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.

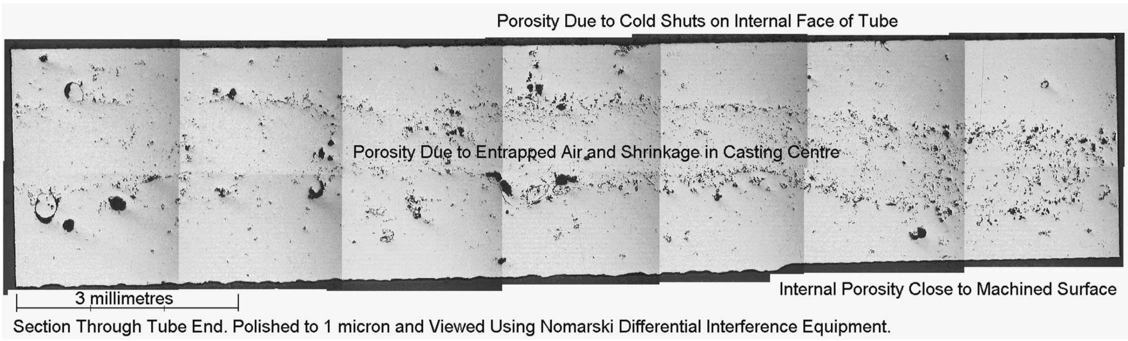

Figure 5.1 Cross Section Through Tube Wall Showing Cold Shuts, Internal Porosity, and Material Removal Combining to Provide a Path for Leakage.

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.