# 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.

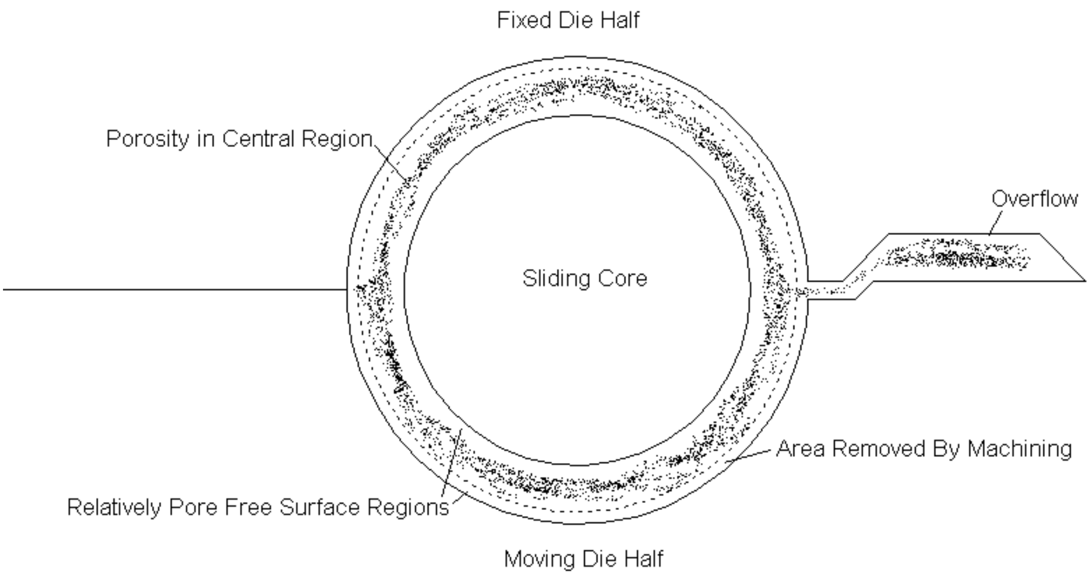



**Figure 3.2 Likely Porosity Distribution at Tube End, Showing Effect of Overflows and Machining.**

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.

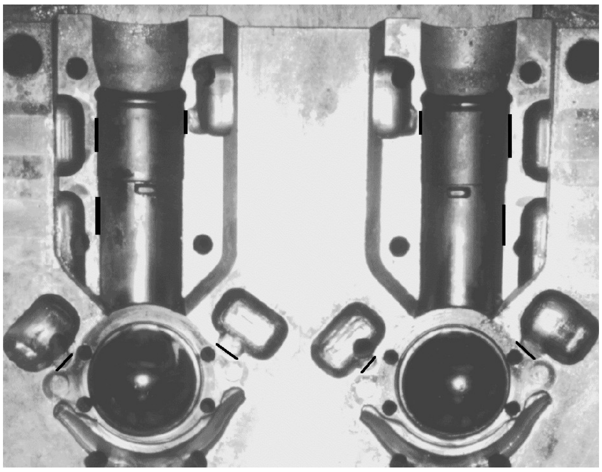


**Figure 3.3 Water Inlet Die Cavity Showing Location of Overflows. The Gates to the Overflows are Marked in Black.**

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.

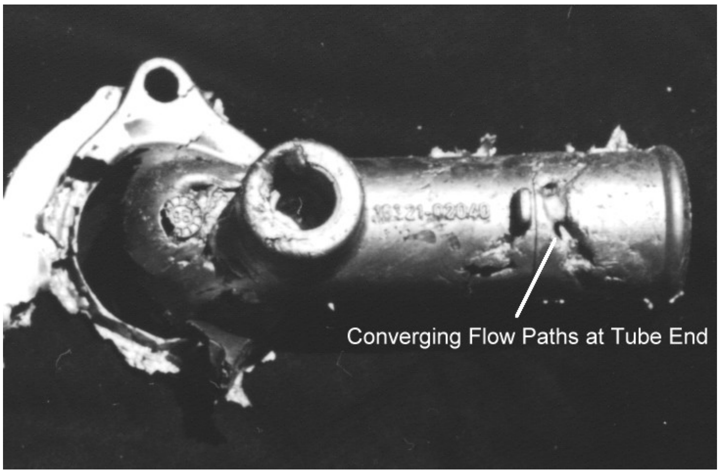



**Figure 3.4 Short Shot Showing Last Areas to Fill.**

### *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.

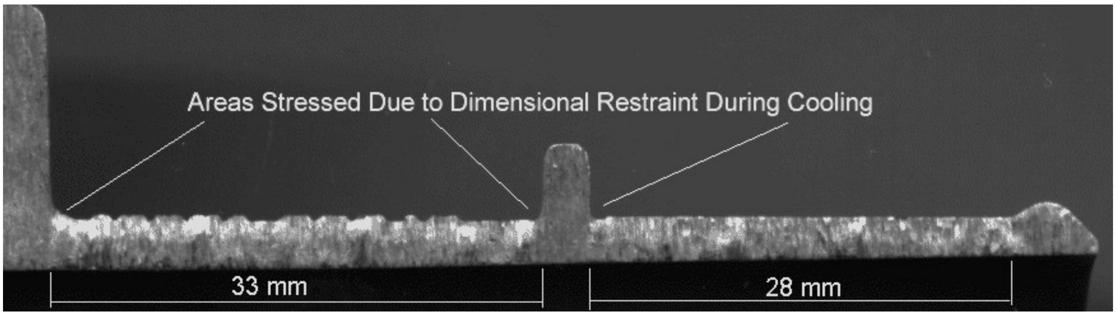



**Figure 3.5 Restrained Sections Near Tube End.**

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.

| | |
|---|---|
| Coefficient of Linear Thermal Expansion $(20\text{-}200\ °C) \approx 22 \times 10^{-6}$ m/m.$k$ | [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:

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

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

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

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

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

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.

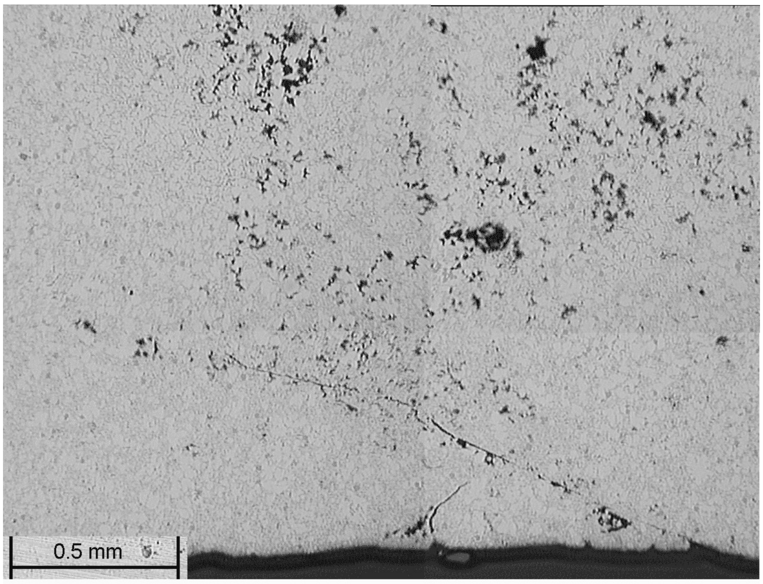
- Cold shuts in various locations and of various sizes on the internal face of tube.
- Exposed gas/shrinkage porosity on machined surfaces.
- Surface porosity on the internal surface of the cylinder.
- Drag marks on the internal surface of the cylinder.
- Small cracks associated with other defects around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

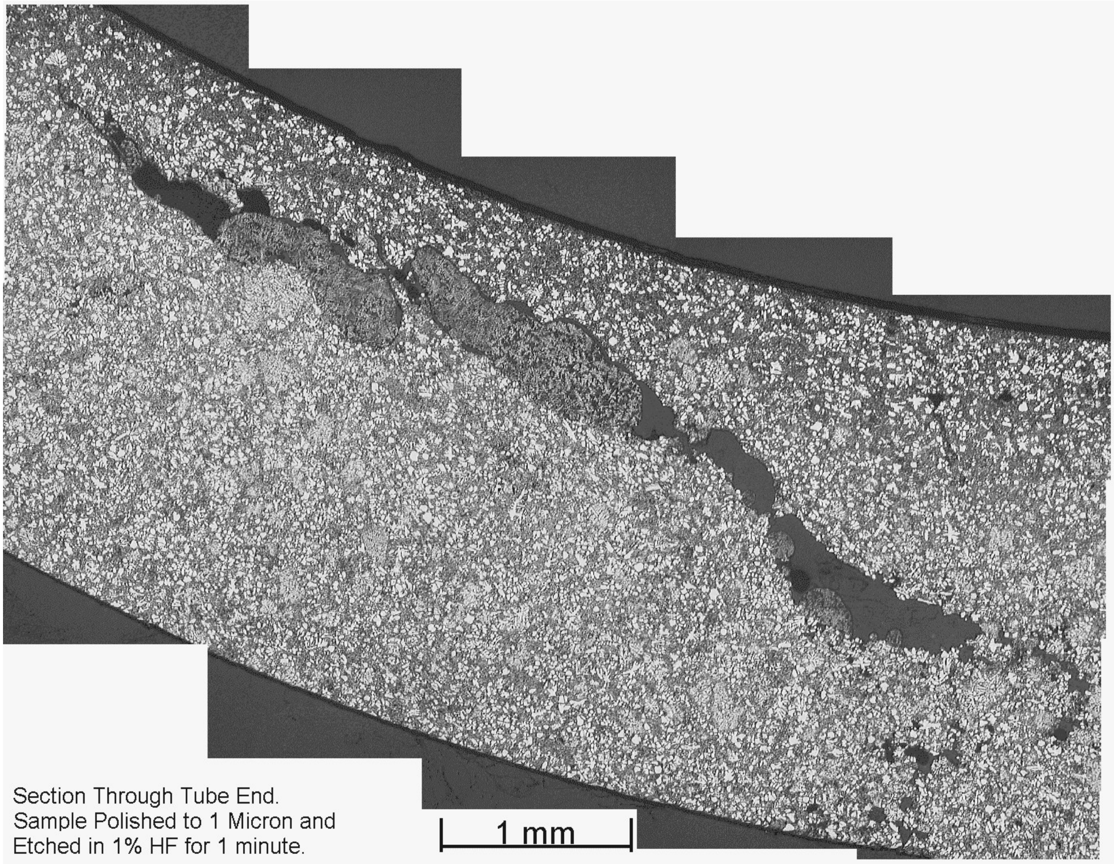



Cross Section Through Surface Cold Shut. Polished to 1 micron, Unetched.

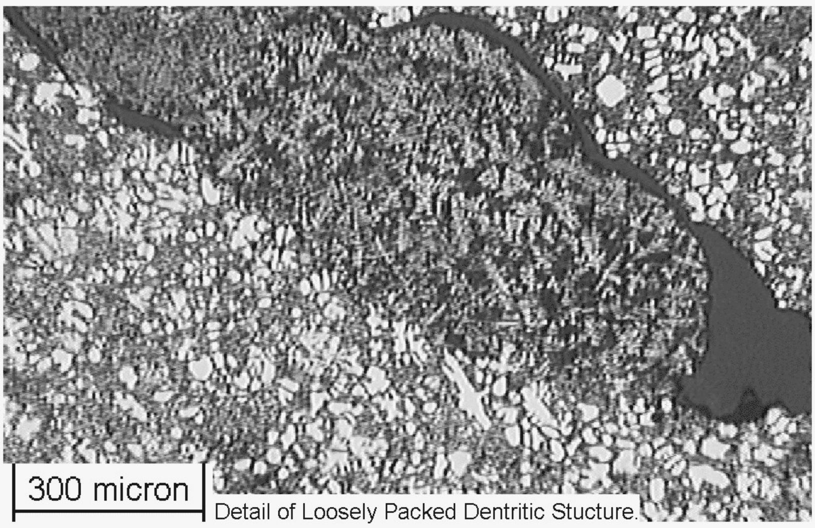
**Figure 3.6 Cold Shut at Surface of Leaking Casting Leading to Porous Inner Region.**

- 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.

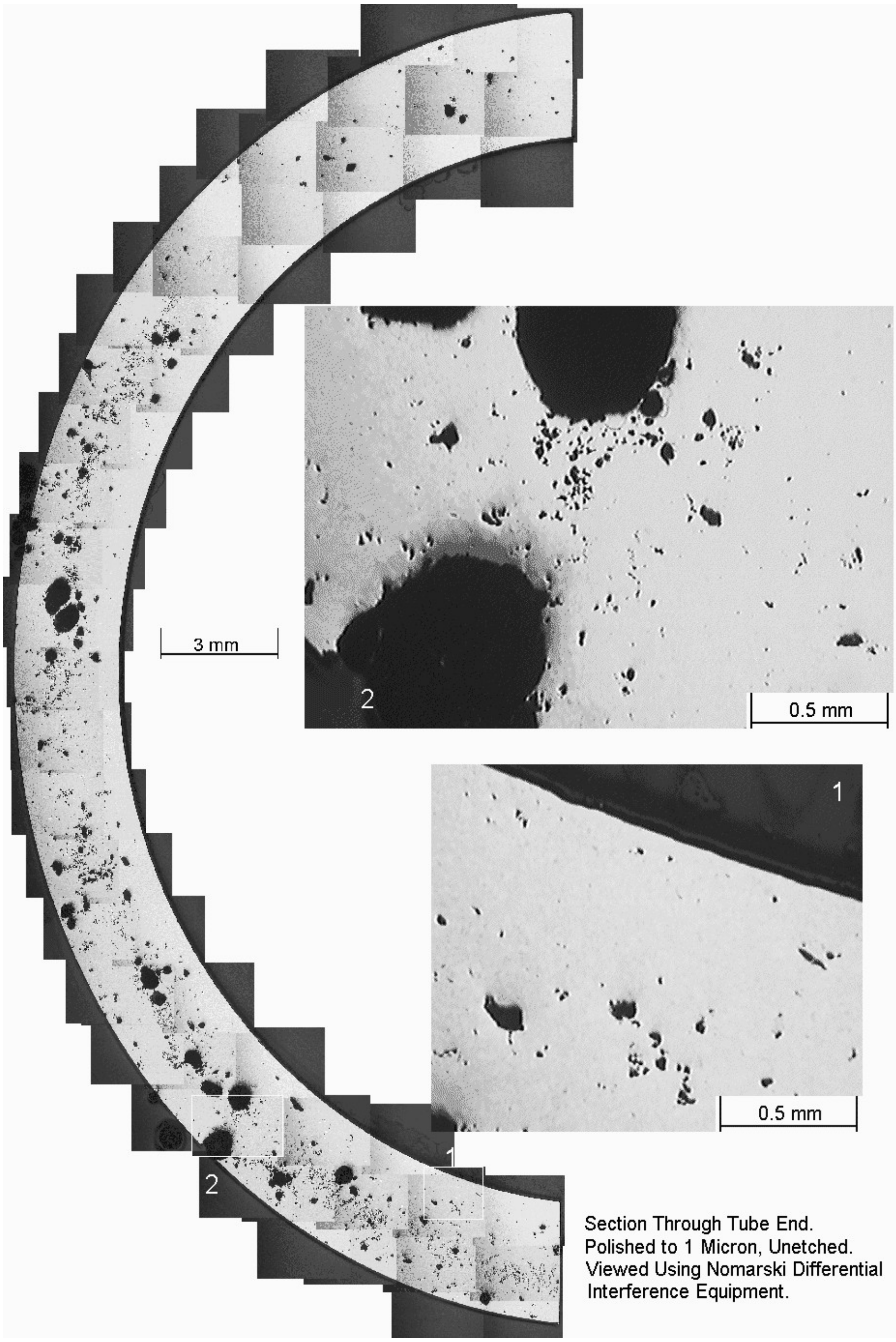



**Figure 3.8 Extensive Gas Porosity Found Through Section of Tube End.[2]**

[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.

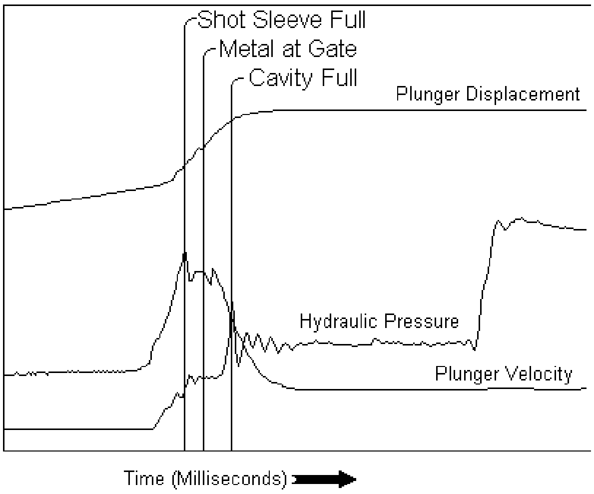



**Figure 3.9 Shot Timing for Water Inlet Casting.**

**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.

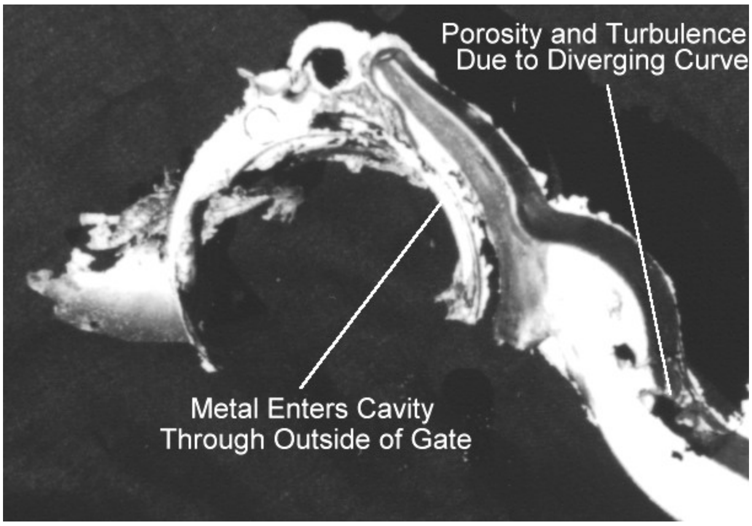



**Figure 3.11 Short Shot Showing Flow Through Runner.**

**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.

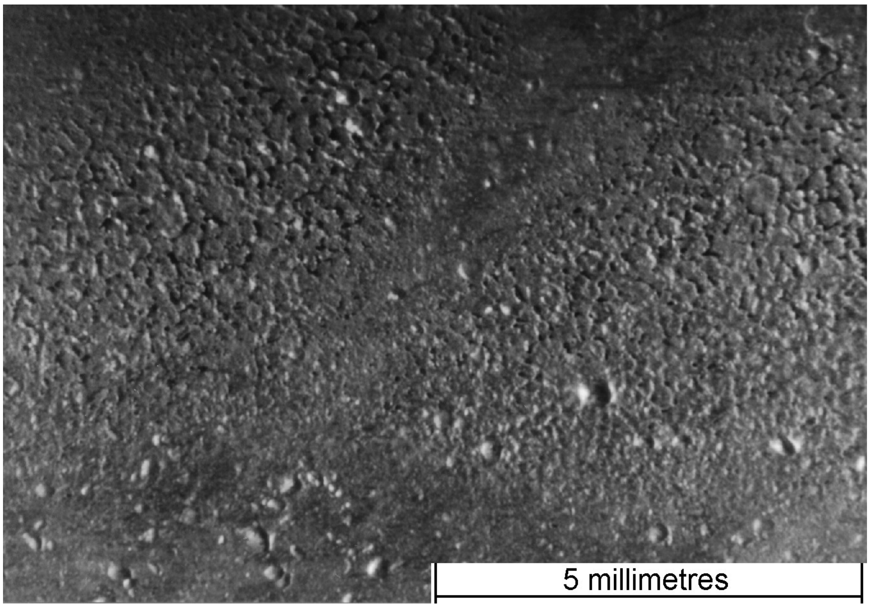



**Figure 3.12 Surface Porosity on Internal Face of Tube.**

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.

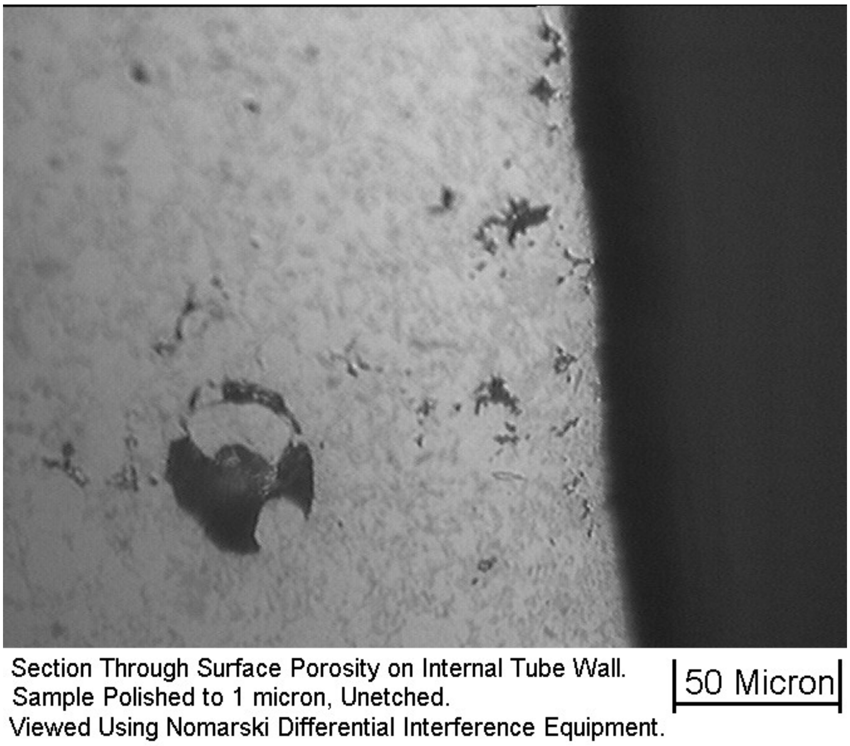



**Figure 3.13 Section Through Surface Porosity on Internal Face of Tube Leading to Interconnected Pores Within the Casting.**

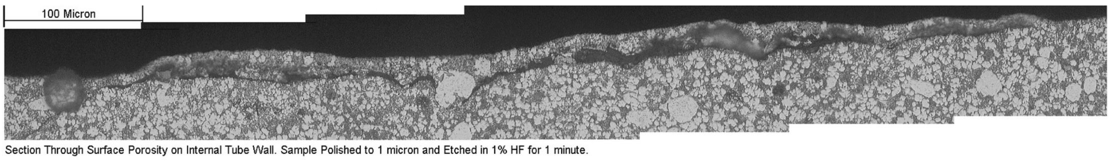



**Figure 3.14 Section Through Surface Porosity on Internal Face of Tube that Appears to be Isolated from Porosity Within the Casting.**

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.

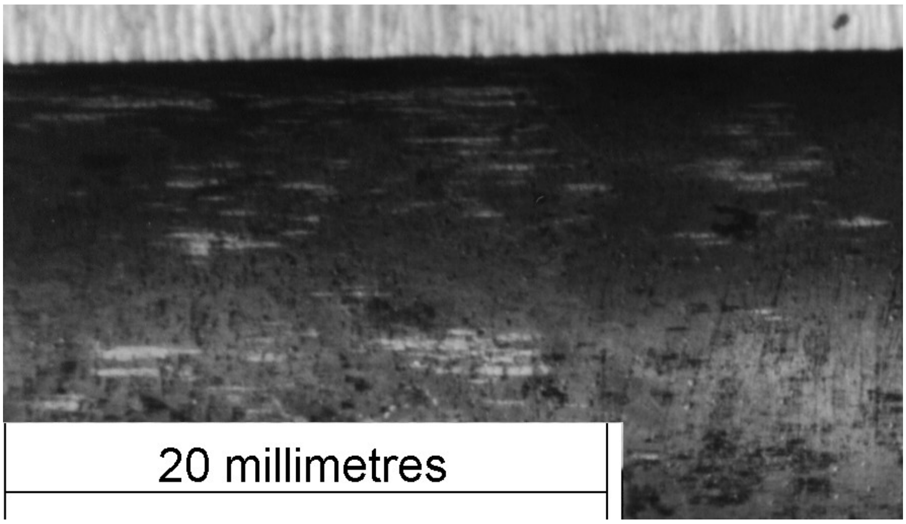



**Figure 3.15 Drag Marks on Internal Wall of Tube.**

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.

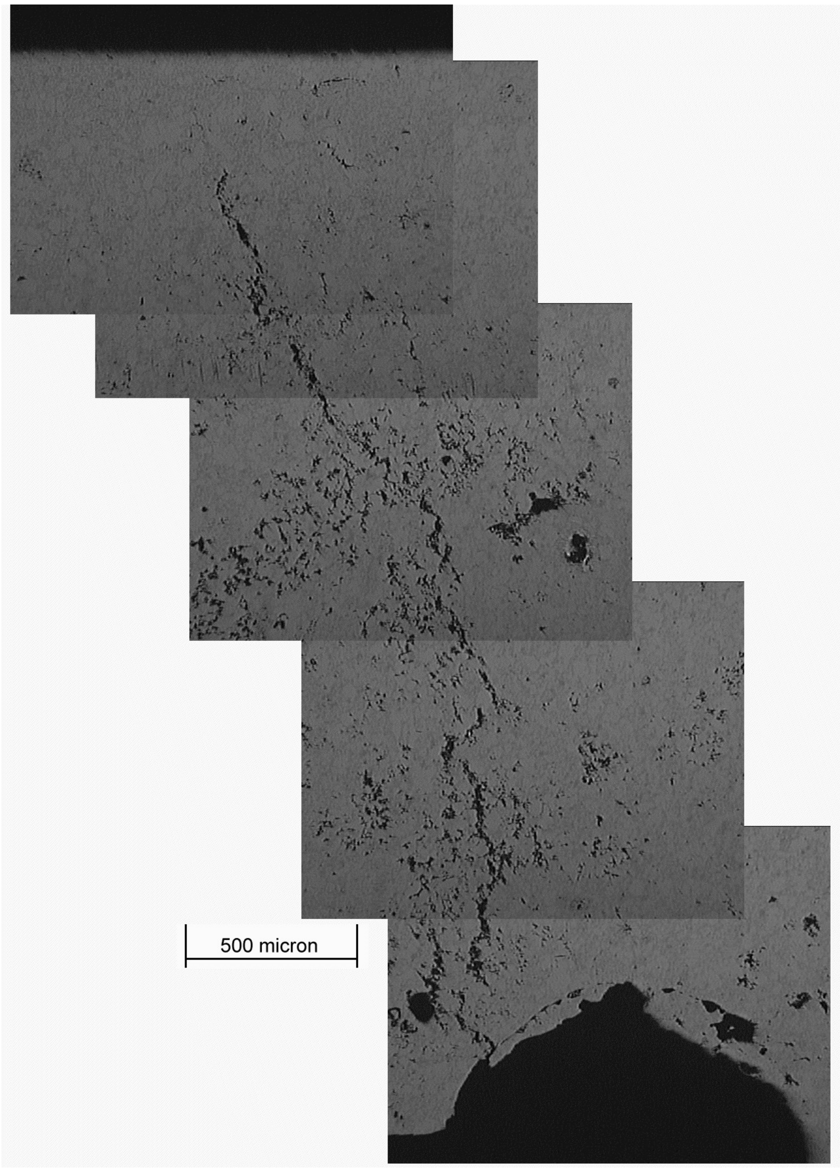



**Figure 3.16 Small Crack Running Through Casting Near Base of Lug.**

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.

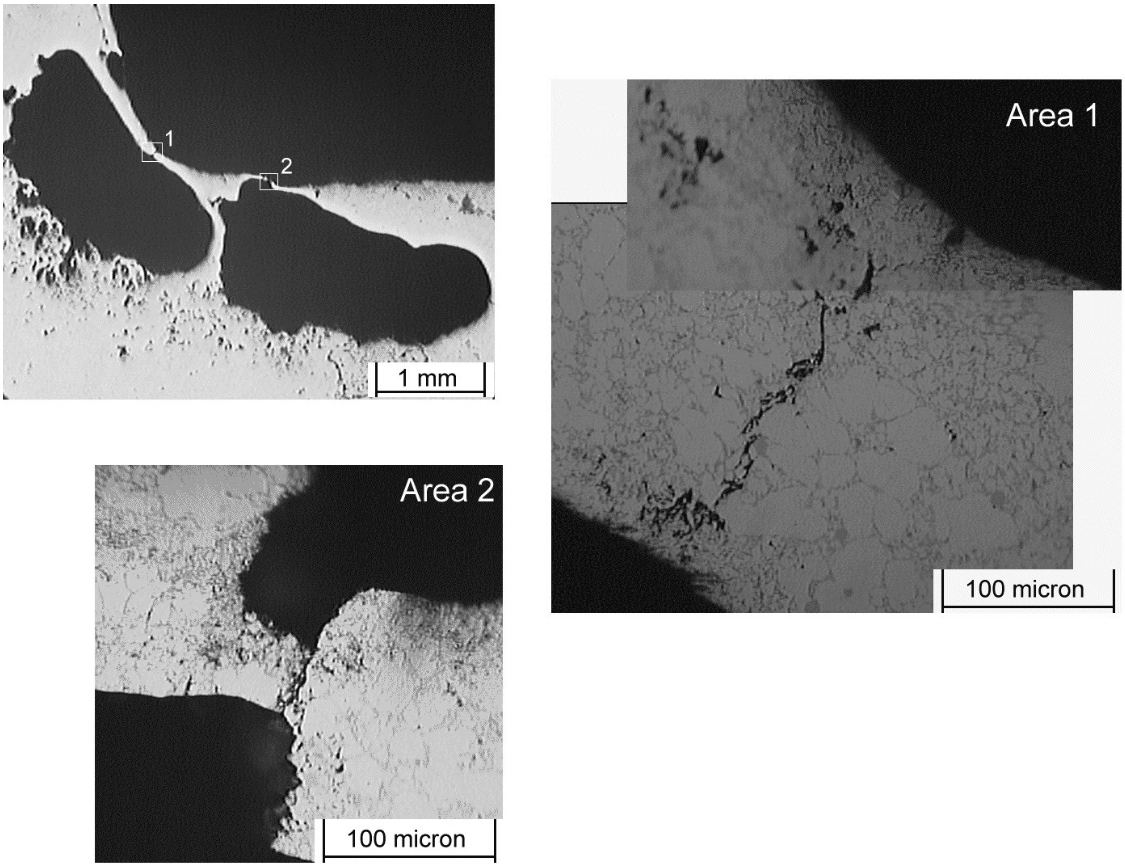



**Figure 3.17 Cracks Associated With Large Gas Pores Near Base of Lug.**

### *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 $\chi^2$ 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.