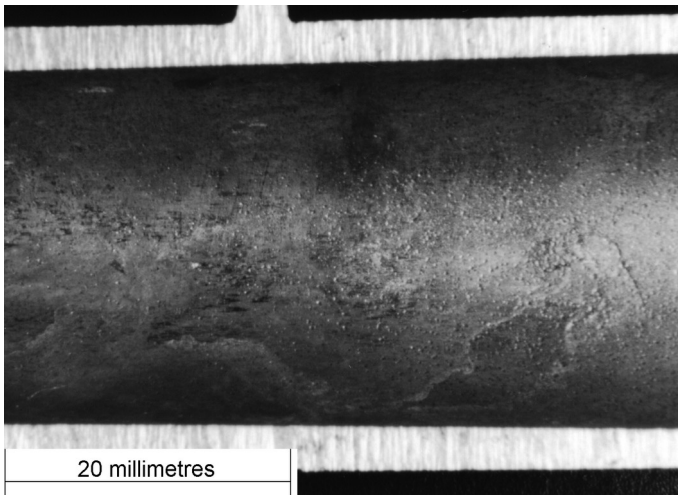


Figure D.4

Level 3 (Extensive Cold Shuts)

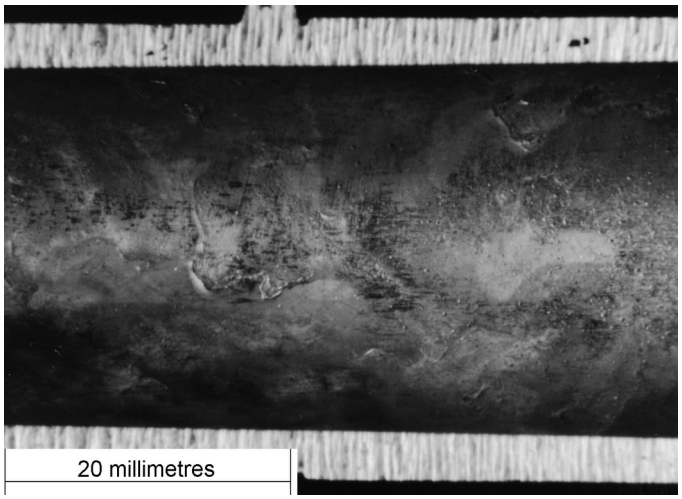


Figure D.5

Level 4 (Severe Cold Shuts)

Appendix E - χ^2 Testing of Correlation Between Cold Shuts and Leakers

Table E .1 gives the number of leakers detected on castings divided into groups of different severity of cold shutting.

Level of Cold Shutting	None	Small	Moderate	Extensive	Severe
Number of Castings	24	15	13	9	4
Number of Leakers	2	4	6	6	4
Leaking Castings/Castings	0.083	0.27	0.46	0.67	1

Table E.1 Relationship Between Level of Cold Shuts and the Occurrence of Leakers.

We can test whether the relationship evident in the data in Table E .1 is likely to occur due to random sampling in a population where there is in fact no relationship between cold shuts and leakers, this is referred to as the "Null Hypothesis". This can be done using a χ^2 test in a similar manner to that used in Chapter 4.

Initially we determine a χ^2 value using Equation E .1. This can then be compared with tabulated values to give a probability of the null hypothesis being correct.

$$\chi^2 = \sum_{i=1}^{k} \frac{(o_i - e_i)^2}{e_i}$$ **Equation E.1 [E1]**

The terms o_i and e_i represent the observed and expected frequencies for the *i*th cell. The term *k* represents the number of groups of data. The observed values are found from the actual data, in our case the number of leakers at each level of cold shuts. The expected value refers to the value we would expect to occur if the null hypothesis were true. For each level of cold shutting this can be found by multiplying the overall leaker rate by the number of castings at each cold shut level. However, when we do this we find that the expected values for cold shut levels moderate, extensive, and severe, are less than 5. It is a requirement of the χ^2 test that the expected value of each sample must be greater than 5, [E2]. In order to overcome this problem we can regroup the data as shown in Table E .2. This will allow us to perform a χ^2 test on the data. Should the null hypothesis be proven unlikely on this regrouped data, it will be similarly unlikely on the original data, Table E .1.

Cold Shuts	None	Small	Moderate to Severe

Castings	24	15	26
Leakers (Observed Value)	2	4	16
Expected Value	8.123	5.077	8.800

Table E.2 Regrouped Cold Shut Levels and Expected Values.

Using the expected values given in Table E .2 we can now calculate a χ^2 value as follows.

$$\chi^2 = \frac{(2 - 8.123)^2}{8.123} + \frac{(4 - 5.077)^2}{5.077} + \frac{(16 - 8.800)^2}{8.800} = 10.73$$

We can compare this value with tabulated χ^2 values on [E1]. For 2 degrees of freedom[1] we see that the probability of χ^2 exceeding 10.597 is 0.5 %. This indicates that the probability of the null hypothesis being true is slightly less than 0.5%. Thus in all probability, there exists a relationship between the occurrence of cold shuts and the occurrence of leakers.

E.1References

E1 Walpole and Myers, *'Probability and Statistics for Engineers and Scientists'*, Fifth Edition, Macmillan Publishing Company, 1993.

E2 Moroney, *'Facts from Figures'*, Second Edition, Penguin Books Ltd., 1957.

[1] The number of degrees of freedom is defined as the number of classes whose frequencies may be arbitrarily assigned [E2] without changing the overall frequency. In this case it is given by k-1 = 2.
If we arbitrarily assign the number of leakers in two of the groups in Table E .2 then the number of leakers in the third group is determined by the fact that there must be 22 leakers overall.

Appendix F: Data from Casting Trial

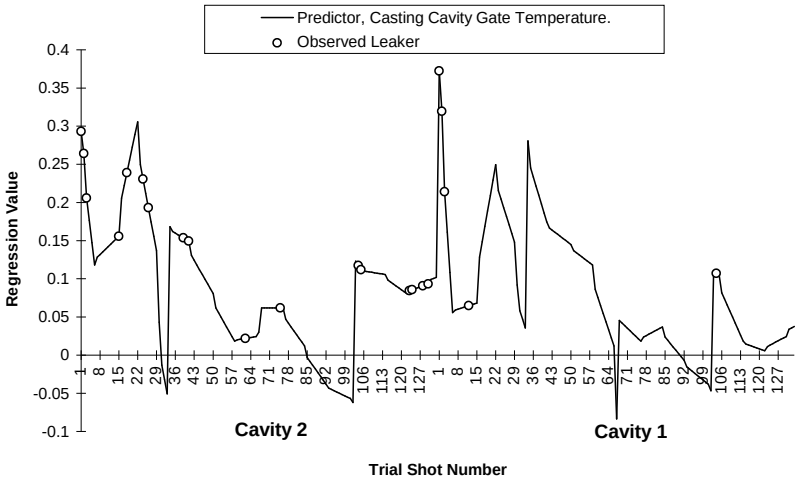
F.1 Linear Regressions Between Input Parameters and Leaker Occurrence

The following plots detail the likelihood of leaker occurrence as predicted by the single parameter named in the legend of each plot. The mean, minimum, maximum, and standard deviation of the parameter values recorded during the trial are also given for reference. The plots are listed in order of the strength of the correlation between the input parameter and the occurrence of leakers.

The plots for the die temperatures detail the results for each cavity and trial shot number. The remaining plots group the cavities together as for the shot end parameters and the metal temperature the regression value is the same for each cavity. An observed leaker on these plots indicates that either or both cavities produced a leaking casting.

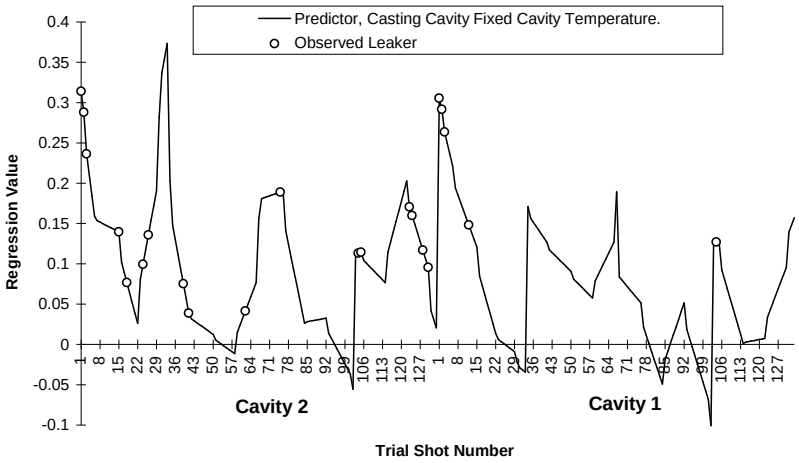
Casting Cavity Gate Temperature, °C.

Mean	Minimum	Maximum	Standard Deviation
141	94	167	13.20



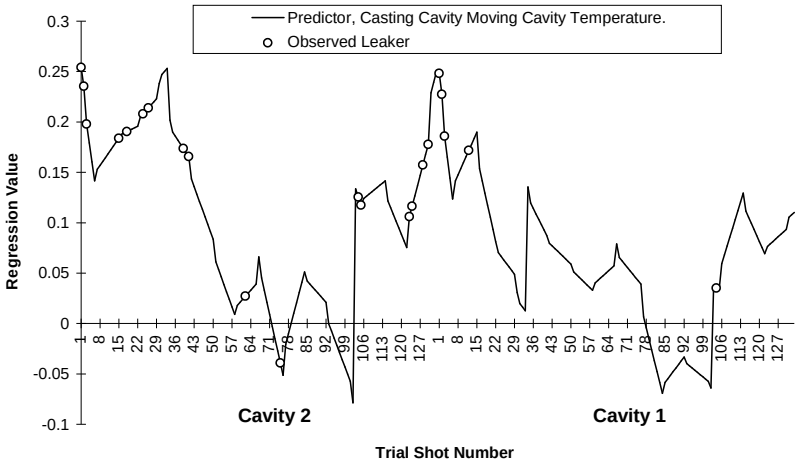
Casting Cavity Fixed Cavity Temperature, °C.

Mean	Minimum	Maximum	Standard Deviation
117	71	146	12.77



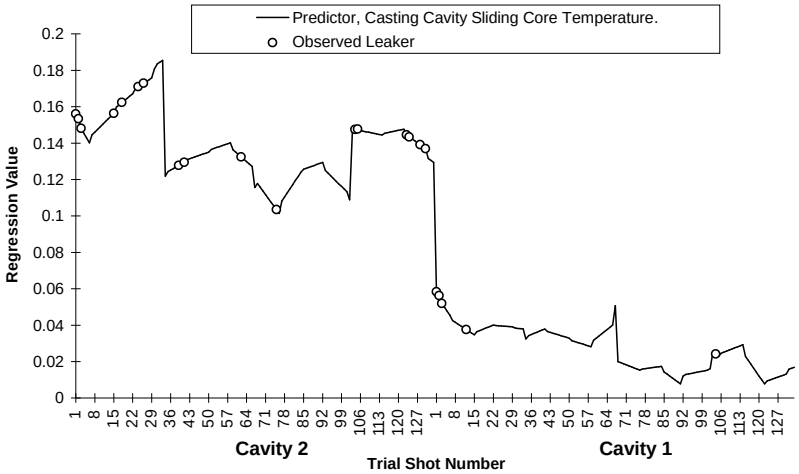
Casting Cavity Moving Cavity Temperature, °C.

Mean	Minimum	Maximum	Standard Deviation
118	89	145	13.10



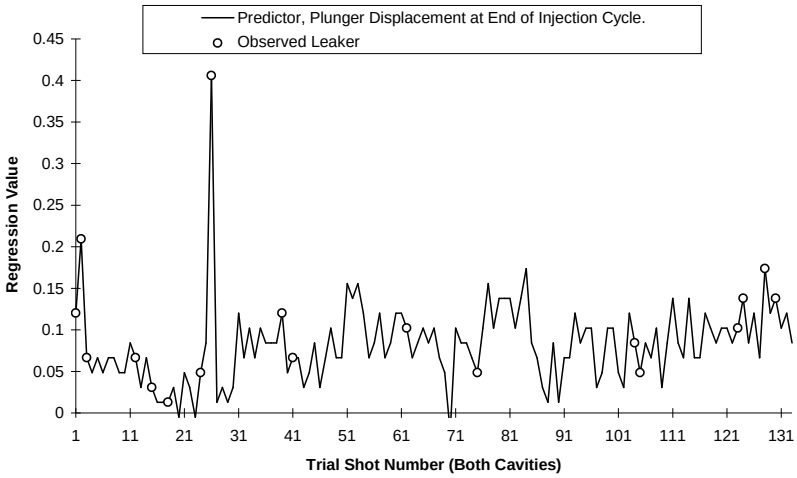
Casting Cavity Sliding Core Temperature, °C.

Mean	Minimum	Maximum	Standard Deviation
213	118	283	53.45



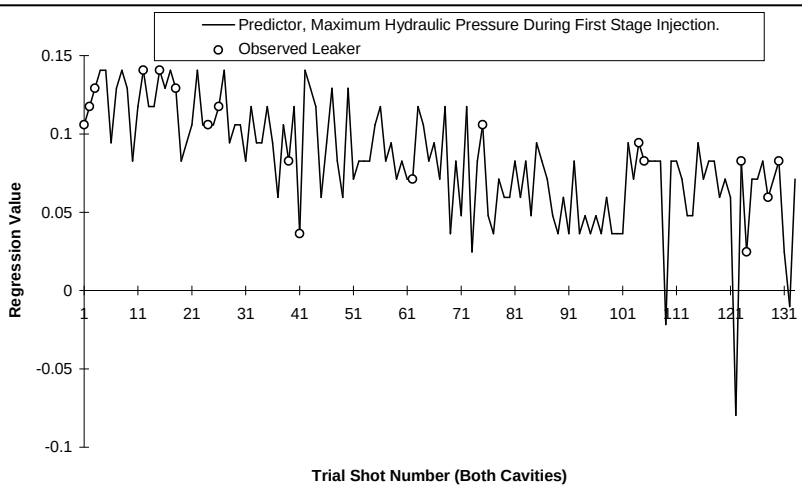
Plunger Displacement at End of Injection Cycle, mm.

Mean	Minimum	Maximum	Standard Deviation
365	359	383	2.75



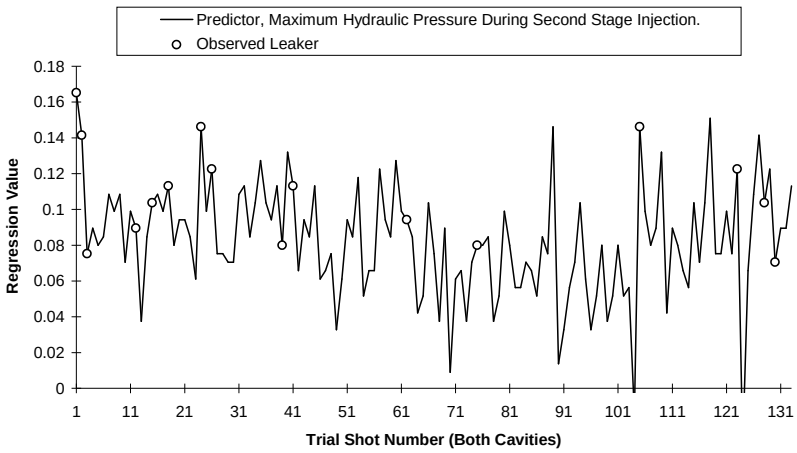
Maximum Hydraulic Pressure During First Stage Injection, Bar.

Mean	Minimum	Maximum	Standard Deviation
5	0	19	3.07



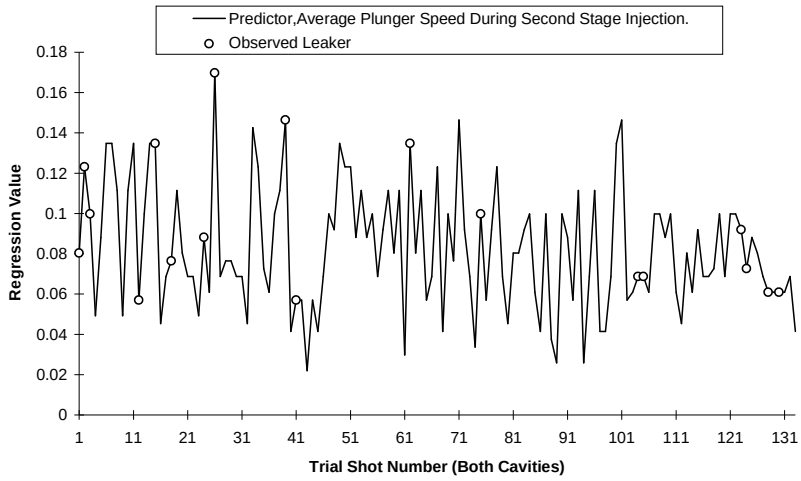
Maximum Hydraulic Pressure During Second Stage Injection, Bar.

Mean	Minimum	Maximum	Standard Deviation
134	117	159	6.70



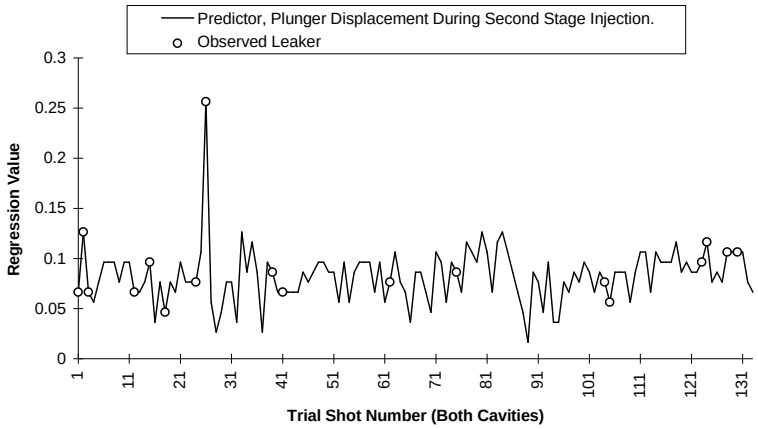
Average Plunger Speed During Second Stage Injection, m/s.

Mean	Minimum	Maximum	Standard Deviation
1.93	1.77	2.15	0.08



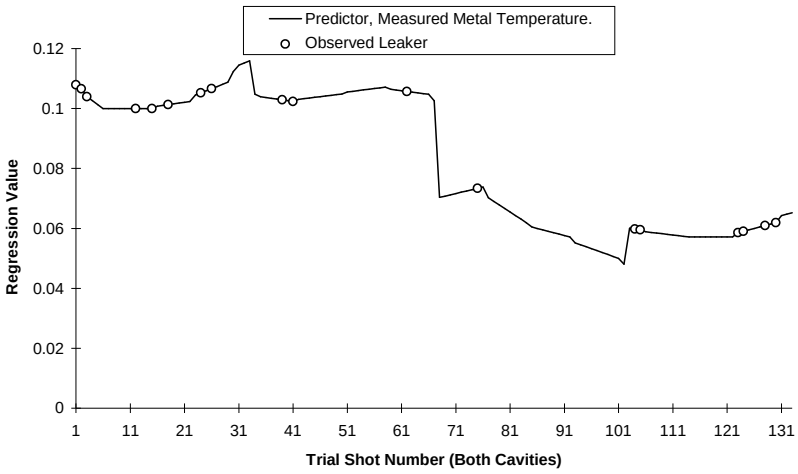
Plunger Displacement During Second Stage Injection, mm.

Mean	Minimum	Maximum	Standard Deviation
71	64	88	2.68



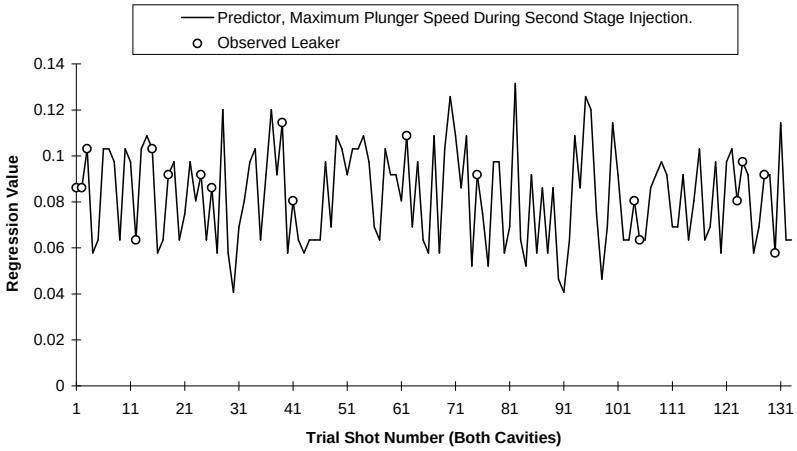
Measured Metal Temperature, °C.

Mean	Minimum	Maximum	Standard Deviation
749	722	787	12.87



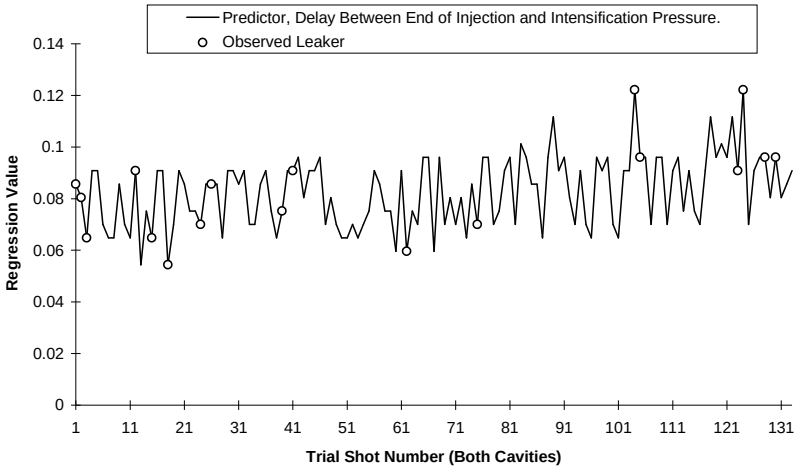
Maximum Plunger Speed During Second Stage Injection, m/s.

Mean	Minimum	Maximum	Standard Deviation
3.34	2.60	4.20	0.37



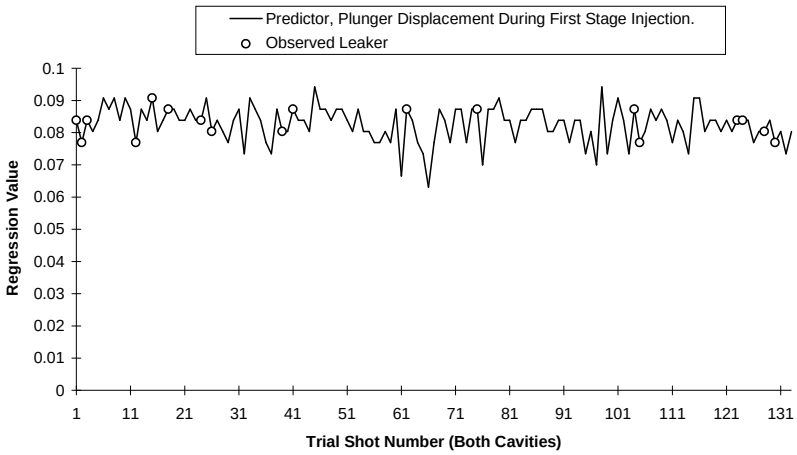
Delay Between End of Injection and Intensification Pressure, ms.

Mean	Minimum	Maximum	Standard Deviation
58	50	63	2.61



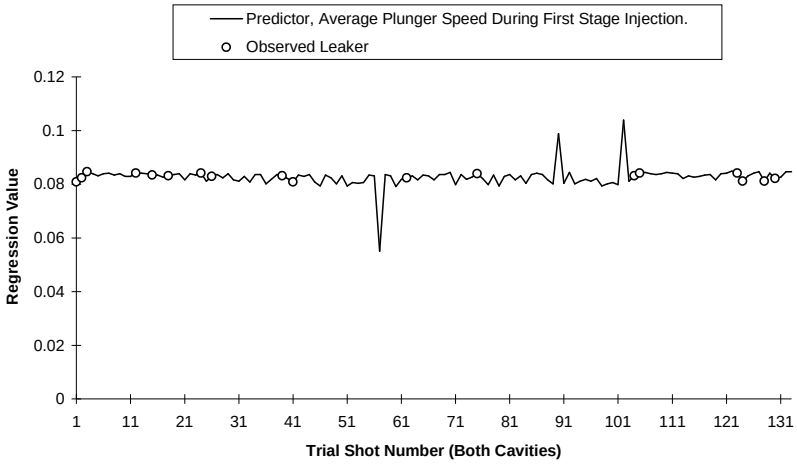
Plunger Displacement During First Stage Injection, mm.

Mean	Minimum	Maximum	Standard Deviation
289	286	295	1.57



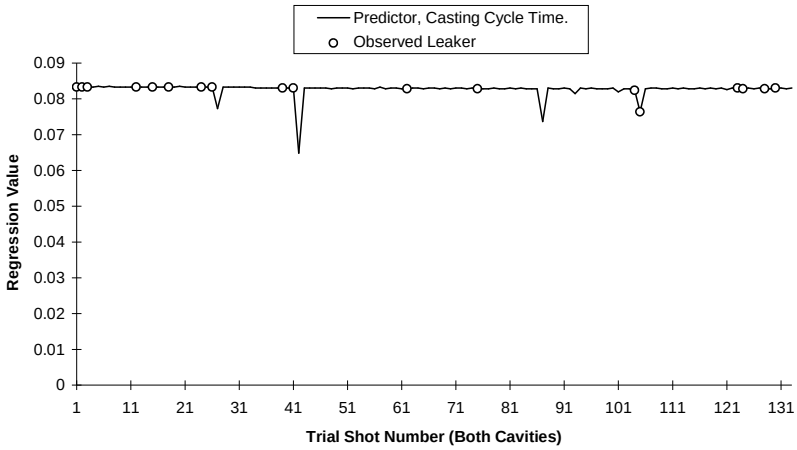
Average Plunger Speed During First Stage Injection, m/s.

Mean	Minimum	Maximum	Standard Deviation
0.30	0.19	0.38	0.01



Casting Cycle Time, s.

Mean	Minimum	Maximum	Standard Deviation
51	47	131	8.64



F.2 Results of Analysis of Alloy Composition of Castings Made During Trial

Table F .1 shows results of compositional analysis carried out on three water inlet castings sampled during the course of the trial discussed in Chapter 4. During the course of the trial the holding furnace was refilled with molten alloy from the melting furnace twice. The data in Table F .1 represents one casting made between each refill. The variation witnessed was deemed insufficient to warrant analysis of further castings.

	Casting Sampled Near Start of the Trial	Casting Sampled Near Middle of the Trial	Casting Sampled Near End of the Trial
Aluminium	Balance (85.93)	Balance (85.52)	Balance (86.00)
Silicon	8.41	8.7	8.34
Copper	3.08	3.2	3.05
Iron	0.89	0.86	0.88
Magnesium	0.2	0.2	0.2
Zinc	1.11	1.15	1.15
Lead	0.06	0.06	0.06
Chromium	0.03	0.03	0.03
Nickel	0.05	0.05	0.05
Manganese	0.21	0.2	0.21
Titanium	0.019	0.019	0.019
Tin	0.01	0.01	0.01
Strontium	<0.001	<0.001	<0.001
Zirconium	0.005	0.005	<0.005

Table F.1 Results of Analysis in Weight % for Three Sample Castings.