Detection of Cast Residue on High Pressure Die Casting Die Surface

by

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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 or college of advanced education, and to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made.

Matthew Patrzalek
Date: 12/05/2006
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Abstract

This thesis aims to develop a temperature feedback system that could provide the basis for automated detection of anomalies on the die surface (e.g., soldering) or for control systems that could improve product quality. A key factor in the provision of temperature feedback was the application of temperature probes positioned within the casting die. Ideally, one would have liked to have as many probes as possible in order to acquire a meaningful temperature profile. In production environments, this was a difficult situation to achieve due to the die geometry and because of the practicalities of embedding numerous temperature probes into a commercial die.

The development of such a feedback system would have, in fact, represented several research projects because of the die complexity and the production factors involved in the process. This thesis therefore represented the first step in such a process. As a starting point, a simplistic die geometry (i.e., a block) was chosen to initiate the research. This was fitted with a number of temperature probes and the objective became to: investigate the maximum distance that a temperature probe could detect the development of an unwanted adhered layer on a periodically heated metal block that is water-cooled.

From the literature review, there were two analysis methods that were compared in terms of their ability to detect the unwanted adhered layer based upon thermocouple reading(s). These were: specific temperatures and times within a temperature profile of a HPDC (High Pressure Die Casting) cycle; and the theory pertaining to measurement distance from a periodically heated surface. The method that was employed to conduct this research program was based upon the development of an experimental rig in which to simulate an HPDC die. The development of the unwanted adhered layer on the HPDC die could not accurately be controlled in the HPDC process. The experimental rig was designed to allow the location of the unwanted adhered layer (via an artificial layer on the die surface) to be varied relative to the thermocouple position(s) which were at fixed locations of 3 mm from the periodic heat source. Thus, some of the
variables associated with the artificial layer could then be varied (i.e., width, thickness and time of occurrence).

The results obtained from the experiments showed that the theory pertaining to measurement distance from a periodically heated surface and not the specific temperatures and times within a temperature profile of a cycle was the most stable data representation for all the experimental variables. This data representation was compared statistically against the theoretical equations and noise function to determine the maximum practical distance that a thermocouple could be away from the artificial layer for the two different cycle times (40 and 80 seconds). The maximum practical distance from the artificial layer where a thermocouple could detect the presence of an artificial layer and for this experimental set-up were approximately 0.017 and 0.026 meters for a 40 and 80 second cycle time respectively.
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<tr>
<td>κ</td>
<td>Thermal diffusivity</td>
<td>m² s⁻¹</td>
</tr>
<tr>
<td>T</td>
<td>Temperature</td>
<td>°C</td>
</tr>
<tr>
<td>t</td>
<td>Time</td>
<td>s</td>
</tr>
<tr>
<td>k</td>
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<tr>
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<tr>
<td>A</td>
<td>Temperature Amplitude</td>
<td>°C</td>
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<tr>
<td>i</td>
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Chapter 1

Introduction
1.1 Overview

This thesis documents a Doctoral research program which was undertaken at the Industrial Research Institute Swinburne (IRIS) at the Swinburne University of Technology in Victoria, Australia, between the years of 2000 and 2005. The research was funded by the Cooperative Research Centre for Cast Metals Manufacturing (CRC CAST).

The broad objective of this research program was to enhance the high pressure die casting (HPDC) process by improving the automated control regime. Specifically, the emphasis was in examining the issue of temperature feedback, as it pertained to dies, and the possible mechanisms for improving the quality of this information. Improved temperature feedback could provide the basis for automated detection of anomalies on the die surface (e.g., soldering) or for control systems to improve product quality or reduce production time. However, neither detecting die soldering or providing better feedback of die temperature were trivial issues and both were compounded by the general complexity of the die shapes involved in commercial HPDC production.

A key factor in the provision of temperature feedback was the application of temperature probes positioned within the casting die. Ideally, one would have liked to have as many probes as possible in order to acquire a meaningful temperature profile. In production environments, this was a difficult situation to achieve due to the die geometry and because of the practicalities of embedding numerous temperature probes into a commercial die. For these reasons, a useful contribution to die casting process would be to be able to provide a temperature feedback profile based upon a minimal number of temperature probes.

The development of such a feedback system would have, in fact, represented several research projects because of the die complexity and the production factors involved in the process. This doctoral research therefore represented the first step in such a process. As a starting point, a simplistic die geometry (i.e., a block) was chosen to initiate the research. This was fitted with a number of temperature probes and the objective became to:
Investigate the maximum distance that a temperature probe could detect the development of an unwanted adhered layer on a periodically heated metal block that is water-cooled.

This would provide the basis for a system that could then be applied to dies of a more complex geometry.

1.2 Background of Die Casting

The High Pressure Die Casting (HPDC) process was a near net-shape manufacturing process employed to manufacture light metal alloy components. The HPDC process was based upon the use of metal dies. Production dies were typically labour intensive and costly to manufacture (Fraser, 2000), due to the complex casting shapes that had to be produced for common production items. For example, the HPDC dies for aluminium automotive components could range in cost from $20,000 to several million dollars (Hairy and Richard, 1997). This cost depended upon the casting alloy and final casting geometry.

The production life for a typical die could range from between 5,000 to 2,000,000 parts (Wang, 1999). The primary base alloys that were used in the HPDC process were aluminium, zinc, magnesium and copper, and the lesser used base alloys were lead, tin and iron (Moore et. al., 2003). The HPDC process produced low scrap, complex geometrical parts that had excellent surface finish (Moore et. al., 2003). A commercial HPDC cycle consisted of 5 stages, seen in Figure 1.1, which were:

(i) Pouring

(ii) High velocity filling

(iii) High pressure and solidification

(iv) Casting ejection

(v) Die cooling and lubrication.
Ideally, the entire casting alloy that was delivered in the shot stage was removed during the ejection stage. However, within a practical production process, some localised casting alloy could adhere to the die cavity surface. This adhesion of the casting alloy to the die cavity surface had been observed for more than half a century (Doehler, 1951) and had been estimated to cost some $25,000 over 100,000 shots (Chellapilla et. al., 1997). This costing was based upon their estimation of the total costs of lost production (every 4 hours a machine was stopped for cleaning and the average cleaning time was 30 minutes) and the replacement of parts (approximately every 15,000 shots). A solution to this casting alloy adhesion, used for over 50 years (Doehler, 1951), was the use of lubrication (as seen in Figure 1.1 in stage 5 of the HPDC cycle). However, as noted by Graff (1997), the lubricant could also adhere to the die cavity surface just like the casting alloy, and this could build up to produce casting defects (i.e., porosity or surface finish).

Figure 1.1- Typical commercial High Pressure Die Casting (HPDC) cycle for a cold chamber HPDC machine - abstracted from Fraser (2000, p.4)
The detection of this unwanted adhered layer was still performed manually and if the detection method could be automated then this information could subsequently be integrated into a control system that could reduce the impact of this unwanted layer in a casting cycle through its early removal (Graff, 1997). At the very least it would provide an automated warning signal advising operators of the need to clean up or maintain the die surface.

There were various theories as to why the casting alloy or lubricant adhered to the die cavity surface, but many researchers believed that temperature of the die cavity surface was a factor in the adhesion process. Some researchers suggested that the casting alloy adhered to the die surface at hot spots on the surface (Shankar and Apelian, 2002; Lakare et. al., 1999; Chen and Jahedi, 1998a; Chen and Jahedi, 1998b; Tsuchiya et. al., 1997). Unfortunately, these publications did not include a detailed explanation of what was actually meant in terms of the unwanted adhered layer. Some of the HPDC cycle temperatures that were noted in the literature included:

- Maximum periodic temperature of die cavity surface (Shankar and Apelian, 2002).
- Temperature of die cavity surface and/or casting just prior to ejection (Norville et. al., 2003).
- Temperature of the molten casting alloy within the holding furnace (Shankar and Apelian, 2002).

In theory, the use of an infrared camera that measured the die cavity surface in 2D would have been an ideal means of determining temperature because it could provide a non-contact measure of multiple locations at once. However, in practice, such measurements could only occur when the dies were separated from one another (i.e., Stages 4 and 5 of the HPDC cycle).

Venkatasamy et. al., (1997), on the other hand, noted that temperature probes in the die were the only way to see the entire temperature cycle through the entire HPDC cycle. These different temperatures at specific times can be seen in the temperature profile (temperature versus time plot for one HPDC cycle) in Figure 1.2.
The problem with employing temperature probes in the die was that they only provided information for localised temperatures and did not necessarily represent the true die temperature (Doehler, 1951). The location of thermocouple position was therefore important for an accurate estimation of HPDC die temperature. However, in practical HPDC applications, the locations of thermocouples were often selected for 'convenience rather than for utility' (Doehler, 1951, p.148). There was also a reluctance to put thermocouples into HPDC dies because of their intrinsically complex and expensive nature (Niu et. al., 2003).

The use of embedded temperature probes could, however, provide some useful information. For example, once the distance from a temperature probe to the HPDC die cavity surface increased, then the following temperature parameters could be observed, because the HPDC die cavity surface was periodically heated (Carslaw and Jaeger, 1959):
- The amplitude of the temperature oscillation diminished with increased distance from the steady periodically heated surface.

- A progressive lag in the phase of the temperature oscillations occurred with an increase in distance from the steady periodically heated surface.

Some of the phenomena of these temperature parameters can be seen in Figure 1.3 and had the potential to be used to detect an unwanted build-up layer on the die surface.

![Diagram](image)

**Figure 1.3 - Temperature oscillations at various depths due to a periodic square temperature wave on the surface (abstracted from Carslaw and Jaeger, 1959, p.69)**

### 1.3 Statement of Research Problem

It has already been noted that the specific goal of this research program was to investigate the possibility of determining the maximum distance that a temperature probe could be located from an unwanted build-up layer on the die surface but still be able to detect it through changes in steady die temperature readings. The determination of the localised unwanted adhered layer(s) would be via changes in steady periodical die
temperature readings near the die surface. When this research commenced, the prevailing technique was for an operator to manually inspect the die and/or the castings for signs of adhesion build up on the die surface (normally as a result of the casting alloy adhering to the die surface). If successful, this research had the potential to provide an automated form of feedback that could trigger some sort of corrective action.

The determination of the maximum distance from this unwanted adhered layer on a die surface would be via two methods:

(i) The specific time and temperature

(ii) Theory from a periodically heated solid (as noted in Section 1.2).

The specific time and temperature method would be applied according to recommendations emanating from previous investigators who had researched the HPDC process and, more specifically, the prevention of the unwanted adhered layer.

In order to undertake such an investigation, from an experimental perspective, a simple block-shaped die was used and a controlled, prolonged, artificial layer (at specific locations along the die face) was applied to simulate the unwanted adhered layer. This would enable the unwanted adhesion factors to be analysed in terms of the die geometry and the temperature probe position. Temperature probes would be placed at specific distances from artificial layer so the maximum distance could be determined. The artificial layer used in the experimentation in this research could be removed from the die surface to facilitate a range of testing regimes.

In the context of this research, it was necessary to confine the study to a simple die geometry in order to provide a tractable starting point and to facilitate an in-depth analysis of the problem at hand. The in-depth analysis that was undertaken was in terms of:

- The cooling channel and bulk thermal mass (with respect to the thermocouple positions)
- The artificial layer parameters simulating the unwanted adhered layer.
In understanding the scale of the problem, it was first necessary to acquire some knowledge of the commercial production parameters associated with the casting process. To this end, the commercial partner companies involved in this research were able to provide data which, in their view, was representative of that which was applicable (internationally) in an industrial context. Figure 1.4 shows a typical automotive production component produced through the HPDC process by one of the industrial collaborators (Nissan Australia and Ford Motor Company of Australia).

The geometric complexity of such components, which were relatively commonplace in modern manufacturing environments, underscored the need to view this research, and its focus on a simplistic die geometry, as a starting point for a much larger stream of research, rather than as an end in its own right.

![Figure 1.4 - A typical automotive component produced through High Pressure Die Casting. a). Components from Nissan Australia b). Ford Motor Company of Australia](image)

*Figure 1.4 – A typical automotive component produced through High Pressure Die Casting. a). Components from Nissan Australia b). Ford Motor Company of Australia*
1.4 Overview of Proposed Methodology

The starting point for this research investigation was to obtain experimental evidence of an unwanted adhered layer on an HPDC die surface from temperature readings. The HPDC process had many interrelated variables, so controlled experiments on an experimental rig that simulated the heat transfer of the HPDC die cavity surface were conducted. The experimental arrangement is shown schematically in Figure 1.5. The simple-geometry die and artificially-introduced unwanted layer are shown in Figure 1.6. These arrangements enabled the fundamental problem of the heat transfer process to be investigated and the unwanted adhered layer to be controlled.

It was self-evident, due to the time and technical limitations, that not all the parameters of the unwanted layer detection could be considered, so this investigation focused upon some of the more critical ones, specifically:

- Geometric size of the artificial layer (i.e., width)
- Location of the artificial layer, particularly focusing on the influence of the cooling channel
- Source strength of the artificial layer (i.e., thickness)
- Cycle time (i.e., different cycle times)
- Consistent and repeatable cycle times (i.e., little or no variations in cycle time from the start of the process).

This testing regime was achieved by changing the particular parameter that was associated with the artificial layer or the external parameter (i.e., cycle time). Parameter trials were repeated to determine the reproducibility of the results but, between the trials, a common atmospheric temperature was maintained.
Chapter 1 – Introduction

Figure 1.5 – Experimental rig used as the basis of experimental testing

Figure 1.6 – Die Geometry, Unwanted Layer and Measurement Parameters
In order for the unwanted layer to be detected, the initial steady temperature patterns and/or profiles had to be established. Thus, real-time temperature readings were required to determine the steady periodic temperature readings within the die. The initial steady temperature profiles were determined through individual temperature measuring devices that were strategically positioned according to recommendations emanating from earlier investigations. The individual temperature measurements were derived from transducers that provided raw voltage signals which were, in turn, entered into a data acquisition software package. The software package provided a profile of temperature over time, within the casting die. Once the steady periodic temperature profiles were determined, then a controllable and reproduceable artificial layer on the die surface could be introduced and varied to investigate the influence that such a layer had on the temperature profiles.

Once the investigation of parameters was complete, their influence on the temperature pattern had to be investigated. This was primarily through comparisons between the normal steady periodic die temperatures and those that arose when the unwanted layer was introduced (refer to Figure 1.7). These comparisons were made in the individual simulated HPDC cycle for the two different temperature regions (refer to Figure 1.2). Once the two different HPDC cycles were obtained (i.e., one without the unwanted layer and one with the layer in place), then the two analysis methods (i.e., specific times and temperatures, and theory of periodically heated solids) were employed for the unwanted adhered layer.
Figure 1.7 - General temperature versus time trend highlighting the different stages of the experiment

The two analysis methods were evaluated against the unwanted layer parameters. This comparison would be made from one thermocouple position (i.e., comparison from a single measurement device) at a time. Then a cross comparison, between the thermocouple positions and the controlled parameters of the unwanted layer, was undertaken. However, this was in terms of the distance that the thermocouple positions were from the unwanted layer. One of the unwanted layer parameters was width and so a standard measurement of the horizontal distance between the centre of the artificial layer and the thermocouple position was employed.

The criteria that was employed to determine the superior method was from the perspective of:

- The maximum distance
- Greatest reliability

that a method could achieve in terms of detecting the unwanted layer, in terms of all the artificial layer parameters and the die geometry.

Chapter 1 – Introduction
1.5 Perceived Specific Contributions of the Research

At the conclusion of this research program it was perceived that a number of contributions of knowledge had been made to the field of HPDC. Specifically these were identified as follows:

(i) An extensive review of research in the field had been completed which highlighted the process variables, and their interaction with one another in the pressure die casting process. Once the process variables were identified then the body of research in the area of process improvement was investigated so that directions for this research could be determined.

(ii) The determination and evaluation of the some of the parameters that were associated with unwanted layer build up on HPDC die surfaces.

(iii) The development of a methodology that could compare different detection methods of the unwanted layer phenomenon.

(iv) Examination of the maximum detection range for the unwanted layer on the surface based on positions of thermocouples.

Further research would therefore be to strengthen the arguments presented here in terms of dies having the complex geometries associated with commercial components produced by HPDC. Notwithstanding this limitation, the contributions and method, presented here, were subjected to international peer review through publication in the Transactions of 22nd International Die Casting Congress (2003). For further publications refer to Appendix A.
1.6 Thesis Structure

The objective of the thesis structure was to systematically explain the concepts and processes associated with achieving the research objectives but also to defend the methods that were adopted. Therefore, the remainder of the thesis is structured as follows:

- **Chapter 2: Background to the High Pressure Die Casting process**

  This chapter provides an overview of the research and development that had been undertaken prior to the commencement of this project. The presented summary will cover a brief history of the High Pressure Die Casting (HPDC) which will be followed by the fundamentals of the process and the factors that influenced it.

- **Chapter 3: Literature Review**

  This chapter summarises the literature review that was undertaken to identify key researchers and the forums where the work was published. It also acknowledges the limitations of the review process. The presented summary of the review is intended to be an impartial one where alternative approaches and ideas are presented. It was this summary that led on to the research directions adopted in this research. Hence, the review attempts to demonstrate a natural progression of knowledge from other learned researchers through to this research.

- **Chapter 4: Background Theory**

  This chapter summarises two theories present in the Literature Review Chapter to detect the unwanted adhered layer which were the Inverse Heat Conduction Problem (IHCP) and the temperature observations from a periodically heated solid surface.
• Chapter 5: Methodology

This chapter follows on from the literature review, and outlines the ideas and concepts that were put forward to achieve the desired objectives. Reasons are presented, with regard to the proposed concepts; the chosen path, and possible alternative concepts. The chapter also documents reasons why alternative ideas and concepts were excluded from consideration. The chapter outlines the experimental design and flags its potential deficiencies or limitations.

• Chapter 6: Experimental Results

This chapter systematically presents and summarises the experimental and research data, in a straightforward and coherent. The presented and summarised data is justified through explanatory notes.

• Chapter 7: Analysis of Experimental Results

This chapter evaluates the experimental data statistically. The experimental data from the Experimental Results Chapter is statistically compared with the theory that was presented in the Background Theory Chapter.

• Chapter 8: Discussion

This chapter discusses the experimental results at a higher level. This includes how the experimental results compared with other researchers and published work, with respect to their significance to the field of study and to industry.

• Chapter 9: Conclusion

This chapter summarises, in a cogent manner, the findings of the research. This includes how the findings of the research were related to the stated objectives in this introductory chapter. This final chapter also highlights the limitations of the research, as they were assessed, and how these limitations could be pursued through further investigation.
Chapter 2

Background to the High Pressure Die Casting Process
2.1 Overview

In order to place this research work into context, it is important to understand the enormous scale of the research and development that had been undertaken prior to the commencement of this research program. This section endeavours to provide an overview of that work. This section will cover a brief history of the High Pressure Die Casting (HPDC) which will be followed by the fundamentals of the process and the factors that influenced it.

2.2 History of the HPDC Process

Table 2-1 was generated from information obtained from Doehler (1951) and Street (1986), which were two (oft cited) fundamental texts on the subject of HPDC. For general definitions of the different casting process refer to Appendix B. Table 2-1 summarises the progression made in the pressure die casting process from the first patented machine (circa 1850) to the diagnoses of the process (circa 1960). Table 2-2 summarises the progression of the pressure die casting process from the 1950s onwards but mainly concentrates on the progression of lubricants. However, this still highlights the progression made in pressure die casting in relation to its primary parameters.

Table 2-1 – Summary of the progression of the pressure die casting process

<table>
<thead>
<tr>
<th></th>
<th>Commercial Pressure Die Casting Machine</th>
<th>Commercial Cold Chamber Pressure Die Casting Machine</th>
<th>Development of Cold Chamber Machines Horizontal &amp; Vertical</th>
<th>Automation of Ladle in Cold Chamber Machine</th>
<th>Diagnoses of Pressure Die Casting Machinery</th>
</tr>
</thead>
<tbody>
<tr>
<td>1850</td>
<td>1900</td>
<td>1920</td>
<td>1930</td>
<td>1950</td>
<td>1960</td>
</tr>
</tbody>
</table>

Chapter 2 – Background to the High Pressure Die Casting process
Table 2-2 – Highlights the progression of the pressure die casting process (abstracted from Graff, 1997, 97/13).

<table>
<thead>
<tr>
<th>Pre-1950s#</th>
<th>Die Temperature Control</th>
<th>Shot-end Control</th>
<th>Spray Equipment</th>
<th>Die Lubricant Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal water cooling channels and predetermined number of cycles to control die temperature. Die temperature range and the use of 'close die temperature control' (Doehler, 1951, p.143)</td>
<td>Switches, controls and hydraulicscope equipment (Refer to Doehler, 1951, p.157 for the schematic diagram for the set up)</td>
<td>Dip and blow Shift to air atomization</td>
<td>'many particular types of die lubricants that are used with each of the die-casting alloys' (Doehler, 1951, p.163)</td>
<td></td>
</tr>
</tbody>
</table>

1960s

| Internal water | Valve settings | Dip and blow Shift to air atomization | Oil, graphite Beginning of water-base products First "synthetic" First use of waxes, silicones |

1970s

| Beginning of closed loop (feedback) controls Beginning of recognition of value of better control Increasing use of external water or die spray for cooling | Beginning of closed loop (feedback) controls Beginning of use of motion and pressure sensors to analyse performance | Beginning of use of robots and fixed head sprays to replace operator skill Trials of airless, electrostatic spray | Beginning of decline in use of graphite First solution (clear) lubricant Better mixture of balanced ingredients Use of inorganic anti-solder additives Increasing dilution length Exploration of permanent coatings |

1980s

| Improvement in controls via better sensors, micro-processors Use of heat exchange fluid in place of water | Improvement in controls Better knowledge of shot sleeve dynamics | Gradual speed of automation | Optimization of composition Imposition of wastewater and worker safety laws Development of better microemulsions Beginning of research on wetting, deposition |

1990s

| Better die design via thermal modelling | Further improvements in shot sleeve design and control systems | Dominance of automation Application equipment for carrier-free lubricants | Continued optimization Continued research on wetting, deposition Semi-permanent coatings Carrier-free lubricants Research on insulation properties |

# Information contained in Doehler (1951)
2.3 HPDC Process

2.3.1 Overview

At the most basic level, the purpose of the casting technique was to produce a specific shape from an alloy, through the placement of liquid metal into a die cavity, and by allowing the metal to cool to a solid state. The general casting process had components and processes that were interdependent and this interdependence is examined herein. In this section, the machinery used in the HPDC process was first evaluated, in relation to the HPDC process. An evaluation of the dies used in the HPDC process then followed. Subsequently, the factors that affected the final casting were examined, in regard to the fluid and thermal dynamics. These investigations are documented in Sections 2.3.2 – 2.3.6 respectively. Finally, the metallurgical considerations are reviewed.

2.3.2 Machinery

The HPDC process was different to other die casting techniques in that high pressures were applied to a molten metal so that the flow into the die cavity was rapid and uniform. Refer to Figure 1.1 for the complete HPDC cycle. There were eventually two types of machines employed in practice to feed cast metal into a die under pressure:

a) Hot chamber machine (shown in Figure 2.1). The hot chamber machine had a furnace to melt and hold the metal. A plunger sucked the molten metal into the cylinder until it filled up then it forced the metal into the die (Jain, 1979). The excess metal returned for the next shot, therefore waste was reduced.
b) Cold chamber machine (shown in Figure 2.2). The cold chamber machine imported molten metal from a furnace via a ladle. The machine was used for high melting point metals such as aluminium. Aluminium could not be used in hot chamber machines because it reacted with the iron in the casting machine (DeGarmo et. al., 1988). Excess cast metal was fed into a shot chamber (i.e., shot sleeve in Figure 2.2) then a plunger (plunger rod in Figure 2.2 controlled with the hydraulic cylinder) forced the metal into the die. The plunger then paused for solidification and ejection of the metal to occur so it could force out the excess metal ("biscuit") from the cold chamber (Jain, 1979). Aluminium could be cast in the cold chamber process because it had little time to react with the iron in the shot chamber (Jain, 1979).
2.3.3 Die and Die Cavity

One of the functions of the machinery used in the HPDC process transported molten metal from a furnace into a die. The die was composed of many features that enabled the casting to be produced to a specific quality. The required quality depended on a casting's function in relation to the overall manufacturing of a complete part or assembly. Each feature of a die contributed, in a specific manner, to the outcome of a casting.

A die was usually divided into two halves, referred to as the "cope" and "drag", along the parting line or surface (DeGarmo et al., 1988). Other commonly applied terms for the die halves, in the HPDC process were "ejector" (movable half) and "cover" (stationary or fixed half). Refer to Figure 2.1 and Figure 2.2. The main components of the die, in a general casting process, are shown in Figure 2.3.
These components, together with other features of the die, enabled a cast metal to be fed into a die cavity; facilitated the removal of gases; and provided a mechanism for the clamping, and ejection of the casting (Jain, 1979).

The pouring cup, sprue, runner, and gates were all parts of the gating system (Jain, 1979) which had many functions in the control and delivery of the molten metal flowing into the die cavity (refer to Figure 2.3). In a typical industrial HPDC process, pouring cups were not employed because a plunger forced molten metal directly into a sprue. The main objectives of the gating system are summarised from Jain (1979), where they were described as being to:

(i) Minimise the turbulence and gas absorption of the molten metal to the die cavity

(ii) Ensure that the cast metal completely fills the die cavity in the shortest possible time frame

(iii) Reduce the addition of impurities into the molten metal
(iv) Contribute minimal waste material to the overall casting and the waste must be able to be removed with the casting.

(v) Limit the soldering and erosion of the die walls (Further discussed in Section 3.2).

The gating system was one of many contributing factors in the quality of the casting and was an important feature of the die.

As a metal cooled down, it resulted in contraction and increased density – thus, a volume change occurred, which had to be compensated by the addition of more metal (Moore H. and Kibbey D., 1982). In a typical HPDC process, the plunger forced the excess metal from the gating system into the casting (DeGarmo et. al., 1988). Refer to Figure 2.2. Therefore, the gating system was theoretically the last region to solidify.

A draft was defined by Doehler (1951) as a tapered section in the die cavity to aid in the removal of the casting. The dimensions of the draft were dependent on the thermal contraction of the metal used for the casting and the effects of shrinkage on a casting's geometry (Further discussed in Section 3.2)

Cores were used to produce a range of cavity types in the casting and they came in different forms, fixed or movable, permanent or single use. Their construction depended on the desired purpose of the core: that is, to reduce weight, minimise further manufacturing processes, or to aid in the casting process, in relation to the finished casting (Further discussed in Section 3.2).

In the HPDC process, the die could be defined as a permanent mould, which meant that the die would be used more than once. A permanent die used in the HPDC process was made of metal, usually cast iron or steel, and they were mostly used for low melting point alloys, because the alloy could affect the die life, and the casting designs were sometimes complex (Moore H. and Kibbey D., 1982).

The main components of the die in the general casting process were often discussed in literature in regard to their purpose and interaction. The desired sequences, within the die, of the cast metal were to enter into all regions with in the die cavity, and
then to solidify in the desired shape (DeGarmo et al., 1988). If the cast metal did not perform these sequences properly then defects would occur.

2.3.4 Fluid

The HPDC process involved a plunger to force the molten metal into the die and its components; this resulted in a quicker cast metal flow rate than most other casting processes. DeGarmo et al. (1988) and Campbell (1993) both agreed that turbulence (especially common in the HPDC process) was a cause of trapped air in the casting, which resulted in problems, such as: blow holes\(^1\), porosity\(^2\), or misruns\(^3\). As a result of such problems, the final casting’s potential usage and treatment was reduced, because the voids developed in the casting and reduced the strength in particular areas. Moreover, certain post-casting processing, including chemical and mechanical removal, could expose the voids to the surface finish (Campbell, 1993). If an incomplete fill of the die cavity, within the solidification process was to occur, this could lead to cold shuts\(^4\), soldering\(^5\) and die wear.

The common factors in the casting process that involved fluid dynamics were the fill time and flow velocity of the cast metal into the die cavity, but the end design had to be removable with the rest of the casting (Campbell, 1993). The plunger cycle was the first to affect the fluid flow patterns in the HPDC process. The initial fluid flow was influenced by the plunger velocity, mechanical properties of the cast metal (and quality), together with the geometry of the shot sleeve. The original fluid flow was assumed to be in the form of a wave. Thome and Brevick (1995) investigated the initial wave formation as a plunger accelerated from rest to a critical slow shot velocity. Thome and Brevick (1995) developed a theoretical model of the plunger’s initial acceleration to the critical slow shot velocity, and the way this could be controlled to

\(^{1}\) Blow holes as defined by North American Die Casting Association (Anonymous, 1998, p.10): Voids or holes in a casting that may occur due to entrapped air or shrinkage during solidification of heavy sections.

\(^{2}\) Porosity as defined by NADCA (Anonymous, 1998, p.72): Voids or pores, commonly resulting from solidification shrinkage, air trapped in a casting or hydrogen exuded during electroplating.

\(^{3}\) Misruns as defined by Anonymous (1978-1989, Vol. 15 p.8): Denotes an irregularity of the casting surface caused by incomplete filling of the mold ...

\(^{4}\) Cold Shuts as defined by Anonymous (1998, p.19): A lapping of solidified metal that sometimes occurs in the formation of die castings, which constitutes an imperfection on or near the surface of the casting.

\(^{5}\) Soldering will be defined in Chapter 3
reduce trapped air in the molten metal. Their work concluded that trapped air and turbulent flow could be reduced if the plunger acceleration was controlled.

Tian et. al., (2002) noted that 'porosity in high pressure die castings is usually classified as gas porosity, shrinkage porosity and flow porosity'. Shrinkage and entrapment of air gases could also lead to the formation of porosity. Talbot's (1988) analysis related the porosity within the metal to the solubility of a gas (hydrogen) in liquid to solid states, and the addition of another metal element. Talbot's (1988) investigation was on a macro scale, where the total amount of gas in the metal was compared to the overall mass of the metal. Fang et. al., (1988) investigated the affects of porosity, with regard to solubility on a micro scale. Both Talbot (1988) and Fang et. al., (1988) found that the differences in solubility between liquid and solid states and the inclusion of different metals influenced porosity. (Fang et. al., 1988) also found a relationship between cooling rates, pore size and volume.

Klein and Wimmer (1995) investigated the causes of porosity in the zinc HPDCs, with respect to gas pores and shrinkage of the casting, and the factors that contributed to their formation. Klein and Wimmer (1995, p.101), stated that the “volume and location of gas pores in a cast part depend on the filling conditions.” These conditions of fill were influenced by the geometry, the relative position of the gate to the die cavity, and the ability to direct gas pores to non essential parts of the casting. While temperature and die casting geometry influenced the contribution of shrinkage to porosity, these factors were shown to be true through experiments.

Siauw et. al., (1997) investigated the fill pattern, and its importance in the final casting quality, but more specifically on the design of the runner and gate systems. They showed, through practical examples, that the quality of the casting was not just dependent on the cavity fill time and gate system but also on the cavity fill pattern.

Hu et. al., (2000) used the squeeze casting process, but used both the squeeze and HPDC gate design systems to show the importance of the fill pattern. Computer numerical simulation was undertaken, which was facilitated experimentally with an X-ray analysis to verify the soundness of the casting in a non-destructive manner. They found that laminar flow could be achieved through the use of numerical analysis, and an optimisation process, which led to a reduction in the formation of pores in the final
casting. They also found that high melt flow rates led to turbulent flow patterns and resulted in porosity defects in the final casting.

In the HPDC process, the fluid flow could not be simulated by common simplification techniques, like laminar and viscosity dominated flow, but required the complete Navier Stokes equations, including the momentum terms (Venkatesan and Shivpuri, 1995).

Venkatesan and Shivpuri (1995); and Schmid and Klein (1995) had investigated and compared numerical simulation software packages using the HPDC process with a water analogy. Both Venkatesan and Shivpuri (1995); and Schmid and Klein (1995) found that under certain conditions or simplifications used in their mathematical models that numerical simulation had agreement with the water analogy. Schuhmann et. al., (2000), further highlighted these conclusions, through a comparison of the water analogy technique, and numerical simulation with real-time X-rays but used the gravity die casting process. They found that the water analogy agreed with the molten aluminium flow under certain conditions but one needed to be careful with the interpretation of their results because of the differences between water and molten metal.

A number of the simulation packages were based on the “volume-of-fluid (VOF) methods and require stationary grids which limits their ability to handle highly dynamic flows,” (Thorpe et. al., 1999, p.23). Thorpe et. al., (1999, p.23) had developed a simulation package but with a Lagrangian method, which “means that any degree of surface irregularity can be handled easily, and highly dynamic flows are well represented”. They incorporated the heat transfer and solidification into their model and compared the numerical results with water analogies. Their different numerical models had an agreement with the water analogues. They also highlighted the “importance of proper boundary conditions for the mould” (Thorpe et. al., 1999, p.32) in the numerical model.
2.3.5 Heat Transfer

Fluid flow in general could be divided into two categories: laminar (the appearance of fluid elements that slid over one another) and turbulent (the appearance of fluid elements that had chaotic motion) flow. Both of these flows were affected by temperature, (Street et al., 1996). Another factor that temperature influenced was heat and in a typical casting process the cast metal’s temperature was higher than its surroundings thus the heat energy would be transferred from the cast metal to its surroundings. As per basic thermodynamic theory, there were several distinct modes of heat transfer, namely:

- Conduction, transfer of heat through a medium (solid or fluid)
- Convection, transfer of heat between a surface and a moving fluid
- Radiation, the emission of energy between two surfaces.

These occurred when a temperature difference was present in a medium or between media (Incropera and DeWitt, 1996).

Conduction could be described as the energy transfer from a higher to a lower energy particle as a result of interactions within their medium (Incropera and DeWitt, 1996). This could result in a temperature gradient from the higher to lower temperature and therefore a resulting net transfer of energy in the same direction (Incropera and DeWitt, 1996). The net transfer of energy was “random molecular motion as a diffusion of energy” (Incropera and DeWitt, 1996, p.3). Conduction only described and quantified the heat transfer within a medium (solid or fluid) whereas convection described and quantified the heat transfer between a solid and fluid.

In basic thermodynamics, convection was composed of two mechanisms: energy transfer by random molecular motion (the same as in conduction) and bulk or macroscopic motion of the fluid (Incropera and DeWitt, 1996). Convection heat transfer referred to the interaction between a boundary layer, solid, and a fluid in motion, when a temperature difference was present.

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*Fluid substance is defined as a liquid or gas.*
Radiation did not require a medium for heat transfer because “radiation transfer occurs most efficiently in a vacuum” (Incropera and DeWitt, 1996, p.9). Thermal radiation was electromagnetic radiation that emitted from a body as a result of its temperature (Holman, 1972). If radiation energy hit a surface then part of the radiation energy would be reflected, absorbed and transmitted (Holman, 1972). The degrees to which these three phenomena occurred depended on the surface shape, and texture; material properties, and the source factors.

All three modes of heat transfer were present in the casting process as can be seen in Figure 2.4. Conduction occurred within the solidifying metal and the die; convection between the solidifying metal and the die; and radiation throughout the process (Poirier and Poirier, 1992). The heat transfer depended upon a number of factors relating to the cast metal, die and external environment of the die.

Figure 2.4– Varies heat transfer methods in the high pressure die casting process taken from Anonymous (1978-1989, p.293) a) die open and b) die closed with casting.
Variations in the cross sections of the die influenced the heat transfer and solidification process which could result in thermal stresses (a consequence of different temperatures at various locations throughout the die). Refer to the location in Figure 2.4 where it highlights the no conduction, small heat flow and high conduction. If these variations were too high then the die quality or life could be affected (Anonymous, 1978-1989). The die quality and life, and casting quality, were some reasons why die temperature and heat transfer control were important but they were still amongst the least controlled variables in the HPDC process (Street, 1986).

One of the first considerations of the casting process, with respect to heat transfer, was the removal of superheat and latent heat from the cast metal, which usually occurred in the filling process (Anonymous, 1978-1989). These considerations, together with the heat conductivity and the solidification temperature of the molten metal, were all material properties and were needed when considering the fill time and velocity (Doehler, 1951). Once the casting metal was in the die cavity, the main factor that affected heat transfer was the casting metal and die cavity interface (Anonymous, 1978-1989). Refer to the casting/die interface in Figure 2.4. The interface was an important factor influencing the heat transfer process, but it too was affected by numerous factors, such as die shape and surface finish, die lubrication and the steel oxide state (Anonymous, 1978-1989).

Some of the techniques that were used to control parts of the HPDC process have been shown in Figure 2.4 (refer to the heat flow arrows in the Figure 2.4). The two main heat control mechanisms shown in Figure 2.4, which will be discussed further, were cooling channels (usually drilled holes throughout the die where coolant fluid was circulated) and spray cooling.

The cooling channels' effectiveness in controlling the heat transfer process depended on some of the following factors, which were summarised from Anonymous (1978-1989) and Street (1986):

- *Location and geometry* - a major consideration which was restricted by the complex casting geometry.
• *Coolant flow rate* – a relatively insensitive parameter that could affect the heat transfer rate by ±20% or by 20 – 40°C.

• *Temperature of the coolant* - this depended upon the employed coolant. The typical range that water could affect the die temperature was 20 – 40°C and for oil was up to 100°C.

• *Pressure* was noted but they did not specify what effects that it caused.

• *Scale build-up* (could cause a reduction in flow rate) - this could affect heat transfer by 30% to as much as 200% but usually heat transfer was affected by other factors before scale build-up was noticeable.

The other temperature control method (shown in Figure 2.4) was an external die spray (usually a combination of lubricants and water) that occurred between casting cycles which produced rapid heat transfer when internal methods were insufficient. The main concern with the use of this method in the control of heat transfer was its detrimental affect on die life, so there was generally a trade-off between the cost of die maintenance (including time lost due to down-time) and the potential reduction in cycle time for castings (Anonymous, 1978-1989).

2.3.6 Metallurgy

The mechanical properties of a finished casting were related to the microstructure obtained from the casting process but were also dependent on temperature and time (Callister, 1991). According to Callister (1991) more than one phase could be present in a given solution (together or separately) on a macro (solid, liquid, and gas) or micro (physical arrangement of atoms) scale. Phase diagrams demonstrate the relationship between different states for different alloys and conditions (i.e., temperature, alloy compositions and pressure) (Callister, 1991).

Many phase transformations did not occur instantaneously but over time so the “continuous cooling transformation” diagrams were more suitable because they could graphically represent the relationship between time and temperature, of phases, for specific alloy compositions. For a given cast alloy, the microstructure could have had a
range of different structural features present in the final casting which depended on the solidification parameters such as the kinetics of heat, fluid and mass flow (Bever, 1986).

Some of the microstructural growth patterns, which could occur in a casting process, can be seen in Figure 2.5. These schematic diagrams highlight the different microstructures that could form from a metal alloy because of this solidification process.

![Figure 2.5 - Shows some of the microstructure growth sequences (taken from Bever, 1986, Vol.1 p.537)](image)

The cooling process contributed to the final casting microstructure but so too did impurities in the molten metal. The impurities could change the mechanical properties of the final casting in a positive or negative manner. For example, the presence of gas in the molten metal could lead to gas porosity because the saturation levels of the gas could change with temperature (DeGarmo et al., 1988).

Loong and Heathcock, (1989) reviewed the grain refined techniques in aluminium foundry alloys. Grain refined techniques were associated with cooling rates, addition of alloys, and how variables could affect solidification (i.e., microstructural behaviour as shown in Figure 2.5). The main purpose of grain refinement was to achieve a desired microstructure so that the properties of an alloy could be improved (an example of the possible effect of impurities). Abbott and Parker (1988) investigated the influences in the casting process of the thermal and fluid conditions that were required to achieve a particular microstructure for a particular alloy. Chu et al., (1988) investigated how undercooling conditions affected the microstructure growth and heat flow behaviour on a particular alloy.
The microstructure growth conditions could be controlled in laboratories but not as well in a practical casting process so Ghomashchi, (1993, p.61) investigated the "solidification mechanism and microstructural characteristics of one of the most widely used Al-Si alloys in high pressure die casting, LM24, which contained a large number of impurity elements". He found that different microstructures and growth could be found in different areas of the casting (refer to Figure 2.5).

Solidification mechanism and microstructures were important but so were the formation of casting problems, in relation to microstructural growth. One of the casting problems was soldering (further discussed in Section 3.2) and it arose as a result of the interaction between the cast alloy and die. Another problem was the formation and/or presences of cold flakes\(^7\), in HPDC, which "may cause a reduction in mechanical strength and may also result in pressure-tightness defects" Gershenzon et. al., (1999, p.305). If the presence of cold flakes was near the trimmed area of a casting, then it could cause a fracture in the cold flake region, causing the casting to be rejected or welded. They developed a temperature control system in the shot sleeve that was shown to reduce the occurrence of cold flakes in the casting and gating system.

2.4 Summary

The HPDC process was dependent on many variables and process considerations but the discussion here was limited to HPDC process. The following salient points emerged:

- The main aim of HPDC dies was to provide a receptacle for molten metal in the die cavity and allow it to solidify.

- The molten metal in the HPDC process was forced into the die and had to travel to the die cavity so fluid dynamics was deemed important and thus investigated. The fluid dynamics was shown to be an important consideration in the development of the casting defects such as porosity.

\(^7\) Flakes as described by Gershenzon et. al., (1999): are pre-solidified alloy which originate in the shot sleeve.

Chapter 2 – Background to the High Pressure Die Casting process
• The temperature difference throughout the casting process enabled heat (energy) to be transferred. Heat transfer consisted of three modes, these being convection, conduction, and radiation, which were found to occur in the HPDC process.

• Metallurgy was concerned with the microstructure of a casting metal and how it occurred. The way the microstructure formed and subsequent growth depended on time, heat transfer, and fluid flow.

All these variables had to be considered in the casting process. These research areas highlighted the complex and interdependent nature of the elements in the HPDC process, and how one factor in the process could affect another. Figure 2.6 highlights some of the variables, determined during the course of the literature review, thus far.

### Casting variables

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X - some influence  /- little influence  ?- could influence

**Figure 2.6 - Relationship between casting variables in a high pressure die casting process**
Chapter 3

Literature Review
3.1 Overview

The literature review for this research was conducted throughout the course of the research from the period between 2000 - 2005. The objective of the review was to define the research strategy for this program by obtaining an understanding of the past and current state of knowledge and by identifying key research groups, seminal authors and the forums in which their research was presented and subjected to peer review.

In order to achieve an unbiased review of literature, information was collected from various sources (i.e., texts, journal publications and conference proceedings) so that a range of views could be compared to one another. The literature review process represented a reasonable, but non-exhaustive, collection of data because of the limitations of data that could be obtained. Not all the literature could be read because of the sheer volume of data in the field and the limitations of accessing some of the literature due to industry not publishing their work in the public domain.

The literature review that follows is composed of the history of high pressure die casting (HPDC), followed by background information in relation to the general casting process (including definitions) and then, more specifically, HPDC. A particular research area, relevant to this Doctoral program, was the automatic monitoring and control associated with HPDC, as it pertained to detection/reduction of defects. This was a focus of the review process in terms of establishing research directions.

At the end of this literature review chapter, a summation is provided which brings together the key pieces of work that contributed towards the research directions in this Doctoral research.

3.2 Unwanted Adhered Layer Build Up on HPDC Die Surface

3.2.1 Overview

The HPDC process was quite complex and Balasubramaniam et. al., (1999) listed 36 die casting variables from shot to shot and 23 die casting variables over time. Some of these were incorporated in HPDC machines as noted by Midson and Iten (1997). However, adding sensors to control parameters in the HPDC die dated back to the 1970s
when Harris (1970) and Booth (1970) inserted thermocouples to control the cycle time and the cooling channel flow rates within the die, respectively.

The detection and monitoring of the occurrence and build up of an unwanted adhered layer on the HPDC die surface was one area of the HPDC process where the monitoring and control was manual (Tsuchiya et al., 1997; and Rogers et al., 2003). The manual detection of the unwanted adhered layer build up was via visual inspection of the die casting die and/or the final casting, by an operator (Tsuchiya et al., 1997). This was despite a lot of research into the formation and prevention of the occurrence and build up of this unwanted adhered layer due to the casting alloy. However, Rogers et al., (2003) suggested, that in an ideal world, an operator could detect most defects on-line. This project was aimed at finding ways of automatic detection of the unwanted adhered layer on the HPDC die surface.

This section provides a definition of the unwanted adhered layer build up on the HPDC die surface in order to clarify the different types and description of the adhered layer. This is followed by factors affecting the build up of aluminium casting alloy on the HPDC die surface, which is followed by the factors affecting the build up of non-aluminium HPDC casting alloys on the HPDC die surface. Methods to prevent the adhered HPDC casting alloy build up and the benefits of automatic detection of the adhered built up layer follow. Common techniques for the detection of the unwanted adhered layer are presented. One of these techniques was pursued during the course of this research, so it was necessary to also investigate literature that highlighted its limitations in detecting unwanted build-up layers.

3.2.2 Definition of the unwanted adhered layer build up on HPDC die surface

In HPDC, squeeze casting and semi-solid casting processes, two types of unwanted adhered layers could form and build up on the die surface, leading to defects in the product or die. In a broad context these unwanted adhered layers would consist of either (or both) lubricants and the casting alloys (Graff, 1997). Within a casting cycle, lubricants were employed and, ideally, all of the lubricant and cast alloys would be removed after each casting cycle. Refer to Figure 1.1 for the different stages of the HPDC process. However, the build up of an unwanted adhered casting alloy layer had
been observed as far back as the 1950s (Doehler, 1951) under a few different names. This unwanted layer was a problem in the different casting processes because the unwanted layer could build up and lead to defects within:

i). *The casting* – geometry, porosity, surface finish and leakage problems (Osborne and Brevick, 1997; Persson *et al.*, 2001; Joshi *et al.*, 2001; Graff, 1997; Chu *et al.*, 1997; and Munson and Pacholke-Dumont, 1997)


It could also lead to lost production in order to clean the die surface (Chen *et al.*, 1999a; Gulizia *et al.*, 2001; and Fraser *et al.*, 1997).

The unwanted adhered layer from the casting alloy had been defined by different names and the some of the more common ones were “soldering” (Shankar and Apelian, 2002), “sticking” (Venkatesan and Shivpuri, 1995), and “build up layer” (Hairy and Richard, 1997). The unwanted layer on the die surface sometimes consisted of an intermetallic layer (Tsuchiya *et al.*, 1997) which was found to be harder, more brittle (Chu *et al.*, 1997) and more difficult to remove (Gulizia *et al.*, 2001 and Arai, 1995) than mechanical bonding. The rest of the unwanted layer on the die surface had no chemical interaction and was just mechanically bonded to the surface. Within these definitions there were different meanings and interpretations for different areas of the die (Argo *et al.*, 1997). From the literature, the layer build up from the cast alloy could be defined in three general cases, which are shown in Figure 3.1.
However, there was confusion as to the definition of what was 'soldering' in the literature and all of the general definitions in Figure 3.1 had been defined as 'soldering.' For this research all the definitions in Figure 3.1 could cause defects in the cast product and production had to be stopped to remove them. Therefore, all the unwanted layer types were important and will be defined as unwanted layer build up for this research.

In HPDC, the layer build up by the cast alloy was found to occur for three different alloys which were: aluminium (Hairy and Richard, 1997), magnesium (Mangold, 1997), and zinc (Argo et al., 1997). Argo et al., (1997) stated that the mechanism for this unwanted layer build up was not the same for zinc and aluminium alloys. Therefore, these three different HPDC based alloys are discussed in terms of the unwanted adhesion of the HPDC die surface.

3.2.3 Factors affecting the build up of aluminium casting alloy on the HPDC die surface

The HPDC industry was estimated to be valued at $3.2 billion per annum in the United States of America alone (Salas et al., 2003). Therefore, there had been significant research into the understanding and reasons why aluminium HPDC alloys

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1 The die surface sometimes had coatings or layers on them for example an oxide layer
adhered to die surfaces. One of the reasons for this research into the HPDC base alloy was because of the cost benefits that would accrue if downtime, die failure and reject castings could be reduced. An estimation of the cost was $25,000 over 100,000 parts produced (Chellapilla et al., 1997). The aluminium HPDC alloy was the most commonly used alloy in the HPDC process.

The research in the adhesion of the aluminium HPDC alloy to the die surface could be categorised into six broad areas in the HPDC process. These areas were:

Composition of alloy

Metals have a different tendency to adhere to one another and (Buckley, 1972) conducted adhesion experiments for various metals contacting an iron surface, including copper, gold, silver, nickel, platinum, lead, tantalum, aluminium, and cobalt. The results indicated that, with 'the various metals contacting iron, the cohesively weaker would adhere and transfer to the cohesively stronger' (Buckley, 1972, p.89). It was also shown that the metal aluminium had the greatest adhesion force to the iron. Kajoch and Fajkiel (1991) took a step further into the adhesion of aluminium-based alloys to steel. They found that the primary aluminium based alloys had the greatest tendency and that Al-Si alloy had the least to adhere to the steel. Other researchers found that the iron, manganese and titanium content in the aluminium-based alloy reduced the tendency of adhesion to the die steel (Shankar and Apelian, 1999; and Shankar and Apelian, 2002). An increase in silicon in the Al-Si alloy to approximately 18% increased the dissolution of the die steel (Chu et al., 1997) and an increase of nickel in the aluminium based alloy increased the thickness of the inter-metallic layer (Shankar and Apelian, 2002). Therefore, the aluminium alloy composition affected the unwanted adhesion layer in different ways, from the initial adhesion to the growth of the adhered layer.
Aluminium alloy temperature

"The temperature of the melt is a critical factor in creating "hot-spots" on the die surface" (Shankar and Apelian, 2002, p.115). These hot spots on the die surface had a greater tendency for the aluminium alloy and die steel to create an inter-metallic adhesion layer on the die surface (Zhu et al., 2002). Therefore, one of Hairy and Richard's (1997) recommendations to reduce the adhesion of the aluminium alloy to the die surface was to reduce the metal temperature. This was further highlighted, by Guo et al., (1997) who found that prolonged exposure of the die surface at elevated temperatures was responsible for the formation of the inter-metallic adhesion layer. Their analysis modelled the die temperature distribution and diffusion reaction of the HPDC process with the melt temperature as the initial die surface temperature in the gate area. A relationship between the aluminium alloy temperature and inter-metallic adhesion layer was further progressed in the close interrelated phenomena between HPDC adhesion and hot dip aluminising. A few researchers had analysed the hot dip aluminising in order to understand and prevent HPDC adhesion (Shankar and Apelian, 1997; and Shankar and Apelian, 1999). Chen and Jahedi (1998a) and Chen and Jahedi (1998b) did not believe that this inter-related phenomena (between HPDC adhesion and hot dip aluminising) took place because "aluminizing takes place at a constant temperature approximately 100°C above the liquidus temperature" and adhesion "occurs over many cycles at a temperature equal to and below the liquidus temperature of the HPDC alloy" (Chen and Jahedi, 1998a, p.101). They highlighted that the peak temperature in the shot sleeve, before the aluminium alloy was in the die, was equal to and below the liquidus temperature, which is not what other researchers believed (Shankar and Apelian, 1997; & Shankar and Apelian, 1999; Guo et. al., 1997; and Hairy and Richard, 1997). They went further by placing a thermocouple that was exposed to the aluminium alloy of the HPDC process and found that the peak temperature was equal to and below the liquidus temperature and not the molten metal temperature in the furnace (refer to 2.4). Their experiments were conducted in a HPDC die which accelerated the inter-metallic adhesion of an aluminium HPDC alloy to the die surface. Therefore, it was not clear whether the molten aluminium alloy temperature affected the adhesion of the alloy to the die surface but it did affect the die surface temperature.
Die temperature

The temperature of the aluminium alloy interface with the die surface and the die surface itself depended upon the pouring temperature of the molten metal and the heat transfer conditions (Zhu et. al., 2002). Shankar and Apelian, (1997, p. 244) stated that "the die surface temperature should not be too hot or too cold" because it could lead to adhesion of the aluminium based casting alloy to the die surface. Some definitions of the 'hot' die surface temperature term will be discussed in Section 3.2.7. Zhu et. al., (2002) suggested that if the die surface temperature was 'low' then the formation of the inter-metallic adhesion layer of the casting alloy to the die surface was rare. However, neither Shankar and Apelian (2002 & 1997) or Zhu et. al., (2002) define 'low' die surface temperature. Some of the reasons why the inter-metallic adhesion layer occurred when the die surface temperature was 'high' were: the activation energy required for a chemical reaction between the casting alloy and the die surface (diffusion); at higher temperatures more iron was able to dissolve into aluminium with a maximum value of 3% at 700°C (Zhu et. al., 2002; and Shankar and Apelian, 2002). The adhesion of the casting alloy to the 'hot' die surface could occur as suggested by Norville et. al., (2003) because the casting had not shrunk enough at the time of ejection. Only Shankar and Apelian (2002) suggested a temperature range from other researchers as to the 'hot spot' temperature range, 500-560°C. This work was from Chen and Jahedi (1998a, 1998b) and Chen et. al., (1999b) who suggested the time of exposure of the die surface at elevated temperature (i.e., above the liquidus temperature) was responsible for the inter-metallic adhesion layer forming and not a specific die temperature. Therefore, the die temperature could affect the adhesion of the aluminium alloy to the die surface but it was not clear as to what die surface temperature was required for adhesion to occur and this will be further discussed in Section 3.2.7.

Die material

The type of die material affected the heat transfer, which affected the temperature of the die and how quickly a casting solidified. Doehler, (1951) suggested that the appropriate selection of the die steel for the casting alloy could minimise the impact of the adhesion of the casting alloy to the die surface. For aluminium based casting alloys, Shankar and Apelian (2002) suggested the use of molybdenum alloy instead of H-13 die
steel because it helped reduce the formation of the inter-metallic adhesion layer. However, they also suggested that molybdenum was more expensive and softer metal than H-13 and this softness could lead to a shorter die life. Die surface coatings were applied to specific areas of die material in order to reduce the total costs of the dies but with the benefits of materials that minimise adhesion of the casting alloy. This will be further discussed in Section 3.2.5.

Die surface characteristics

The initial design and the manufacturing tolerances play a part in the adhesion and/or the inter-metallic adhesion layer. These die design and die manufacturing considerations were the draft angle, and the thick sections and undercuts in the die manufacturing process (Shankar and Apelian, 1997 and 2002).

Some researchers believed that the rougher the die surface was, then this would promote adhesion and/or inter-metallic adhesion and the ability of this unwanted layer to grow in terms of total adhered layer to the die surface (Shankar and Apelian, 1997; and 2002); Arai, 1995; and Wang, 1999). However, Chen and Jahedi (1999) suggested that the inter-metallic adhesion development was not affected by the die surface roughness but the surface roughness assisted in the adhesion wear process.

Therefore, the die design, in terms of the die surface angles, could reduce adhesion from occurring. The die surface roughness could alter the adhesion not the inter-metallic adhesion which was more difficult to remove.

Fluid flow

A few researchers highlighted that the direct flow impact of the casting alloy or its movement past the die surface could mechanically or chemically interact to washout/erode and corrode the die surface (Shankar and Apelian, 1997; Mitterer et. al., 2000; and Venkatesan and Shivpuri, 1995). These could cause or be a part of the process of adhesion of the casting alloy to the die surface (Shankar and Apelian, 1997). The washout and erosion effects had been described in terms of mechanical impingement, whereas, corrosion and inter-metallic adhesion was more the chemical interaction between the casting alloy and the die steel surface (Shankar and Apelian, 1997; and Chen and Jahedi, 1999). Chen and Jahedi (1999) studied the die erosion
process and its effects on the soldering formation (inter-metallic adhesion). They concluded that direct measurement of erosion in HPDC process had not been documented in the literature and from the theories studied that erosion before the soldering phenomenon was not likely. They also believed that the mechanisms of long term erosion in the HPDC process was not well understood and needed to be examined. Therefore, the role of the fluid flow of the adhesion of the aluminium alloy to the die surface was not clear.

The adhesion of the aluminium alloy to the die surface had been investigated in terms of the heat transfer, die construction, metallurgical reaction and fluid flow which, as noted in Section 2.4, were the fundamental aspects of the HPDC process. There were conflicting statements as to why the aluminium casting alloy adhered to the die surface either just mechanically or chemically and no clear evidence that could relate or dispute the claims of other researchers. The adhesion of the aluminium casting alloy to the die surface in the HPDC process also occurred with the other HPDC casting alloys.

3.2.4 Factors affecting the build up of non-aluminium casting alloy on the HPDC die surface

The adhesion of zinc based and magnesium based HPDC alloys to the die surface were not reported as much as the aluminium HPDC alloy mainly due to the small market size in the HPDC market. Some of the reasons why these two different HPDC based alloys adhered to the HPDC die surface are summarised as follows:

Zinc based HPDC alloy

Some of the reasons for adhesion of aluminium based HPDC alloys to the die surface were not evident in the zinc based HPDC alloys. The reasons that they were not evident were: erosion, inter-metallic layer, impact velocity, percentage of alloy contents (aluminium in particular), and metal temperature (Argo et. al., 1997). The main contributing factors that enabled the adhesion of the zinc based alloy to the HPDC die surface were die temperature, surface roughness and draft angle (Goodwin, 1997; and Argo et. al., 1997). An interesting observation that Argo et. al., (1997) and Goodwin (1997) made was that a thin layer of approximately pure aluminium was present in the adhered layer next to the HPDC die surface (refer to Figure 3.1). Therefore, the
presence of aluminium in the zinc HPDC alloy could be a factor in the formation of an adhered layer.

Mg-based HPDC alloy

As noted by Tang et. al., (2004b and 2004a), the adhesion of magnesium based HPDC alloys had received little attention. The importance of understanding and prevention of the adhesion of magnesium based HPDC alloys could be more important than aluminium based HPDC alloys because magnesium die castings were known for their thin walls (i.e., ultra-thin walls 0.4-0.6mm Hu et. al., 2000) and surface finish. Tang et. al., (2004b) found that the alloy contents (mainly aluminium and manganese) were factors in the chemical adhesion of the magnesium based HPDC alloy to the HPDC die surface. They found that the formation of the chemical adhesion was very slow when the aluminium content was below 7% but manganese helped in the early stages of the chemical adhesion process. They also found that the growth rate of the chemical adhesion layer was reduced with the manganese in the magnesium based HPDC alloy.

It appeared that further work needed to be conducted on both of these two HPDC alloys in terms of the causes for adhesion to the die surface.

3.2.5 Methods to prevent the build up layer

Die coatings were applied in many die casting processes (gravity, low and high pressure) to act as insulation or lubrication or both. Application of lubricants was commonly employed to HPDC die surfaces, in industry, to aid in the ejection process. Refer to Figure 1.1 for the time of application within the HPDC cycle. The lubricants were usually sprayed onto the die surface but the surface had to be at a sufficient temperature for application (Anonymous 1978-1989). In some cases, the spraying sequence was used to cool the surface of the die, where other cooling techniques were limited in their performance. In terms of unwanted adhesion, the two primary methods that were employed were:
Lubrication

In HPDC, the die surface was sprayed with lubricant before every casting shot in order to form a thin protective film between the molten aluminium and the die surface; to provide a release agent for the ejection of the casting and to aid in the removal of heat from the die (Fraser and Jahedi, 1997). The performance of the lubricants were affected by die temperature, spray parameters and lubricant chemistry (Fraser and Jahedi, 1997). The use of lubricants to prevent the adhesion of the HPDC alloys to the die surface had been employed since the 1950s (Doehler, 1951). However, Graff (1997), and Munson and Pacholke-Dumont (1997) had observed that when adhesion of lubricant to the die surface occurred then little or no adhesion of the casting alloy to the die surface occurred. Munson and Pacholke-Dumont (1997) observed that the adhesion and build up of lubricant could be difficult to remove. Graff (1997, p. 97/13) noted that “in-cavity build-up from the use of the wrong die lubricant or over application of the proper die lubricant may, in fact, be solder” (i.e., inter-metallic HPDC alloy adhesion to the die surface).

Therefore, the adhesion of lubricants to the HPDC die surface occurred for a few different reasons and some of these were:

1) Over-spraying of a die area which could lead to the build up of die lubricant material, lubrication by-products or other substances that stick to the die (Mangold, 1997; and Graff, 1997)

2) Die lubricant compositions (Munson and Pacholke-Dumont, 1997; and Graff, 1997) and the water used to dilute the die lubricant (Graff, 1997)

3) Failure of the die lubricant to decompose after the casting cycle (Osborne and Brevick, 1997)

Die coatings and/or surface treatments

The main requirements of the die coatings and/or surface treatments, as highlighted by Lakare et. al., (1999, p.383), were:
Coatings should be chemically stable in the molten aluminium and at the die casting temperatures and be thick enough to prevent direct diffusion of aluminium into the die steel.

Coatings should have high oxidation resistance and should maintain their adhesion and properties at the die casting temperatures but they should have less porosity and defects.

The development and evaluation of the die coatings and surface treatments were considered in two different ways, one with laboratory trials (Chellapilla et al., 1997; Joshi et al., 2003; Joshi et al., 2001; Salas et al., 2003; Persson et al., 2001; Mitterer et al., 2000) and the other in HPDC trials (Chellapilla et al., 1997; Moore et al., 2003; Gulizia et al., 2000; Gulizia et al., 2001; and Tsuchiya et al., 1997). Both of these two areas will be discussed.

A few of these investigations were under laboratory conditions that used the holding furnace temperature to produce the results (Chellapilla et al., 1997; Joshi et al., 2003; and Joshi et al., 2001). However, Chen and Jahedi, (1998a and 1998b) reported that the temperature was at about the liquid temperature of the casting alloy. Therefore, the temperature of experiments was too high as Shankar and Apelian (2002) had noted. However, Lakare et al., (1999) noted that the surface coatings and treatments for HPDC dies had mixed results from a production and laboratory environment perspective. This may be explained by (Venkatesan and Shivpuri’s (1995) observation that the simulated laboratory tests could simulate a factor, whereby, in the HPDC process it could be from multiple factors.

Even though the prevailing method to detect an unwanted layer on the die surface was through manual inspection, Tsuchiya et al., (1997) observed a variation in percentage build up and maximum height when the unwanted layer from the casting alloy was measured after specific shot cycles in the HPDC trial. These observations were from coated die pins within the die cavity. They concluded that the unwanted layer that was formed must have been removed after subsequent shots. An examination of the quality of the casting surface revealed that there was minor evidence noticed when a thin layer built up, but when the layer was thicker then the quality of the surface castings was reduced. The minor build up of an unwanted adhered layer did not affect
the quality of the castings and had been observed by other researchers (Chellapilla et al., 1997). This mechanical bonding between the casting alloy and the die surface had been observed by Gulizia et al., (2001) when they coated the surface of their die pins.

In summary, the preventative methods to reduce or eliminate the adhesion of the HPDC alloys to the die surface could reduce the problem but the adhesion problem did still occur and a solution was not found for all the HPDC alloys.

3.2.6 Benefits of other detection methods and automatic detection of built up layer

Tsuchiya et al., (1997) highlighted that, with the manual visual inspection method, it was difficult to notice the initial minor adherence of the casting alloy to the die surface. It was also noted by Graff (1997) that the adhesion of the lubricant could cause porosity casting defects and Tian et al., (2002) stated that porosity casting defects in HPDC were generally classified into three main categories. He also stated that flow porosity could be caused by numerous factors that affected the “fluid flow conditions during the cavity filling” Tian et al., (2002, p.82). Therefore, if an efficient method could be developed to detect the unwanted adhesion on the HPDC die surface, then the factors causing the initial minor adhesion from the casting alloy could also be determined, and operators could be alerted to the formation of porosity casting defects (arising from the adhesion of the lubricant).

Alternatively, Graff, (1997, p. 97/13) noted that “acidic or alkali materials may be formulated into the die lubricants to help remove solder as it is formed, rather than to prevent its formation in the first place.” However, it was subsequently noted that there were a few problems with this idea (i.e., worker safety and chemical attachment to HPDC components). Therefore, if a warning system could be developed that once the level of unwanted adhered layer reached a specific level then an automatic spray could be formulated that could remove the unwanted adhered layer from the surface at specific locations on the die.

3.2.7 Common factor(s) influencing built up layer – hot spots

There were a number of mechanisms that caused the unwanted layer to build up in different casting alloys, but a common theme amongst researchers was that this layer
occurred in a hot spot on the die surface (Shankar and Apelian, 2002; Graff, 1997; Lakare et al., 1999; Chen and Jahedi, 1998a; Chen and Jahedi, 1998b; and Tsuchiya et al., 1997). The actual definition of a hot spot on the die surface was not always clear and received varying degree of explanations. Some of the definitions of a hot spot on the die surface (when the adhesion layer was the casting alloy) were: maximum die surface temperature between 500-560°C, for aluminium casting alloy, (Shankar and Apelian, 2002) and uneven temperature on the die surface, for example localised hotter and colder regions were some other temperature factors mentioned.

A few authors had reported layer build up at temperatures below 500-560°C (Tsuchiya et al., 1997; and Mitterer et al., 2000) and even Shankar and Apelian (2002) mentioned that if the die temperature was too low then 'cold solder' could occur but they did not define 'cold solder' or low die temperature. Many of the values were obtained from thermocouple readings that were a few millimetres below the surface but the die temperature surface could be higher than the reported measured temperature (refer to Section 3.4 for further discussion). However, Argo et al., (1997) investigated the causes of unwanted layer build up from the zinc casting alloy. For the experiments conducted, their casting alloy holding furnace temperature was between 420-430°C but the unwanted layer consisted of a rich aluminium next to the die surface and next to the aluminium layer was the zinc casting alloy. This means that aluminium could adhere to the die surface even below the melting temperature of aluminium which had not been noted by the research on the adhesion of aluminium to the HPDC die surface.

There were a wide range of lubricants used in the HPDC process and, as noted by Osborne and Brevick (1997, p. 331), due to the 'wide range of die temperatures experience[d, it] can make it very difficult to design a lubricant.' As such the adhesion of the lubricant to the HPDC die surface did occur which could have been due to: the excessive lubricant application temperature which prevented proper adherence to the die surface (Shankar and Apelian, 1997), or uneven temperatures on the die surface during lubricant application. For example, the lubricant could move from the hotter areas to the colder areas on the die surface (Graff, 1997). Even the die temperature could be higher than the maximum working conditions of the lubricant (Graff, 1997).
3.2.8 Summary

Adhesion of the HPDC alloy to the HPDC die surface was a phenomenon that had been observed for more than 50 years. The main reasons why this was a problem were: casting defects, die failure, and lost production to clean the die surface. There had been significant research into the understanding of why the HPDC alloy adhered to the die surface which, in a broad context, could be categorised into six areas that were investigated in the adhesion of the aluminium HPDC alloy. An example of the events that led to the formation of the unwanted adhered aluminium casting alloy to the die surface is shown in Figure 3.2.

Figure 3.2 – Example of the events producing an unwanted layer on the die surface via the aluminium casting alloy (abstracted from Shankar and Apelian, 1997, p.245).
Some of the preventive methods that were in use, when this research was conducted, had been used since the 1950s (i.e., lubricants). However, even a preventive lubricant could adhere to the die surface and could cause casting defects. The other preventive method of surface coatings and/or surface treatments prolonged or prevented more severe chemical adhesion from occurring but the casting alloy still adhered to the HPDC die surface.

The more recent methods employed to detect these unwanted adhered layers were manual visual inspection of the die and/or casting surface. If an automated system could be developed then some spray material could be used to remove the unwanted adhered layer(s) from the die surface. At the very least it could warn the operator to clean the die surface.

Multiple causes were presented as to why and/or how the unwanted adhered layer occurred but one common theme amongst the researchers was die temperature. However, the specific temperatures and/or times of occurrence within the HPDC cycle at which build up commenced were not clearly defined. Therefore, the temperature of the die surface at specific times within the HPDC cycle could provide a method for developing an alternative (automated) method for the detection of an unwanted adhered layer on the HPDC die surface. The latter is what this research attempts to investigate.

3.3 Potential Automatic Monitoring of Layer Build Up on HPDC Die Surface

3.3.1 Overview

There were four potential methods to monitor the presence or build up of an unwanted layer on the die surface namely: infrared thermal image of the die surface; visual image detection system; application of inverse heat conduction problem (IHCP); and temperature monitoring. These four different areas are discussed in Sections 3.3.2 to 3.3.5.
3.3.2 Infrared thermal image of the die surface

The use of infrared cameras in the HPDC process was used as a research and diagnostic tool (Niu et al., 2003; and Bishenden and Bhola, 2003). Some of the benefits outlined by Niu et al., (2003) were: fast response time of 2 dimensional real thermograph images that had high accuracy and did not have the some of the restrictions of thermocouple and infrared spot measuring surface directly (scattered results due to non-repeatable measurement locations and limitations of operator measuring surface). They also noted some of the negatives of the use of infrared cameras which required calibration and correct radiation value to determine the temperatures but the distance from the die surface had to be determined. Another negative that they noted was that the camera shooting angle had to be carefully positioned to obtain the maximum image.

Infrared cameras can determine the location of hot spots on the die surface, online, when comparing temperature differences as highlighted by Niu et al., (2003). However, the thermal images could only be taken when the dies were open (i.e., before and after the spray cooling cycle, refer to Figure 1.1). As noted in Section 3.2, the unwanted layer was caused at the hottest temperature of the die surface when the dies were closed and the lubrication application temp could be important to unwanted layer formation. Some disadvantages of the use of infrared cameras for monitoring the unwanted layer in real time were: adapting the thermal image information into space and time (Le Niliot and Gallet, 1998) which would normally require selection of the “appropriate portion of the data” to be used (Nguyen and Bendada, 2000, p.869).

3.3.3 Automatic vision image systems

An automated vision image system would contain the visual images of defects to automatically monitor the ejected castings, thus, could aid or replace the operator’s role to visually inspect the castings (Webster, 1995). A system could give real time information about the quality of the parts that could be fed back into the HPDC process (Webster, 1995). Their system contained a “substantial amount of knowledge (over 250 rules and 200 functions)” (Webster, 1995, p.297) and 400 images of defects both internal and external defects of various severity.
An automated vision image system would have to identify a few different casting defects that were associated with the build up of an unwanted layer for it to detect those highlighted in Section 3.2. Some of these signs were not obvious unless the build up was thick (Tsuchiya et al., 1997), and this could be more difficult to remove from the die. An image of the unwanted build up on the die surface (by the casting alloy) can be seen in Figure 3.3 which highlights that the unwanted adhered layer emanating from a specific location, and the growth patterns and thickness changes over the number of castings produced. The early signs of the unwanted build up on the casting can be seen in Figure 3.4 which highlights that if the unwanted adhered layer occurred in a cavity then it may be difficult to visually detect. Some of these defects could be due to other reasons, for example the build up of lubricant could cause porosity but porosity was associated with the filling process (Webster, 1995). Therefore, the signs of the defects could be caused through two different mechanisms. However, this type of system would be more beneficial as a feedback control system to reduce casting defects through process and parameter control as highlighted by Webster (1995).

![Figure 3.3 - Visual evidence on the die surface (core pin) where an unwanted layer build up over the number of casting cycle (abstracted from Fraser, 2000, p.55). A cross section of the casting shape can be seen in Figure 3.4](image-url)
Evidence of adhered layer on the casting is hard to see if in a deep hole

Figure 3.4 – Visual evidence of the unwanted layer on the casting surface. a). Cross section of casting showing the location of the core pin b). magnified of the casting surface where the unwanted build up occurred after 5 casting cycles. (both pictures abstracted from Fraser, 2000, p.86)

3.3.4 Inverse Heat Conduction Problem

The Inverse Heat Conduction Problem (IHCP) that could be used to detect the build up of an unwanted layer on the die surface was based on the surface boundary conditions. Refer to Chapter 4 for more background theory and details on IHCP. Therefore, any changes in surface boundary conditions, for a particular boundary, such as an increase or decrease over time, could be determined. The benefits of using the IHCP technique was that not only could the surface temperatures be estimated but also the heat fluxes. The ‘surface temperature and the heat flux histories are equivalent in the sense that if one is known the other can be found in a straightforward fashion’ (Beck et. al., 1985, p.1). This additional information could highlight whether or not an inter-metallic layer had been formed in the unwanted layer because it had a ‘low thermal diffusivity’ compared to the die steel, which was suggested to be a reason why the casting alloy adhered to this layer more readily than the die steel (Shankar and Apelian, 1997, p.246). With a lower thermal diffusivity, the heat flux history would change which, as highlighted in Section 3.2.2, meant that the inter-metallic layer was harder to remove than if mechanical bonding of the casting alloy to the die surface had occurred.
The IHCP had been in used in the HPDC process (Bounds et. al., 2000), but the potential use of IHCP in real time was divided amongst researchers. Attia et. al., (1999); and Alifanov and Gejadze (1997) employed the IHCP in real time with numerical methods technique. However, Janicki et. al., (1998) believed that only an analytical solution could be used in real time. All authors agreed that the limitation of IHCP for real time estimations was due to poor computational efficiency but Attia et. al., (1999); and Alifanov and Gejadze (1997) also highlighted the need for future data to be used, which was to ensure the solution was stable (refer to Chapter 4 for more information about the need for future data for the solution to IHCP). However, both Attia et. al., (1999); and Alifanov and Gejadze (1997) highlighted that the use of future time steps could not be used in real time solution of IHCP.

The location of thermocouple positions was important for an accurate estimation of the boundary conditions but in HPDC the location of the thermocouple was traditionally selected for 'convenience rather than for utility' (Doehler, 1951. p.148). There was a reluctance to put thermocouples into the HPDC die because of its complex and expensive nature (Niu et. al., 2003). Other concerns regarding solutions of IHCP in real time for the HPDC process were:

- Number of unknowns (temperature locations) had to equal the number of measurements (i.e., thermocouple locations or extra boundary measurements). Refer to Chapter 4.

- IHCP required other boundary conditions to be known (refer to Chapter 4) and (Bounds et. al., 2000) highlighted that the cooling channels may not be predicted accurately.

Therefore, IHCP was useful to determine the boundary conditions of the HPDC die surface but not for the detection of the unwanted adhered layer because the solution of the IHCP’s reliance on the thermocouple position and accurate boundary conditions for the rest of the HPDC die. A few more reasons why IHCPs may not work for the detection of the unwanted adhered layer are highlighted in Chapter 4.
3.3.5 Temperature monitoring

There were disadvantages of using thermocouples in HPDC dies, as noted in Section 3.3.4, but temperature probes had been used in HPDC research since the 1930s (Doehler, 1951). Another fundamental disadvantage of the use of thermocouples in a HPDC die, as noted by (Doehler, 1951), was that the recorded temperature was only of a localised area. Nevertheless, real time monitoring and control with thermocouples had been reported as early as 1970 (Harris, 1970; Booth, 1970; and Larkin et. al., 1970), which continued from zinc to aluminium and HPDC process time to cooling channels and electric heaters (Kaiser et. al., 1972; Dent and Fifer, 1972; Peterson, 1975; Hopkins and Murray, 1989; Venkatasamy et. al., 1997; Gershenzon et. al., 1999); (Bishenden and Bhola, 1999; Bishenden and Bhola, 2003 and Hu et. al., 2003).

One advantage of the use of thermocouples over the infrared camera for detection of the build up of an unwanted layer was that they could measure the die temperature for “all the times during the casting cycle” (Venkatasamy et. al., 1997, p.151). Refer to Figure 1.2. Thus, the use of temperature monitoring devices inside the HPDC die was potentially the most appropriate technique of all the four different techniques mentioned to detect the unwanted adhered layer on the HPDC die surface.

3.4 Periodically Heated Solid Surface

The HPDC die had a steady periodically heated surface (where the casting alloy solidified) and so the general aspects of a periodically heated surface needed to be investigated and discussed. A solid surface with a constant temperature distribution, that was periodically heated, could be represented by two components. These two components and/or solutions were the transient disturbance and a steady oscillation (Carslaw and Jaeger, 1959). The transient disturbance dies away as time increases but both of these components can be seen in a HPDC die temperature time profile, as in Figure 3.5. The transient disturbance was referred to as the preheat zone and the steady oscillation was referred to as the die operating zone in Figure 3.5.
The study of solids which had periodically heated surfaces dated back to the 1860s when Thomson (also known as Sir Kelvin) derived for the first time the problem mathematically (Thomson, 1861) for the steady oscillation component. The equations were formulated through harmonically analysing mean temperatures over 18 years. The harmonic analysis was through Fourier transforms of the data (refer to Everett, 1861). Some of the general properties of a solid with a steady periodically heated surface from (Carslaw and Jaeger, 1959, p.66) were (Refer to Figure 1.3 for the different representations):

a) The amplitude of the temperature oscillation diminishes with increased distance from the steady periodically heated surface.

b) A progressive lag in phase of the temperature oscillations with an increase in distance from the steady periodically heated surface.

c) The positions of maxima and minima temperatures propagated into the solid with a velocity that was a distance from the steady periodically heated surface.

For an extensive review of analytical solutions to different problems involving steady periodically heated surfaces, refer to Carslaw and Jaeger (1959).
These general properties could be used to detect the unwanted layer, whereby, if the thermocouple distance from the steady periodically heat surface was increased by the formation of a layer then these observations could be used. This will be further discussed in Chapter 4.

3.5 HPDC Dies with Embedded Thermocouples and Unwanted Layer Formation

There were relatively few researchers that placed thermocouples into the dies for research purposes, even though the HPDC dies were designed with the specific adhesion problem in mind; temperature probes had been used in the HPDC process for more than 65 years, and even though temperature had been identified as a main factor in the adhesion of the casting alloy to the HPDC die surface. More specifically, it was the core pin where the adhesion layer was most likely to occur. Some of the researchers that placed thermocouples into the core pins were: Chen et. al., (1999b); Chen and Jahedi (1998a; & 1998b); Goodwin (1997); Argo et. al., (1997); and Tsuchiya et. al., (1997).

Argo et. al., (1997) placed three thermocouples at different depths (0.0254, 0.0762 and 0.2286 centimeters from the tip of the pin) within the core pin. Their results of the temperature pin(s) was a single measured temperature for each trial (approximately 300 shots). There was no indication of how or what this single measured temperature came about from the thermocouple(s). However, they found that the die temperature and pin draft angle were the main factors that caused the zinc based alloy to adhere to the HPDC die surface.

Goodwin (1997) work appeared similar to Argo et. al. 's, (1997) work. Both were on the adhesion of zinc on the die surface, with the same die design, variables and outcomes. Goodwin (1997) used four temperature pins but a single die pin temperature was highlighted for each trial of 300-350 shots. Goodwin, (1997) found that the die temperature and pin draft angle were the main factors that caused the zinc based alloy to adhere to the HPDC die surface.

Tsuchiya et. al., (1997) had an eight cavity HPDC die with seven pins in each die cavity that were placed throughout the cavity. Each core pin had a thermocouple that was 2mm below the top surface of the pin but the core pins had a surface coating on
them. The temperature cycle stabilized in 50 shots (periodically stable temperature). The peak temperatures of the four different cavities with the seven pins in each cavity were graphically presented (these were obtained from the temperature profiles of each HPDC cycle). They found that the generation and growth of the adhered layer and the pin damage were related to the velocity and die temperature, whereby, the worse occurrence was at high velocity and high die temperature.

Chen et. al., (1999b); and Chen and Jahedi (1998a & 1998b) used one production HPDC die and two HPDC trial dies wherein the thermocouples were placed into pins that were near the gate section. For their experiments, the thermocouples were placed 5 mm from the pin tip for the production HPDC die trial and 2.5 mm for the HPDC trial die. They highlighted the different temperature profiles for the different pin locations and from these temperature profiles they concluded that the inter-metallic adhesion occurred when the peak surface temperature was at or above the liquidus temperature of the HPDC alloy for long periods of time. Therefore, the greater the time that the temperature was at or above the liquidus temperature then the greater the propensity for an inter-metallic adhesion of the HPDC alloy to the die surface. Hence, their last HPDC trial die had the greatest time for the pin surface temperature to be at or above the liquidus HPDC alloy temperature.

These researchers placed thermocouples in the HPDC die when the unwanted casting alloy adhered to the die surface, but none of these researchers noted the specific temperature trend when the adhered later took place. This doctoral research, on the other hand, was to investigate whether a temperature trend could be used to detect the unwanted adhered layer on a HPDC die surface. Thus, in turn, determining the maximum distance that a thermocouple could be placed from the unwanted adhered layer whilst still detecting it.
Chapter 4

Background Theory
4.1 Overview

As highlighted in Chapter 3, there were two theories present to detect the unwanted adhered layer which were the Inverse Heat Conduction Problem (IHCP) and the observations from a periodically heated solid surface. Therefore, the background to these two theories, in relation to the detection of the unwanted adhered layer, is presented in Sections 4.2 and 4.3.

4.2 Theory of IHCP

The heat conduction problem consists of a partial differential equation (PDE) such as the one shown in Equation 4-1. Bleecker and Csordas (1995) suggested that if the initial temperature distribution and the boundary conditions were specified then the temperature distribution could be determined. However, as Janicki et. al., (1998) highlighted, the information required to solve the PDE in Equation 4-2 (abstracted from Janicki et. al., (1998, p 51) included:

- Thermal material properties
- Heat generation
- Boundary and initial conditions.

Therefore, the problem could be well-posed\(^9\) and known as the direct problem. Itō (1987), however, suggested some problems that may not be well-posed. As highlighted by Janicki et. al., (1998), if any of the necessary information to solve the problem was not obtained then it could be described as an inverse heat conduction problem (IHCP).

\[
\nabla^2 T = \frac{1}{\kappa} \frac{\partial T}{\partial t}
\]

where \( T \) = temperature, \( t \) = time \& \( \kappa = \frac{k}{\rho C_p} \) (diffusivity)

\(^9\) (Itō, 1987) "A problem is said to be mathematically well posed (properly posed or correctly posed) if, under assigned additional conditions, the solution (i) exists, (ii) is uniquely determined, and (iii) depends continuously on the assigned data."
This is an example of the heat conduction problem that is a PDE:

\[
\frac{\partial^3 T}{\partial x^2} + \frac{\partial^3 T}{\partial y^2} + \frac{\partial^3 T}{\partial z^2} = \frac{C_p \rho}{\kappa} \frac{\partial T}{\partial t} - \frac{g}{\kappa} \]

...(4-2)

where: \( T \) = temperature, \( \kappa \) = thermal conductivity, \( C_p \) = specific heat, \( t \) = time, \( g \) = generated heat density & \( \rho \) = density.

Beck et al., (1985, p.1) highlighted the fact that the IHCP was “more difficult to solve analytically than the direct problem.” They mentioned some of the practical reasons why the IHCP were used rather than direct problem and some of those reasons related to the difficulty of positioning a temperature sensor at a required location. One of the general methods to solve IHCP (using numerical methods) was iterative and solving the direct problem Le Niliot and Lefèvre (2001). Typically, for IHCPs, the number of measured positions had to be greater or equal to the number of unknowns that needed to be determined Le Niliot and Gallet (1998). Refer to Figure 4.1 and Figure 4.2.

However, Beck et al., (1985) stated that the IHCP was an ‘ill-posed’ problem. Janicki et al., (1999, p1099) stated that the solution of inverse heat conduction problems “usually exists and is unique, but the obtained estimates are not numerically stable.” Beck et al., (1985, p14) gave an example when the estimate was not stable unless the experiment was designed properly and the sensitivity of the temperature sensor’s response was within acceptable accuracy. They also noted that the IHCPs were difficult because the solution was extremely sensitive to errors in measurement and highlighted “eight standard statistical assumptions regarding the temperature measurements” (Beck et al., 1985, p10). There were some methods to reduce the sensitivity of ill-posed problems to measurement error (Beck et al., 1985) and one of the many methods used was know as the “future time steps” method. This method as described by Le Niliot and Gallet (1998) solved the problem at time \( t_a \) with the measurements taken at \( t_a, t_{a+1}, t_{a+2}, \ldots, t_{a+b} \). (i.e., knowledge obtained in the future of time).
There were two IHCPs that seemed similar to the detection of hot spots in HPDC. The HPDC hot spots were due to differences in surface temperature, whereas, the IHCP where hot spots due to heat sources\(^{10}\). An example of this is shown in Figure 4.1. Some of the positive and negative aspects of those types of IHCP were:

- Prior information had to be known (i.e., functional form of the heat sources) to solve the problem (Yang, 1999; & 1998; Videcoq \textit{et. al.}, 2003; LefeVre and Le Niliot, 2002).

- More information was required to stabilise solution (Le Niliot, 1998); and (LefeVre and Le Niliot, 2002).

- The solution to the problem had to be restricted (Le Niliot and LefeVre, 2001).

- The optimum positions of sensors (measurement locations) were not always based on the closest thermocouples to the heat source because the sensor location could be sensitive to more than one heat source, so the result may not be correct (Videcoq \textit{et. al.}, 2003).

- The position of sensor was critical to finding the correct solution (Videcoq \textit{et. al.}, 2003; LefeVre and Le Niliot, 2002; and (Le Niliot and Gallet, 1998).

- A limit in over-determining the equations because the solution could be degraded. For example, more sensor measurements than unknowns (Su and Silva Neto, 2001).

- A three dimensional problem was more sensitive to measurement errors and the computational time was longer (Nortershauser and Millan, 2001).

---

\(^{10}\) Heat sources could be generated by a number of reasons for example chemical reactions or electric wires.
• Position of initial guess was important to converge on a solution (Le Niliot and Lefèvre, 2001; and Lefèvre and Le Niliot, 2002).

\[ N \text{ boundary elements} + N' \text{ internal points (measurements)} \]

\[ N + N' \text{ equations} \]

\[ M = N + K \text{ unknowns (} K \leq N' \text{)} \]

**Figure 4.1- Schematic diagram of inverse heat conduction problems to determine the heat source strength (abstracted from Le Niliot and Gallet, 1998, p.633)**

For the detection of hot spots on the HPDC die surface there was potentially one IHCP, which is shown in Figure 4.2. The IHCP to determine the surface boundary conditions was extensively covered in Beck *et. al.*, (1985) but the methods to solve the IHCP varied and some of the methods used were: conjugate gradient method (Huang, 2002); maximum entropy method (Kim and Lee, 2002); and sequential function specification (Chantasiriwan, 1999).
Temperature and flux unknown (1 equation and 2 unknowns per element)

N boundary elements

boundary \( \Gamma \)

domain \( \Omega \)

N' internal points (measurements)

Temperature and flux known (1 equation and 0 unknown per element)

N + N' equations
M unknowns with M ≤ N + N'

Figure 4.2 – Schematic diagram of potential inverse heat conduction problem, abstracted from Le Niliot and Gallet (1998, p.633)

Le Niliot and Gallet (1998) highlighted the use an infrared camera to measure the boundary conditions of one boundary surface so as to estimate the boundary conditions on another boundary surface. They found that the distance from the measured to the estimated boundary surface affected the results of the estimation. Therefore, they found the closer the distance at which the measurements were made then the better their estimations. This was further highlighted by Beck et. al., (1985) who stated that the ‘heat flux component, \( q_m \), is much less sensitive to measurement errors when sensors are used near the heated surface’ (Beck et. al., 1985, p.129). As highlighted in Section 3.6.4, the IHCP could not be used to detect the unwanted adhered layer because all the other boundary conditions had to be known and the number of thermocouples had to equal (or be greater) than the unknowns of the unwanted adhered layer(s).

4.3 Theory of Periodically Heated Solid Surface

Some of the general information of periodically heated solid surfaces was presented in Section 3.4. Presented in this section is how this theory could be used to detect the unwanted adhered layer and some theory relating to the maximum distance that this method could possibly detect the unwanted adhered layer. Some properties of a
solid with a steady periodically heated surface from Carslaw and Jaeger (1959, p.66) were highlighted in Section 3.4 but here are the formulae accompanying that information:

- The amplitude of the temperature oscillation diminishes with increased distance from the steady periodically heated surface as a distance from the steady periodically heated surface. Refer to Equation 4-3.

\[ A = \exp^{-\sqrt{\frac{\omega}{2\kappa}}} \]  

where \( \omega = \) frequency \& \( \kappa = \) thermal diffusivity of the solid

- A progressive lag in phase of the temperature oscillations with an increase in distance from the steady periodically heated surface. Refer to Equation 4-4.

\[ \text{Phase lag} = x\sqrt{\frac{\omega}{2\kappa}} \]  

- The positions of maxima and minima temperatures propagated into the solid with a velocity that was a distance from the steady periodically heated surface. Refer to Equation 4-5.

\[ \text{Velocity of temperature fluctuations} = \sqrt{2\kappa_0} \]  

Some of the properties of a solid with a steady periodically heated surface were shown in Figure 1.3. As mentioned in Section 3.4, for an extensive review of analytical solutions to different problems involving steady periodically heated surfaces, refer to Carslaw and Jaeger (1959).

Without the unwanted adhered layer on the periodically heated surface, the behaviour of the temperature readings within the solid would behave in the manner that Carslaw and Jaeger (1959) suggested. When the unwanted layer develops on the solid surface, the periodic energy has to travel through the unwanted layer which has an additional resistance to flow of the heat energy (this can be seen in Figure 4.3). Depending on the casting alloy thermal properties (namely the thermal diffusivity, \( \kappa \))
then the heat energy could be used to heat-up/cool-down the initial surface or transferred to the rest of the unwanted layer. Either way some of the energy that would normally be transferred to the die would be transferred to the unwanted layer first, which would absorb and distribute this energy. Therefore, some of the periodic heated energy that would normally be detected by the thermocouple would be absorbed by the unwanted adhered layer and so this reduction in energy may be noticed in the thermocouple readings.

![Figure 4.3 - Schematic diagram highlighting the additional resistance once the unwanted adhered layer formed.](image)

The thermocouples are at a fixed position from the die surface, so if an artificial layer does develop between the die surface and the heating element then the thermocouple is effectively further separated from the periodically heated surface. Thus, changes in the thermocouple readings should be observed just as if the thermocouple position was moved (as seen in Figure 4.4). Hence, the changes in temperature readings from the fundamental theory of a periodically heated solid and temperature readings should occur. In turn, the signs of moving the temperature readings away from a periodically heated surface could be used to detect the unwanted adhered layer on the die surface. Refer to Figure 4.4.
Figure 4.4 – Theoretical idea which could convert the knowledge from a periodically heat surface to detect the unwanted layer on a HPDC die surface

Even if a small segment of an unwanted layer occurred then it would impact on the volume around it because the small segment would absorb and distribute the heat energy, as shown in Figure 4.5. As mentioned in Section 2.4, the heat is transferred from a higher temperature to a lower temperature through the three heat transfer mechanisms. This would be in a similar manner as highlighted in Figure 4.3 and Figure 4.4 but the spread of the effect should be less due to the reduced mass of the segment, as shown in Figure 4.5.
Therefore, if the thermocouple readings could observe the development of the unwanted adhered layer according to the above theory then what is the maximum theoretical distance that the thermocouple could be from the unwanted layer? Formulae from Carslaw and Jaeger (1959) will be explored to define the theoretical behaviour and variables which concern the answer to this question.

Carslaw and Jaeger (1959) formulated the relationship concerning the reduction in temperature amplitude as the distance from the surface increases, but this was only in one-dimension and for an ideal case where the solid material was infinitely long (refer to Equation 4-3). The formula depended on two main variables – frequency of oscillation (cycle time) and the thermal properties of the material. Equation 4-3 will be explored further in relation to the HPDC process.

For the HPDC process, the thermal properties of the employed die steel (H13) were approximately constant as the temperature varied as shown in Figure 4.6 and in the temperature range for HPDC die. Therefore, the main factor that influenced the reduction in temperature amplitude was the cycle time. It was noted by Carslaw and Jaeger (1959) that, as the frequency increases (i.e., the cycle time reduced) the temperature amplitude reduction is greater as the distance from the surface increases. If a constant material property of $6.00 \times 10^{-6}$ m$^2$/s for the HPDC process was used in Equation 4-3 then the reduction in temperature amplitude with an increase in cycle time and distance from the periodically heated surface can be seen in Figure 4.7. In this
diagram, the temperature amplitude on the surface normalised for all the calculations to one unit.

**Figure 4.3** – Temperature versus thermal diffusivity for different steels (data abstracted from 2DSOL software V1.2)

**Figure 4.4** – Temperature amplitude reduction versus distance for the surface with a periodic temperature surface when the original temperature amplitude is one for different cycle times
As noted by Carslaw and Jaeger (1959), and shown in Figure 4.7, as the cycle
time increased then the reduction in temperature amplitude (as the distance from the
surface is increased) reduced. At a distance of 10mm from the surface, there was a
reduction in temperature amplitude of 0.1 for a total cycle time of 10 seconds –
compared to a reduction in temperature amplitude of 0.45 for a total cycle time of 80
seconds.

In a HPDC process, the depth of the surface never approximates the assumption of
infinity in the formula, so the critical depth at which the formula was invalid and had to
be determined from another formula from Carslaw and Jaeger (1959). The formula was
derived for a one-dimensional slab with a periodic boundary surface on one side and a
fixed temperature of zero on the other side. The temperature amplitude reduction
formula is (Carslaw and Jaeger, 1959, p.106):

\[ A = \frac{\cosh 2ax - \cos 2ax}{\sqrt{\cosh 2al - \cos 2al}}, \tag{4-6} \]

where \( l \) is the length of the slab & \( a = \sqrt{\frac{\omega}{2\kappa}} \)

A comparison between the two equations (Equation 4-3 and Equation 4-6) highlights that there was little difference between the two (refer to Figure 4.8) except when the bounded length was reduced to 50 mm and the cycle time increased to 120
seconds (refer to Figure 4.8). This result highlighted that either equation could be used
when the material was bounded up to approximately 50 mm and that the thermocouple
position should not be placed near a bounded region (such as a corner or a cooling
channels close to the die surface). Therefore, Equation 4-6 should be used to determine
the limits to which a thermocouple could be placed near a bounded region.
Figure 4.5 – Comparison of the temperature amplitude reduction for the two different formulae for a periodic temperature at one surface (Equation 4-3 and Equation 4-6), when the bounded length is 50 mm from the surface

The diagrams in Figure 4.4 to Figure 4.5 all had a surface temperature amplitude of one, whereas, in a HPDC die, the temperature amplitude of the temperature was a few hundred degrees. Equation 4-3 and Equation 4-6 describe the decay in temperature amplitude against distance but these require the temperature amplitude at the surface. If the temperature amplitude for a HPDC cycle was normally 300 and if the temperature amplitude reduced to 250 when the unwanted adhered layer developed then a temperature amplitude reduction of 50 would occur. If the temperature amplitude reduction was plotted versus distance, as shown in Figure 4.19, then the limits of where the thermocouple could be placed could be known theoretically. The temperature amplitude reduction formulae could be used to determine at what distance the temperature amplitude difference becomes insignificant. Thus, in theory, the maximum distance that a thermocouple should be positioned to observe the change in temperature amplitude from the unwanted layer could be calculated. Figure 4.19 shows the temperature amplitude reduction versus distance for a 40 second cycle time with different temperature amplitude differences and the limits of detection were 20-30 mm for temperature amplitude differences between 15-55°C.
Figure 4.9 – Temperature amplitude reduction versus distance for the surface with a periodic temperature surface when the cycle time is constant at 40 seconds but the original temperature amplitude is different

4.4 Summary

The theory relating to the IHCP highlighted that it could not be used to detect the unwanted adhered layer. However, the theory behind the periodic heated solid in terms of temperature readings and distance from the periodic source may be able to detect the unwanted adhered layer. Furthermore, some equations were explored to determine the theoretical maximum distance that the periodic heat source observations could detect the unwanted adhered layer. The main variables in determining the maximum distance were cycle time and reduction of temperature amplitude at the surface of the periodic heat source.
Chapter 5

Methodology
5.1 Overview

This chapter outlines the methodology employed to detect an unwanted adhered layer on a HPDC die surface based upon thermocouple reading(s). It was noted in Chapter 3 that the locations of thermocouples in HPDC dies were selected in most cases for 'convenience rather than for utility' (Doehler, 1951, p.148) and there was a reluctance to put thermocouples into the HPDC die because of its complex and expensive nature (Niu et. al., 2003). Therefore, the purpose of this research, was to use the thermocouple to detect the unwanted adhered layer on the die surface and, importantly, to determine the maximum distance that a thermocouple could sensibly detect the unwanted adhered layer.

The method that was employed was based upon the development of an experimental rig in which to simulate an HPDC die. This was designed to allow the location of the unwanted adhered layer to be varied relative to the thermocouple position(s). Thus, some of the variables associated with the unwanted adhered layer could then be varied (i.e., width, thickness and time of occurrence). Subsequently, some of the variables in the HPDC process and die (i.e., HPDC cycle times and cooling channels) could be evaluated in terms of their ability to affect the detection of the unwanted adhered layer.

Hence, the basic approach was to control specific variables in terms of the unwanted adhered layer and die and then evaluate these against the detection distance from that layer. The maximum distance that the thermocouple(s) could detect an unwanted adhered layer could then be investigated.

There were two analysis methods that were compared in terms of their ability to detect the unwanted adhered layer based upon thermocouple reading(s). These were:

(i) Specific temperatures and times within a temperature profile of a HPDC cycle

The specific temperatures at specific times with a HPDC cycle were obtained from the literature investigating the reasons why an unwanted layer formed on the surface of a HPDC die. The authors suggested that the temperature at specific
times within the HPDC cycle (e.g., if the lubricant temperature exceeded its maximum application working range), could cause the unwanted layer to form and/or grow. The specific temperatures and times within a temperature profile used to detect the unwanted adhered layer will be discussed in Section 5.2.2.

(ii) Theory pertaining to measurement distance from a periodically heated surface.

The theory pertaining to the measurement readings, as a function of distance from a periodically heated surface was primarily obtained from Carslaw and Jaeger (1959). Two of the observations of the temperature readings when the distance from the periodically heated surface increased, were a decrease in the temperature amplitude (maximum temperature minus minimum temperature) and a phase lag of the periodic temperature curves. The background theory relating to how these observations could be used to detect the unwanted adhered layer was discussed in Chapter 4.

A discussion of the different techniques employed to control the unwanted adhered layer and the chosen technique of an experimental rig. The issues regarding the placement of thermocouples within the experimental die is also addressed, together with the experimental variables that were associated with the unwanted adhered layer and die.

5.2 Techniques to Control Unwanted Adhered Layers

5.2.1 Overview

There were three different methods that were pursued to investigate the adhered layer on the die surface: use of a HPDC machine; numerical simulation of the adhesion problem; and experimental investigation of the adhesion problem. These three different methods will be discussed in Sections 5.2.2 –5.2.4.
5.2.2 HPDC Machine

There were a few research organisations who had developed experimental HPDC dies to investigate the adhesion of an unwanted casting alloy layer to the die surface. These included:

- CSIRO Australia
- Cooperative Research Centre (CRC) for CAST metals manufacturing in Australia
- International Lead Zinc Research Organisation
- Ohio State University, in the USA
- North American Die Casting Association, in the USA.

The design of these HPDC dies was such as to accelerate the adhesion of the casting alloy to the HPDC die surface, in less shots than in typical HPDC production dies. The location of the adhered layer on the dies was one of the main considerations in their design.

There were only a few researchers that had placed thermocouples into the dies even though these particular dies were designed to investigate the specific adhesion problem and temperature was suspected to be a key factor in layer formation. Some of the researchers that had placed thermocouples into the core pins (where the adhesion layer was intended to form) included:

- Chen et. al., (1999b); and Chen and Jahedi (1998a & 1998b)
- Goodwin (1997)
- Argo et. al., (1997)

The information derived from these researchers was evaluated in Section 3.5.
Raw data from Fraser (2003) was obtained which is shown in Figure 5.1. The unwanted layer developed about 5 shots (Fraser 2003) as highlighted in Figure 5.1 and the HPDC trial die is shown in Figure 5.3. Figure 5.3 was designed to accelerate the inter-metallic adhesion affect of the casting alloy to the die surface. Figure 5.2 shows a slight reduction in temperature readings from the normal stable periodic temperature readings.

![Figure 5.1 – Temperature trend when an unwanted layer built up on a HPDC die surface (Fraser, 2003).](image1)

![Figure 5.2 – Temperature trend after 5 shots (Segment of Figure 5.1).](image2)
Some raw results when a thermocouple was embedded approximately 2mm from its surface into the die (shown in Figure 5.3) as shown in Figure 5.4 (Tang, 2003). Tang et. al., (2004b & 2004a) used the same HPDC die (shown in Figure 5.3), they observed that there was a build up of magnesium on the pin surface and removed but reforming as the experiment (Tang et. al., 2004a). Tsuchiya et. al., (1997) observed a similar occurrence whereby the unwanted adhered layer being removed and reforming as the HPDC process was conducted (as shown in Figure 2.9). Figure 5.1 and Figure 5.4 highlight that a HPDC die design could control the location of the unwanted layer on the surface but could not control all the parameters (i.e., the time that the unwanted layer occurred, or the geometry shape of the unwanted layer, refer to Figure 3.3).
Figure 5.4 – Temperature trends when a unwanted layer builds up on a HPDC die surface (Tang, 2003).

Therefore, it was surmised that the maximum and minimum temperatures of the HPDC cycle could be used to detect the unwanted adhered layer from these two types of trends when an unwanted layer occurs, as shown in Figure 5.1 and Figure 5.4.

In order to achieve meaningful outcomes, the unwanted layer had to be controlled more accurately than had been documented in the previous research work. There were two other possibilities for controlling the unwanted layer on a die surface with the objective of determining the maximum distance at which a thermocouple could achieve detection, and these were to undertake the investigation experimental or numerical (i.e., using a heat transfer mathematical model) simulations.

5.2.3 Numerical simulation of the HPDC process and the unwanted adhered layer

All the boundary conditions need to be specified to numerically simulate the HPDC process. Past numerical simulations from other researchers did not highlight the heat transfer boundary conditions when an unwanted adhered layer was present, and the thermal properties of the inter-metallic adhered layer had not been presented in the literature from experimental work. Some work had highlighted the heat transfer boundary conditions for normal HPDC process through the inverse heat transfer method.
as detailed in Section 3.3 and 4.3. This section highlighted that for each unknown parameter a thermocouple was required to solve it but only a few researchers placed thermocouples into the die when the unwanted adhered layer was forming. However, as highlighted in Figure 3.3 and Figure 5.4 the unwanted adhered layer could change in shape as the HPDC process is continued. Thus, these parameters would need to be controlled for the heat transfer boundary conditions to be evaluated when the unwanted adhered layer was forming. The heat transfer boundary conditions would have been required in order to simulate the unwanted adhered layer in the HPDC process. Additionally, some of the control aspects of the unwanted adhered layer were not realised (i.e., time of occurrence and geometrical shape of the unwanted adhered layer). These issues would have made it difficult to undertake numerical simulation.

5.2.4 Experimental simulation of the HPDC process and the unwanted adhered layer

There were numerous researchers who had analysed the HPDC process in different ways and a summary of the general experimental equipment that researchers typically used to replicate the HPDC process is shown in Table 5-1. The first three experimental equipment in Table 5-1 was used to understand the adhesion of the casting alloy to the die surface. However, as highlighted in Chapter 2, there were many factors in the HPDC process, which could be affected within a cycle and/or from cycle to cycle. Therefore, one of the benefits of using experimental equipment was the ability to simplify and control key elements that were being investigated, although, a disadvantage was that the adhesion layer could develop as a result of many factors and/or variables within the HPDC process. The issue then related to the validity of the experimental set up in terms of its representation of the real process and this will be discussed in Sections 5.5 and 5.7.
Table 5-1 – Summary of other experimental methods/equipment used to simulate the HPDC process

<table>
<thead>
<tr>
<th>Experimental replication of HPDC process</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipping of die steel into molten casting alloy for extended periods</td>
<td>Gopal et. al., (2000); Fraser et. al., (1997); Chen et. al., (1999b); and Persson et. al., (2001)</td>
</tr>
<tr>
<td>Dipping of die steel into molten casting alloy for similar time of HPDC process</td>
<td>Wang (1999); Mitterer et. al., (2000); and Joshi et. al., (2003).</td>
</tr>
<tr>
<td>Rotating of die steel in molten casting alloy</td>
<td>Chellapilla et. al., (1997); Shankar and Apelian (1999 &amp; 2002); and Lakare et. al., (1999)</td>
</tr>
<tr>
<td>Die steel inserted into a furnace</td>
<td>Hu et. al., (2003)</td>
</tr>
<tr>
<td>Heating the die surface with infrared heater(s)</td>
<td>Clark et. al., (2000)</td>
</tr>
</tbody>
</table>

5.2.5 Summary

Researchers had designed dies that could control the approximate location of the unwanted adhered layer on the surface but only a few researchers included thermocouples in the controlled locations of the adhered layer (i.e., core pins). However, raw data was obtained from one research organisation that placed a thermocouple into the core pin, showing a change in the temperature trend as the unwanted adhered layer had developed. Despite this, the HPDC die design could not control all of the unwanted adhered layer parameters (i.e., the time that the unwanted layer occurred, or the geometry shape of the unwanted layer).

Numerical simulation of the HPDC process had been common but little evidence pertaining to the unwanted adhesion problem existed. As a result of this investigation, it was determined that, the most expedient method would be to the construction of experimental equipment (i.e., an experimental rig). This would be used to simulate the thermal behaviour of the HPDC die and enable greater control of the unwanted layer to investigation the sensitivity of detection, as a function of distance away from layer build up.
5.3 Experimental rig

There was a large design scope for the experimental rig but the basic restrictions were safety, cost, practicability and adaptability. These factors had to be traded against the different attributes needed to simulate the key elements of the HPDC process, which included the ability to:

- Generate a periodic heat source on a die surface
- Generate an artificial layer on the die surface.

Given these constraints and requirements, numerous possibilities for the design of an experimental rig were available and some of the different rigs used by other researchers were considered in its construction (refer to Table 5-1). From these experimental rigs, a comparison of ideas for the experimental rig is shown in Table 5-2.
### Table 5-2 – A comparison of some of the ideas that were developed for this investigation for the different requirements

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</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Periodic heating</td>
<td>Moving the die block</td>
<td>Depending on how large the die block was, it could be unsafe due to its mass</td>
<td>Periodic heating</td>
<td>Moving the die block</td>
<td>Depending on how large the die block was, it could be unsafe due to its mass</td>
<td>Periodic heating</td>
<td>Moving the die block</td>
<td>Depending on how large the die block was, it could be unsafe due to its mass</td>
<td>Periodic heating</td>
<td>Moving the die block</td>
<td>Depending on how large the die block was, it could be unsafe due to its mass</td>
<td>Periodic heating</td>
<td>Moving the die block</td>
<td>Depending on how large the die block was, it could be unsafe due to its mass</td>
<td>Periodic heating</td>
<td>Moving the die block</td>
</tr>
<tr>
<td>1.2</td>
<td>Move the heat source</td>
<td>Would have to restrict the access to the moving components and heat source</td>
<td>Would have to restrict the access to the moving components and heat source</td>
<td>Move the heat source</td>
<td>Would have to restrict the access to the moving components and heat source</td>
<td>Would have to restrict the access to the moving components and heat source</td>
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<td>Would have to restrict the access to the moving components and heat source</td>
<td>Would have to restrict the access to the moving components and heat source</td>
<td>Move the heat source</td>
<td>Would have to restrict the access to the moving components and heat source</td>
</tr>
<tr>
<td>1.3</td>
<td>Restrict the heat source (i.e., place an object in front of the heat source like Clark et al., 2000, experimental apparatus)</td>
<td>Depending on the heat source, safety and its weight</td>
<td>Depending on the heat source, safety and its weight</td>
<td>Restrict the heat source (i.e., place an object in front of the heat source like Clark et al., 2000, experimental apparatus)</td>
<td>Depending on the heat source, safety and its weight</td>
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<td>Restrict the heat source (i.e., place an object in front of the heat source like Clark et al., 2000, experimental apparatus)</td>
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<td>Restrict the heat source (i.e., place an object in front of the heat source like Clark et al., 2000, experimental apparatus)</td>
<td>Depending on the heat source, safety and its weight</td>
<td>Depending on the heat source, safety and its weight</td>
<td>Restrict the heat source (i.e., place an object in front of the heat source like Clark et al., 2000, experimental apparatus)</td>
<td>Depending on the heat source, safety and its weight</td>
<td>Depending on the heat source, safety and its weight</td>
<td>Depending on the heat source, safety and its weight</td>
</tr>
<tr>
<td>1.4</td>
<td>Turn on and off the heat source</td>
<td>Ok, but depends on the heat source and how much control and heating capacity</td>
<td>Ok, but depends on the heat source and how much control and heating capacity</td>
<td>Turn on and off the heat source</td>
<td>Ok, but depends on the heat source and how much control and heating capacity</td>
<td>Ok, but depends on the heat source and how much control and heating capacity</td>
<td>Turn on and off the heat source</td>
<td>Ok, but depends on the heat source and how much control and heating capacity</td>
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<td>Turn on and off the heat source</td>
<td>Ok, but depends on the heat source and how much control and heating capacity</td>
</tr>
</tbody>
</table>

**Chapter 5 – Methodology**
<table>
<thead>
<tr>
<th>Element</th>
<th>Safety</th>
<th>Cost</th>
<th>Adaptability</th>
<th>Practicality</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 Die design</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.1 Full commercial die</td>
<td>OK</td>
<td>Depends on the complexity and size of the die</td>
<td>May not be adapted and modified</td>
<td>Very practical</td>
</tr>
<tr>
<td>3.2 Simulate a segment of the full commercial die</td>
<td>OK</td>
<td>Depends on the complexity and size of the die</td>
<td>May not be adapted and modified</td>
<td>Very practical</td>
</tr>
<tr>
<td>3.3 Basic block</td>
<td>OK</td>
<td>Depends on how basic the design was</td>
<td>May be adapted and modified</td>
<td>Depends on how basic the design was</td>
</tr>
<tr>
<td>3.4 Dimensional analysis</td>
<td>OK</td>
<td>Depends on the complexity and size of the die</td>
<td>May not be adapted and modified</td>
<td>Very practical</td>
</tr>
<tr>
<td>4 Cooling channels which depend on the die design</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.1 Fountain (spot)</td>
<td>OK</td>
<td>Depends on how basic the design was</td>
<td>May be adapted and modified</td>
<td>Depends on how basic the design was</td>
</tr>
<tr>
<td>4.2 Cascade</td>
<td>OK</td>
<td>Depends on the complexity and size of the die</td>
<td>May not be adapted and modified</td>
<td>Depends on how basic the design was</td>
</tr>
<tr>
<td>4.3 Combination of both</td>
<td>OK</td>
<td>Depends on the complexity and size of the die</td>
<td>May not be adapted and modified</td>
<td>Depends on how basic the design was</td>
</tr>
<tr>
<td>5 Other</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.1 Spray cooling</td>
<td>Fairly safe, but have to restrict the area</td>
<td>Running costs could be quite expensive depending on the number of experiments and the die geometry</td>
<td>Not sure if it could be adapted and modified</td>
<td>May not be that practical if an artificial layer was to be placed between the heat source and the die block. Could make it dangerous</td>
</tr>
<tr>
<td>5.2 Lubrication</td>
<td>Fairly safe, but have to restrict the area</td>
<td>Running costs could be quite expensive depending on the number of experiments and the die geometry</td>
<td>Not sure if it could be adapted and modified</td>
<td>May not be that practical if an artificial layer was to be placed between the heat source and the die block. Could make it dangerous</td>
</tr>
</tbody>
</table>
The final design chosen from these requirements consisted of a die and a movable heat source so that an unwanted layer could be placed between the heat source and the die. This is shown schematically in Figure 5.5 and the actual rig is shown in photographic detail in Figure 1.6. With some modifications, the final heat source was derived from five large gas flame nozzles - molten metal could not be used because it was a safety risk and an infra-red heating element had to be embedded into the die to have an equivalent amount of heat to molten metal.

![Diagram](image)

**Figure 5.5 – Schematic Diagram of Test Rig**

There has been significant study into the heat transfer between impinging gas jets and solid surfaces and Martin (1977) summaries previous researchers' work in this area. Some of the interesting outcomes were:

a. Lateral profile of the heat transfer coefficient distribution on the impinging solid surface, as shown in Figure 5.6. The suggested reason why the second peak occurs in the local heat transfer coefficient is due to the turbulent nature of the jets and they were 'ascribed to a transition from laminar to turbulent boundary layers' (Gardon and Akfirat, 1966, p. 104).

b. The intensity of turbulent in the impinging jet impacted the lateral variation of heat transfer coefficient distribution on the impinged solid surface (Gardon and Akfirat, 1965).
c. Multiple nozzles impacted the heat transfer coefficient distribution on the impinging solid surface, as shown in Figure 5.7 and Figure 5.8. The impinging flow from multiple nozzles include a secondary stagnation zone due to the ‘wall jets of adjacent nozzles impinge upon each other’ (Martin, 1977, p.12). These secondary stagnation zones were shown as secondary peaks in the lateral heat transfer coefficient as seen in Figure 5.7 and Figure 5.8.

d. Martin (1977) highlighted that comparison between three researchers work did generally agree but that ‘larger discrepancies occur in the stagnation zone probably due to the different turbulence levels at the nozzle exit’ (Martin, 1977, p.11).

Figure 5.6 – Lateral variation of local heat transfer coefficient for a single jet
(abstracted from Gardon and Akfirat, 1965, p. 1269)
Figure 5.7 – Lateral variation of local heat transfer coefficient for a two jets
(abstracted from Gardon and Akfirat, 1966, p. 104)

Figure 5.8 – Lateral variation of local heat transfer coefficient for a three jets
(abstracted from Gardon and Akfirat, 1966, p. 104)
Even though, the local heat transfer coefficient was not constant for gas flames impinging on the solid surface, Hatamura et. al., (1989) and Papai and Mobley (1991) had demonstrated from their results that the local heat input into a HPDC die surface from the molten metal was not constant for positions of the die surface.

The heat input into the HPDC die from injection of molten metal to dies opening (refer to Figure 1.1), according to Papai and Mobley (1991) ranged from approximately 750 to 330 kW/m² (from initial die surface temperature from 200 to 400°C, for a 10 second die closed time), whereas, Hatamura et. al., (1989) calculated the “heat from molten metal to die”, which ranged from approximately 2 to 5 MW/m² (for an approximately 5 second die closed time). Papai and Mobley (1991) was used to design the gas burner layout, position and type of gas burner nozzles, which were designed, built and tested by a company specialising in gas burner design.

The movable heat source was controlled to mimic the heating and cooling of the HPDC process. The shape of the die was a rectangular block with a single cooling channel in it, as shown in Figure 5.9. In the HPDC industry this cooling channel type was also know as a fountain or spot cooling channel type as highlighted in Figure 2.4. Insulation was used around the majority of the die block to prevent heat losses – this would better reflect a HPDC die which had a large thermal mass.
Thermocouples were embedded into the die block (refer to Section 5.4 for more details) and the inlet and outlet of the cooling channel. This enabled the temperature readings to be taken so the detection of the unwanted adhered layer could be analysed from the temperature readings. The thermocouples were connected to a commercial data acquisition (Personal Daq/56) system, which was directly connected to a personal computer via a Universal Serial Bus (USB) connection. A “pDaqView 1.9” software package was included with the commercial data acquisition that enabled the raw temperature readings to be converted directly to final temperature readings with the cold-junction compensation for the different thermocouple types. The temperature readings were not averaged but within the software the ‘continuous calibration’ function was used because it was recommend for ‘applications that make use of very long acquisition periods’ and ‘provides greater reading accuracy’ but ‘it can result in a lowering of the maximum scan rate’ (IOTech Inc., 2001). All the thermocouples were automatically saved to a file and they could be seen on the computer monitor (both as a single reading or graphically, i.e., temperature versus time). The file type included the date, time and temperatures of all the thermocouples within it.
A summary of the key elements in the final experimental rig is shown in Table 5-3. The actual experimental rig was constructed mainly by the Aluminium HPDC personnel at the Ford Motor Company of Australia and some of its suppliers. This reduced the total cost and enabled some expert information into the experimental rig design and construction.

Table 5-3- Experimental Rig Specifications

<table>
<thead>
<tr>
<th>Heat Source</th>
<th>100-300 kW/m²</th>
</tr>
</thead>
</table>
| Cooling Sources | Internal: Fountain cooling channel – water at flow rate 3L/min at 20°C  
                     External: Natural air cooling (burner away from die block) |
| Die Block | Steel W302 equivalent to H13 but not heat treated, with dimensions (20×17×3.5) cm³. |
| Insulation | Die block was insulated to reduce heat losses. |
| Logic Controller | PLC to control moving the heat source from the die periodically, similar to cycles in HPDC. |
| Rodless Cylinder | To move the burner and spray gun using compressed air |
| Thermocouples | 1 mm, K-type and sheathed to avoid burn out, positioned 3 mm from the heated die surface, 15 mm apart. |
| Data Acquisition | A commercial system, sampling at 1 Hz |

5.4 Placement of the thermocouples in the die block

One of the critical components to the investigation was the placement of the thermocouples within the die. The general heat transfer throughout the die had to be determined so that the positioning of the thermocouples could be achieved. Therefore, some preliminary experiments were conducted and the general heat transfer was separated into the 3 geometric axes of the die block (i.e., height, width and depth).

The heat transfer throughout the height of the experimental die was obtained through the placement of five thermocouples along the height of the experimental die block. The positions of the five thermocouples in the insert, which was used to hold the
thermocouples in it, can be seen in Figure 5.10. For the heat transfer throughout the width of the experimental die, 2 thermocouples were placed on each of the sides of the experimental die. Their locations are shown in Figure 5.11. The determination of the heat transfer along the depth of the experimental die was through the placement of eight thermocouples on the bottom of the experimental die. The results of these preliminary experiments can be seen in Figure 5.12 to Figure 5.14.

![Thermocouple insert used in the die block to determine the heat flow](image_url)

*Figure 5.10 – Thermocouple insert used in the die block to determine the heat flow*
Figure 5.11 – Location of thermocouple positions and thermocouple insert within the die block

The preliminary experiments highlighted that the heat transfer was not symmetrical about the cooling channel (width, refer to Figure 5.14 and Figure 5.15) or the centre plan (height, refer to Figure 5.12 and Figure 5.13) of the die but these things could also have occurred in a practical HPDC die. As highlighted in Chapter 2, the HPDC die was designed such that the gating section was last to solidify, and so directional solidification occurred throughout the die. It was expected that the heat transfer was symmetrical about the cooling channel but due to the gas burner moving to one side, it continued to heat the air beside the experimental die arrangement, thus keeping this side hotter.
Figure 5.12 – Comparison of the mean temperature for cross section of the experimental die block

Figure 5.13 – Temperature versus time for a cross section of the experimental die block for one cycle
Figure 5.14 – Comparison of the mean temperature for the right and left side of the experimental die block

Figure 5.15 - Temperature versus time for the right and left side of the experimental die block for one cycle

In the literature, the closest distance that the thermocouples were from the die surface in a commercial HPDC die with real time control system was approximately 3 mm (Bishenden and Bhola, 1999). Therefore, in this research, the thermocouples were mounted 3 mm from the periodically heated surface as Bishenden and Bhola (1999) had
done. The final spacing between the six thermocouples was 15mm. This would allow coverage of half the die block with thermocouples and enabled various aspects of the HPDC die to be simulated (i.e., the section from the casting shape to the edge of the die, and the affects of a cooling channel). The final location of the thermocouple positions can be seen in Figure 5.16.

Figure 5.16 - Schematic drawing of the thermocouple positions (mm) in the die block in relation to the cooling channel and heated surface

5.5 Comparison of experimental rig to HPDC die data

Once all the components of the experimental rig were assembled, it was necessary to determine the suitability of the rig in terms of representing the unwanted adhered layer problem as occurring in a practical HPDC process. This was achieved via a comparison of temperature readings, derived from thermocouples in the die on the rig, with those derived from commercial HPDC dies at approximately the same distance from the heat input surface. This required thermocouples and a data acquisition system to convert the thermocouple output readings to temperature readings over time. A comparison of the temperature versus time for a typical HPDC dies and the experimental rig die block are shown in Figure 5.17 to Figure 5.20.
Figure 5.17 – Temperature versus time (temperature profile) graph from a thermocouple (segment from Figure 5.1)

Figure 5.18 – Temperature versus time (temperature profile) graph from a thermocouple that is 3mm from the die surface for one cycle in the experimental die with a 40 second cycle time
Figure 5.19 - Temperature versus time (temperature profile) graph from a thermocouple (segment from Figure 5.4)

Figure 5.20 - Temperature versus time (temperature profile) graph from a thermocouple that is 3mm from the die surface for one cycle in the experimental rig die with a 80 second cycle time

A few points of difference in terms of the comparison:

- The geometry of the two dies were not the same (refer to Figure 5.3 & Figure 5.9)
- The location of the thermocouples below the surface were not the same (HPDC at 1mm and the experimental rig die at 3mm)
- The cycle times were not the same (HPDC 90 & 50 seconds and experimental rig 80 & 40 seconds).

It was clear from the Figure 5.17 to Figure 5.20 that the temperature ranges were in fact quite far apart for the approximate power input into each die. One potential reason for the difference in temperature ranges was due to the large differences in resistance to the heat energy input of the two different dies. However, Mitterer et. al., (2000) conducted some experiments where they immersed their samples into aluminium alloy (AlSi7Mg) at 700°C; air pressure cooled them, and from their results they appeared to have preheated the samples. Their results from a temperature measurement about 0.2 mm below the surface highlighted that the temperature range could not be achieved with the dipping tests (refer to Figure 5.21).

![Temperature trend diagram](image)

**Figure 5.21** – *Results from dipping samples into molten aluminium and air cooling them (abstracted from Mitterer et. al., 2000, p.236)*

Despite the fact that the HPDC and experimental rig temperature ranges were not the same, the graphs show the same general temperature pattern for the cycle. Further
discussion and comparison of the adhered layer to the HPDC die surface and the simulated effects with the experimental rig are in Section 5.7. The experimental rig had the advantage that it presented a more difficult case for detecting changes than the HPDC die because of the reduced temperature and amplitude. In other words, if a technique worked on the rig then it was more likely to work on the HPDC die. This was because the temperature and amplitude reduced exponentially in heat conduction with a periodic heat source on the surface, thus, small variations would be more difficult to determine (refer to Section 3.4 and 4.3).

5.6 Design of experiments to determine the maximum distance from the unwanted layer

The experiments would be conducted by first establishing a periodically stable temperature within the die and then creating an artificial layer between the heat source and the die surface. The artificial layer had to replicate the layer formation on the HPDC die surface but not affect the quality of the surface so that consistent experiments could be conducted. There were two artificial layers that were chosen after some tests which were insulation firebrick (JM-28) and mild steel (grade 250). The geometric size of the artificial layer was restricted to the distance between the gas flame nozzles and the die block (i.e., thickness of the artificial layer). The maximum distance that the artificial layer thickness could have been was 35 mm. The thermocouples were placed along the same plane within the die to make the artificial layer the same height as the die block (refer to Figure 5.22). Therefore, the experiments could be described as a two dimensional problem. Preliminary experiments were conducted with the insulation firebrick to determine an appropriate artificial layer width for the experiments. These preliminary experiments started with a width one half the die block, thus covering all the thermocouple positions. The artificial layer at room temperature was placed on the die surface using tongs. Then the width of the artificial layer was approximately halved until an appropriate width of 12.5 mm or less was determined. The detailed temperature reading results of these preliminary experiments can be seen in Appendix D. A comparison of the unwanted adhered layer and the artificial layer is discussed in Section 5.7.
Once the width of the artificial layer was determined then the locations of the artificial layer were varied with each experiment in order to measure the effects that this movement had on the temperature readings. Specific locations of the centre of the artificial layer were determined so that the 12.5mm width would eventually cover one half of the die block once all the positions were completed (i.e., 9 locations in total). Thus, the centre spacings for the artificial layer were 12.5mm. The thickness and spread of the unwanted adhered layer were mentioned in Chapter 3 to vary over the HPDC process so the artificial layer's width and thickness will be two experimental variables. The different HPDC alloys were highlighted in Section 5.2.2, as shown in Figure 5.1 and Figure 5.4 to have different temperature trends so different types of artificial layer material will represent these two different temperature trends. Finally, in Section 4.3, one of the possible detection ways through data representation was shown to be influenced by the cycle time. Therefore, all of these variables were highlighted as the main variables to consider in analysing the possible detection methods for the artificial layer. The variables for the experiments were: artificial layer width, thickness and...
material type with the final variable being cycle time. A summary of the different parameters undertaken in the experiments is shown in Table 5-4. For each experimental set the artificial layer was positioned in the 9 specified positions.

Table 5-4—Summary of the designed experiments to be conducted

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<th>Artificial Layer Material</th>
<th>Insulation Firebrick</th>
<th>Mild Steel</th>
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<td>Thickness Width</td>
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<tr>
<td>10 mm 12.5 mm</td>
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5.7 Comparison of the unwanted adhered layer and the artificial layer

There were two different temperature trends that were obtained from thermocouples just beneath the die surface when the unwanted adhered layer occurred on a HPDC die, as shown in Figure 5.1 and Figure 5.4. The latter shows a clear trend in that the maximum periodic temperature decreases when unwanted adhered layer occurs, whereas, in Figure 5.1 there was a slight increase in the minimum periodic temperature. Therefore, for these two different trends there would be two different artificial layer materials to replicate those unwanted adhered layer trends as can be seen in Figure 5.23 and Figure 5.24. The artificial insulation layer material represented what had occurred when magnesium alloys unwanted adhered layer to a HPDC die surface (compare HPDC die as in Figure 5.4 to experimental rig as in Figure 5.24), whereas, the steel artificial layer material is an approximate representation of what had occurred when aluminium alloys unwanted adhered layer to a HPDC die surface (compare HPDC die as in Figure 5.1 to experimental rig as in Figure 5.23). Despite the fact that the steel artificial layer material did behave a little differently to aluminium alloy unwanted adhered layer in that the maximum periodic temperature also decreased. This was mostly due to the difference between the unwanted adhered layer effect on the HPDC
die and the experimental rig’s die were the unwanted adhered layer only affected the heat extraction from the die whereas, the steel block affected the heat input as well as the heat extraction.

Figure 5.23 – Simulated temperature versus time graph for steel artificial layer

Figure 5.24 - Simulated temperature versus time graph for insulation artificial layer
5.8 Summary

The method that was employed to conduct this research program was based upon the development of an experimental rig in which to simulate an HPDC die. This was designed to allow the location of the unwanted adhered layer to be varied relative to the thermocouple position(s). Thus, some of the variables associated with the unwanted adhered layer could then be varied (i.e., width, thickness and time of occurrence). Subsequently, some of the variables in the HPDC process and die (i.e., HPDC cycle times and cooling channels) could be evaluated in terms of their ability to affect the detection of the unwanted adhered layer.

Hence, the basic approach was to control specific variables in terms of the unwanted adhered layer and die and then evaluate these against the detection distance from that layer. The maximum distance that the thermocouple(s) could detect an unwanted adhered layer could then be investigated.

There were two analysis methods that were compared in terms of their ability to detect the unwanted adhered layer based upon thermocouple reading(s). These were:

(iii) Specific temperatures and times within a temperature profile of a HPDC cycle

(iv) Theory pertaining to measurement distance from a periodically heated surface.

A discussion of the different techniques employed to control the unwanted adhered layer and the chosen technique of an experimental rig. The issues regarding the placement of thermocouples within the experimental die is also addressed, together with the experimental variables that were associated with the unwanted adhered layer and die. Finally, all the experiments with all the variables are summarised in Table 5.5.
### Table 5.5 - Summary of all the experiments conducted

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<th>Experiment number</th>
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<th>Artificial layer material</th>
<th>Artificial layer width (millimeters)</th>
<th>Artificial layer thickness (millimeters)</th>
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<td>12</td>
<td>20</td>
<td>80</td>
</tr>
<tr>
<td>61</td>
<td>75</td>
<td>mild steel</td>
<td>12</td>
<td>20</td>
<td>80</td>
</tr>
<tr>
<td>62</td>
<td>67.5</td>
<td>mild steel</td>
<td>12</td>
<td>20</td>
<td>80</td>
</tr>
<tr>
<td>63</td>
<td>100</td>
<td>mild steel</td>
<td>12</td>
<td>20</td>
<td>80</td>
</tr>
<tr>
<td>64</td>
<td>112.5</td>
<td>insulation firebrick</td>
<td>12</td>
<td>20</td>
<td>80</td>
</tr>
<tr>
<td>65</td>
<td>125</td>
<td>insulation firebrick</td>
<td>12</td>
<td>20</td>
<td>80</td>
</tr>
<tr>
<td>66</td>
<td>137.5</td>
<td>insulation firebrick</td>
<td>12</td>
<td>20</td>
<td>80</td>
</tr>
<tr>
<td>67</td>
<td>150</td>
<td>insulation firebrick</td>
<td>12</td>
<td>20</td>
<td>80</td>
</tr>
<tr>
<td>68</td>
<td>194</td>
<td>insulation firebrick</td>
<td>12</td>
<td>20</td>
<td>80</td>
</tr>
</tbody>
</table>

*# for each experiment there were 6 thermocouple readings samples each second over the entire experiment

Note: each experiment undertaken ranged had approximately 100 cycles which ranged from approximately 2 to 3 hours*
Chapter 6

Experimental Results
6.1 Overview

Table 5.5, in the previous chapter, summarised all the experiments conducted together with their experimental number. A summary of the objectives of each data representation and a short outcome of the representation is shown in Table 6-1. The main experimental variables that were studied were: position of the artificial layer, width and thickness of the artificial layer, and the overall cycle time of the heating and cooling process. In the following sections (6.2 to 6.4) the experimental data representation shown in Table 6-1 are discussed in detail, to achieve the research objective as noted in Chapter 1.

Table 6-1 – A summary of the data representation methods undertaken together with the objectives and outcomes

<table>
<thead>
<tr>
<th>Method No.</th>
<th>Data representation</th>
<th>Objective</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Statistical measures of each periodic cycle for all the thermocouple positions over one experiment</td>
<td>To determine the possibility of analysing the data (i.e., maximum, minimum and mean temperature measures for each cycle) in order to determine the presence of the artificial layer</td>
<td>The data analysis changed from cycle to cycle over the experiment and the time of placement of the artificial layer could be observed.</td>
</tr>
<tr>
<td>2</td>
<td>Statistical measures of each periodic cycle for a thermocouple position as the artificial layer’s position changes</td>
<td>To identify possible patterns from data analysis that could be observed when the artificial layer position was changed.</td>
<td>No pattern was observed because of the experiment-to-experiment fluctuation. However, specific areas within the experiment were observed to compare data, to further progress the data representation.</td>
</tr>
<tr>
<td>3</td>
<td>Comparison of average statistical measures (with and without the artificial layer) as a function of the distance between the thermocouple and the artificial layer position for the two types of artificial layer material used (steel and insulation)</td>
<td>To reduce the cycle and experimental variation and to identify a pattern for the maximum distance that the artificial layer could be detected</td>
<td>The variations were reduced from Method Number 2 but no identifiable patterns could be identified.</td>
</tr>
<tr>
<td>4</td>
<td>Separating the ‘data representation’ Method Number 3 into the artificial layer position (i.e., effects of the artificial layer position)</td>
<td>To determine the effects of the artificial layer position on the maximum distance that the artificial layer could be detected</td>
<td>The expect trend was observed (i.e., the closer the artificial layer was to the thermocouple then more effect was observed and as the distance increase between them, then the effect reduces)</td>
</tr>
</tbody>
</table>
### Table 6-1 - Continued

<table>
<thead>
<tr>
<th>Method No.</th>
<th>Data representation</th>
<th>Objective</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Separating 'data representation' Method Number 3 into thermocouple locations (i.e., effects of the thermocouple positions)</td>
<td>To determine the effects of the thermocouple locations on the maximum distance that the artificial layer could be detected</td>
<td>A pattern was observed for the individual thermocouple locations but it was not repeatable</td>
</tr>
<tr>
<td>6</td>
<td>Separating 'data representation' Method Number 5 into thermocouple locations for each of the three thermocouple positions</td>
<td>To determine a pattern such that the maximum distance that the artificial layer could be detected</td>
<td>The pattern was affected by the gas burner positions which will be further discussed in Chapter 8.</td>
</tr>
<tr>
<td>7</td>
<td>Temperature amplitude measures of each periodic cycle for all the thermocouple locations for each of the three statistical measures</td>
<td>To analysis the data in terms of the temperature amplitude in determining the presence of the artificial layer</td>
<td>This method highlighted that a reduction in temperature amplitude occurred</td>
</tr>
<tr>
<td>8</td>
<td>Temperature amplitude of each periodic cycle for a thermocouple position as the artificial layer's position changes</td>
<td>To identify possible patterns from data analysis that could be observed when the artificial layer position was changed.</td>
<td>Experiment-to-experiment fluctuation occurred. However, specific areas within the experiment to compare data have been observed.</td>
</tr>
<tr>
<td>9</td>
<td>Comparison of average temperature amplitude measures as a function of the distance between the thermocouple and the artificial layer</td>
<td>To reduce the cycle and experimental variation and to identify a pattern for the maximum distance that the artificial layer could be detected</td>
<td>The same 'Outcome' as Method Number 4. Refer to Appendix H for this figure.</td>
</tr>
<tr>
<td>10</td>
<td>Separating the 'data representation' Method Number 9 into the artificial layer position (i.e., effects of the artificial layer position)</td>
<td>To determine the effects of the artificial layer position on the maximum distance that the artificial layer could be detected</td>
<td>A pattern formed where, most of the peak data, occurred when the distance to the thermocouple was minimum but it was not consistent across all the experiments</td>
</tr>
<tr>
<td>11</td>
<td>Separating 'data representation' Method Number 9 into thermocouple locations (i.e., effects of the thermocouple positions)</td>
<td>To determine the effects of the thermocouple locations on the maximum distance that the artificial layer could be detected</td>
<td>It was possible to identify a pattern to identify the approximate position of the artificial layer.</td>
</tr>
</tbody>
</table>

### 6.2 Temperature versus time for thermocouple positions over an experiment

The general trends of the temperature readings for the two artificial layers were compared against the unwanted layer for the two HPDC alloys in Section 5.7.

Chapter 3 highlighted some of the measures within a cycle that could determine the presence of an unwanted layer build up. This was further discussed in Chapter 5 which highlighted that some statistical measures that could be used to determine the...
presence of the artificial layer. These statistical measures were maximum, minimum and mean temperatures and so for each cycle these were calculated over the entire experiment. The total cycle times were either 40 or 80 seconds and entire experiment was between 2-3 hours. Each experiment started at atmospheric temperature which was approximately 20°C so that after each experiment the die block was cool down.

The result of the data representation (refer to Method Number 1 in Table 6-1) is shown in Figure 6.1. This figure shows that after the artificial layer was placed on the die surface that there was a reduction in statistical measures (mean, maximum and minimum temperatures) but eventually these statistical measures restabilised. Thus, the critical cycles to evaluate the effect of the artificial layer were the final cycles (i.e., approximately cycle 100). Figure 6.1 also shows the initial maximum temperatures for the experiment were not the same for each thermocouple position, which further highlighted the uneven heat distribution for the start of the experiment. It could be observed that the statistical measures (mean, maximum and minimum temperatures) changed from cycle-to-cycle over the experiment and the manual placement of the artificial layer on the die surface at approximately the 70th cycle.

![Figure 6.1 - Graphs of the statistical measures (mean, maximum and minimum temperatures) of each periodic cycle over an entire experiment](image-url)
Fluctuations observed in statistical measures (as shown in Figure 6.1) needed to be evaluated to determine whether or not they were repetitive from experiment-to-experiment. The statistical data for different artificial layer positions, as measured at a single thermocouple position (refer to Method Number 2 in Table 6-1, were graphed, as seen in Figure 6.2. This figure shows 6 artificial layer positions and the experimental variations occurred well before the placement of the artificial layer which meant that for each experiment other factors affected the measurements. Chapter 8 will highlight that variations from cycle-to-cycle were also present in the HPDC process. However, the accuracy of individual data from experiments was not the primary concern in this study as the main aim was to investigate whether it would be possible to identify trends which helped to reveal the existence of an anomaly, and how the greatest practical distance from the artificial layer could be determined.

![Figure 6.2](image_url)

*Figure 6.2 – Graphs of statistical measures (mean, maximum and minimum temperatures) of each periodic cycle for thermocouple position 90 as artificial layer position changes*
6.3 Comparison of the average statistical measures

Further progressing the statistical measures as discussed in Section 6.2, and to reduce the effect of cycle-to-cycle variations, an average of the statistical measures (maximum, minimum and mean temperatures of a cycle) over 5 consecutive cycles was taken. However, to reduce the experiment-to-experiment variations a comparison of the statistical measures within each experiment was calculated. Refer to Equation 6.1 for the comparison of the statistical measures with and without the artificial layer. The time frame for the comparison was just before the artificial layer was in place (i.e., approximately 70 cycles) and at just before the conclusion of the experiment (i.e., approximately 100 cycles). All the average statistical measures before and after the artificial layer was in place are in Appendix F (shown in Table F1 to Table F3, which are: the mean, maximum and minimum temperature respectively) for all the thermocouple positions and experiments.

\[ T_{\text{measure}} = \frac{1}{5} \sum_{i=D}^{n} \text{Measure}_i - \frac{1}{5} \sum_{k=S}^{m} \text{Measure}_k \] ... 6.1

where

- \( D = 6 \) cycles before the artificial layer was placed on the die surface
- \( S = 6 \) cycles before the experiment was stopped
- \( n = D + 5 \)
- \( m = S + 5 \)

Measure = A, B or C (D is used in Section 6.4)

- A = mean temperature
- B = maximum temperature
- C = minimum temperature
- D = Temperature amplitude

An important consideration in this project was the calculation of the distance to the thermocouple from the artificial layer because one of the aims of the project was to
determine the maximum practical distance that a thermocouple could detect the artificial layer. In these experiments, the width of the artificial layer changed and so did its position along the die block surface, whereas, the position of the thermocouples within the die block did not change. Therefore, the algebraic distance between the centre of the artificial layer and the centre of the thermocouple, in the horizontal direction, was used as a measure, as shown in Figure 6.3.

![Distance to thermocouple](image)

**Figure 6.3 – Schematic diagram showing the definition of measure used from the thermocouple to the artificial layer**

A comparison between the statistical measure of the data (as calculated in Equation 6.1) for the two different artificial layer types (steel and insulation) was plotted against the distance between the artificial layer and the thermocouple position (as shown in Figure 6.3). The heat to the experimental die block will be masked near the artificial layer position so when the artificial layer is positioned over the thermocouple then the maximum effect on the temperature measure will occur. The decrease from maximum to minimum effect on temperature measure was expected to gradually change but the exact trend will be revealed through this chapter.

The comparisons in the statistical measure (i.e., $T_{\text{measure}}$) can be seen in Figure 6.4 to Figure 6.9. The graphs for the steel artificial layer were experiment numbers 28-36 & 55-63 and for the insulation artificial layer were experiment numbers 1-27, 37-54 & 64-68. The expected trend was not present (refer to Method Number 3 in Table 6-1 in Chapter 6 – Results.
effect on the temperature measures could be found in the data for further analysis so a reduction in the data in terms of the experimental parameters was undertaken.

Figure 6.4 – $T_{\text{mean}}$ temperature versus distance to thermocouple position for steel artificial layer type

Figure 6.5 – $T_{\text{minimum}}$ temperature versus distance to thermocouple position for steel artificial layer type
Figure 6.6 - $T_{\text{maximum}}$ temperature versus distance to thermocouple position for steel artificial layer type

Figure 6.7 - $T_{\text{mean}}$ temperature versus distance to thermocouple position for insulation artificial layer type
Figure 6.8 - \( T_{\text{maximum}} \) temperature versus distance to thermocouple position for insulation artificial layer type

Figure 6.9 - \( T_{\text{minimum}} \) temperature versus distance to thermocouple position for insulation artificial layer type
6.3.1 Plots of statistical measures versus distance to thermocouple position as the artificial layer position is changed

The $T_{\text{measure}}$ values from one experiment were graphed against the artificial distance to the thermocouple position (refer to Figure 6.3) as highlighted in Method Number 4 in Table 6-1. Then additional experiments were graphed that had the same experimental variables except for the position of the artificial layer (i.e., the experimental data sets that were combined were 1-9, 10-18, 19-27, 28-36, 37-45, 46-54, 55-63). Some of the results can be seen in Figure 6.10 to Figure 6.12. The expected trend is observed in Figure 6.10 and Figure 6.11 (except for experiment numbers 5 & 7) but the expected trend was not consistent in Figure 6.12. However, the observations from Figure 6.10 to Figure 6.12 are interesting, in that, when the distance from the thermocouple position was around zero, there was a range in values. For example, when the distance to the thermocouple position was close to zero the change in average maximum temperature ranged from approximately 30 to 5 (refer to Figure 6.11), the change in average minimum temperature ranged from approximately 10 to -5 (refer to Figure 6.12), and the change in average mean temperature ranged from approximately 18 to -3 (Figure 6.10) for experiment number 10-18. Therefore, the representation of the data in individual experiments could highlight that, in general, the expected trend was observed in practice and that some effect of the artificial layer had occurred. However, this range in statistical measures, when the distance from the thermocouple position was around zero, and the trend from maximum to minimum $T_{\text{measure}}$, will be further investigated through graphs of individual thermocouple positions.
Large variation in change in temperature values when the artificial layer was near a thermocouple position.

**Figure 6.10** - $T_{\text{mean}}$ temperature versus distance to thermocouple position as the artificial layer position is changed

Large variation in change in temperature values when the artificial layer was near a thermocouple position.

**Figure 6.11** - $T_{\text{maximum}}$ temperature versus distance to thermocouple position as the artificial layer position is changed
Figure 6.12 - T_{minimum} temperature versus distance to thermocouple position as the artificial layer position is changed

6.3.2 Statistical measures versus distance to thermocouple position for individual thermocouple locations

The graphs of T_{measure} versus the artificial layer position for an individual thermocouple position can be seen in Figure 6.13 to Figure 6.15 as highlighted in Table 6-1, Method Number 5. The representation of the data from the individual statistical measures versus distance to thermocouple position for individual thermocouple locations did not represent the expected trend (from maximum to minimum effect on the T_{measure} as the artificial layer moves away from the thermocouple position, see start of Section 6.3) for all the thermocouple positions. Refer to Appendix E for all the other thermocouple positions except thermocouple position 60 mm (Figures E1 to Figure E15). Also, the trends from the different thermocouple positions were not consistent with one another (compare Figures E1 to Figure E4; Figure E6 to Figure E9; and Figure E12 to Figure E14 in Appendix E). The comparisons for the different experimental parameters are shown in Figure 6.13 to Figure 6.15 and the variable parameters are:
i). Width: Compare experiment numbers 1-9 and 10-18 as the artificial layer width went from 12mm to 6mm.

ii). Thickness: Compare experiment numbers 1-9 and 19-27 as the artificial layer thickness went from 20mm to 10mm.

iii). Material: Compare experiment numbers 1-9 and 28-36 as the artificial layer material was changed from insulation firebrick to mild steel.

iv). Total cycle time: Total cycle time changed from 40 seconds to 80 seconds, refer to experiment numbers 1-9 and 37-45.

Figure 6.13 – Comparison of the experimental variables for the $T_{\text{mean}}$ temperature measurement located at thermocouple position 60mm
Therefore, to further investigate why the $T_{\text{meas}}$ trends were different for individual thermocouple locations, all the $T_{\text{meas}}$ were graphed together (for the same experiments) for the individual thermocouple locations against the distance from the thermocouple position, which can be seen in Figure 6.16 to Figure 6.18. As highlighted in Table 6-1, Method Number 6. The representation of the data in the form of maximum, minimum and mean temperatures could not produce a meaningful pattern.
and will be further discussed in Chapter 8. Thus, further analysis of the data represented by the maximum, minimum and mean temperatures will not continue.

Figure 6.16 – Comparison of the data for the different temperature measurements at thermocouple location 90mm for experiments numbers 1-9

Figure 6.17 – Comparison of the data for the different temperature measurements at thermocouple location 60mm for experiments numbers 1-9
6.4 Data represented in terms of temperature amplitude

The temperature amplitude was the other data representation that was highlighted in Chapters 3 and 4. Therefore, for each cycle the temperature amplitude (maximum cycle temperature minus minimum cycle temperature) were calculated for all cycles over the entire experiment. The result of the data representation could be seen in Figure 6.19 and Figure 6.20, as highlighted in Table 6-1, Method Number 7. Some general observations from these graphs were:

1. The temperature amplitudes for the different thermocouple positions were not the same, which was expected as highlighted in Section 5.5. The temperature amplitudes ranged from approximately 30 to 45 °C.
2. Normally after artificial layer was placed along the die block surface, at least one thermocouple position had a reduction in temperature amplitude which could be used to highlight the presence of the artificial layer and quantified later in this section.
3. The cause of the ‘spike’ in temperature amplitude and the increase in ‘stable’ temperature amplitude after the artificial layer was placed on the die surface was not known and further research into these phenomenon would be required to determine the cause, which was not critical to this investigation and so this will not be further discussed.
4. The increase in 'stable' temperature amplitude after the artificial layer was placed on the die surface will be further discussed in Chapter 8.

Figure 6.19 – Highlighting two trends in temperature amplitude after the placement of the artificial layer

Figure 6.20 – Temperature amplitude representation highlights an increase in values after the artificial layer placement
The variations from cycle-to-cycle were noticeable in Figure 6.19 and Figure 6.20 and further discussed in Chapter 8 but the variations from experiment-to-experiment, with respect to temperature amplitude, were not known. The temperature amplitude data for different artificial layer positions, but for a fixed thermocouple location were plotted (shown in Figure 6.21 and Figure 6.22). Figure 6.21 and Figure 6.22 highlights 6 artificial layer positions and shows variations from the start of the experiment as highlighted in Table 6-1, Method Number 8. With these variations in cycle-to-cycle and experiment-to-experiment, it could be observed that a decrease in temperature amplitude occurred in all thermocouple locations except thermocouple position 90mm (refer to Figure 6.21). This will be further discussed in Chapter 8. Therefore, Equation 6.1 was used to reduce the effect of cycle-to-cycle and experiment-to-experiment variations.

\[ \text{Figure 6.21} – \text{Comparison of temperature amplitude for each cycle for experiment numbers 55 to 60 for individual thermocouple positions 60 to 90} \]
Figure 6.22 - Comparison of temperature amplitude for each cycle for experiment numbers 55 to 60 for individual thermocouple positions 15 to 45

Temperature amplitude versus the artificial layer position for an individual thermocouple position with different experimental parameters can be seen in Figure 6.23 to Figure 6.25, as highlighted in Method Number 11 in Table 6-1. These graphs show a trend from high to low effect as the artificial layer distance increases away from the thermocouple position and further analysis will be conducted in Chapter 7. The analysis will be to determine the maximum practical distance that a thermocouple could be away from the artificial layer to detect it.
Figure 6.6 - Temperature amplitude measurement versus distance to the artificial layer at thermocouple location 90mm

Figure 6.7 - Temperature amplitude measurement versus distance to the artificial layer at thermocouple location 75mm

Figure 6.8 - Temperature amplitude measurement versus distance to the artificial layer at thermocouple location 60mm
Chapter 7

Analysis of Experimental Results
7.1 Overview

One of the aims of the project was to determine the maximum practical distance from the artificial layer where a thermocouple could detect the presence of an artificial layer. Thus, in this chapter, the experimental data analysis will be statistically compared to an equation (4.3) which was presented in Chapter 4. However, the form of the equation here is modified to take into consideration the different measurement parameters used. Finally, a comparison between the mathematical model and the experimental data analysis will be discussed.

7.2 Mathematical Model

The heat distribution within the experimental die block followed a conventional three-dimensional pattern. However, a simplified one-dimensional model will be used to relate the movement of the artificial layer along the experimental die surface. The one-dimensional model was presented in Chapter 4 and the theory related to the periodic heat source and temperature measurements from that periodic heat source was explored, as shown in Equations 4.3-4.5. Thus, if Equation 4.3 was rearranged, a linear relationship between the periodic temperature amplitude at the surface, and the temperature amplitude at a distance from the surface, could be developed which can be seen in Equation 7.1 and which is graphically represented in Figure 7.1.

\[
\ln \left( \frac{A_x}{A_0} \right) = -x \sqrt{\frac{\omega}{2\kappa}} = -x \sqrt{\frac{\pi}{T\kappa}}, \quad \ldots \ 7.1
\]

where \( T \) is the cycle time and \( \kappa \) is thermal diffusivity (defined in Chapter 4)

(the other variables were defined in Chapter 4)
Distance from periodic surface (m)

\[ \begin{align*}
\text{Distance from periodic surface (m)} & = 0.010, 0.020, 0.030, 0.040 \\
\end{align*} \]

\[ \begin{align*}
A_x/A_0 & \sim -0.5, 0.0, 0.02, 0.03, 0.04 \\
& \sim -1, -1.5, -2, -2.5, -3, -3.5, -4 \\
\end{align*} \]

**Figure 7.1 – Graphical representation of Equation 7.1**

However, Equation 7.1 was theoretical and did not include any experimental noise terms, so if experimental noise was added to Equation 7.1 yields:

\[
\ln \left( \frac{A_x}{A_0} \right) = -x \sqrt{\frac{\pi}{Tk}} + \ln \left( \frac{\text{Noise}}{A_0} \right) \quad \text{.... 7.2}
\]

If one of the terms in Equation 7.2 dominant, such as when:

\[
A_0 e^{-x \sqrt{\frac{\pi}{Tk}}} \gg \text{Noise}
\]

Then

\[
\ln \left( \frac{A_x}{A_0} \right) = -x \sqrt{\frac{\pi}{Tk}}
\]

Else, if the other term dominants, such as when:

\[
A_0 e^{-x \sqrt{\frac{\pi}{Tk}}} \ll \text{Noise}
\]

Then

\[
\ln \left( \frac{A_x}{A_0} \right) = \ln \left( \frac{\text{Noise}}{A_0} \right)
\]
Thus, if this dominant effect was true then Equation 7.2 would be the combination of both of these terms, as represented in Figure 7.2.

\[ \ln\left(\frac{A_x}{A_0}\right) = \ln\left(\frac{Noise}{A_0}\right) \]

Distance from periodic source (x)

Maximun detectable
distance from periodic
source

experimental noise

\[ x\sqrt{\frac{\pi}{T_K}} \]

theoretical

**Figure 7.2 – Graphical representation of the two dominating factors (theoretical and experimental noise)**

It was necessary then to determine how accurately the one-dimensional model reflected the experimental data. The validity of the general trend of the mathematical model, as represented in Figure 7.2, was determined through a comparison with the experimental data based upon the same cycle times (experiments 1-36 for the 40 second cycle time data and experiments 37-68 for the 80 second cycle time, as stipulated in Table 5.5). Equation 7.2 has three main variables namely cycle time, thermal diffusivity and experimental noise but did not include other variables such as artificial layer material, artificial layer width and thickness. However, the artificial layer variables were included in the same experimental data set because these variables were not separated in Equation 7.2. The experimental data all had the same thermal diffusivity because the thermal properties throughout the experimental die block were assumed constant for the experimental die block material and the temperature range for all the experiments (Refer to Chapter 4 and Figure 4.6). This will be further discussed in Section 7.3.

If the noise term in Equation 7.2 had not been present then other techniques could have been used to calculate the uncertainty in the thermocouple readings, such as the low fss method or the ISO guide (both described in Bentley, 1998). To test the
accuracy of the one-dimensional mathematical model relative to the experimental data, a regression analysis was performed which comprised of the combination of two linear equations for the two different cycle times (40 and 80 seconds) which were:

\[ y = a + bx \], for \( x \leq z \) \quad \text{and} \quad \ y = d \), for \( x \geq z \), \quad \ldots \ldots \ 7.3

where \( z \) is the intersection of the two linear equations.

The values of \( a \), \( b \) and \( d \) were determined from the regression analysis.

This type of regression analysis had been called 'piecewise linear regression' (Neter et al., 1990) or 'piecewise regression' (Eye and Schuster, 1998) which had the general formula (Eye and Schuster, 1998, p.278):

\[ Y = b_0 + b_1 X + b_2 (X - x_c)X_2 + \text{Residual} \], \quad \ldots \ldots \ 7.3a

where \( X \) is the predictor variable, and \( X_2 \) has the following conditions:

\[
\begin{align*}
\text{if } X > x_c & \quad X_2 = 1, \quad \text{else} \quad X_2 = 0
\end{align*}
\]

As highlighted by (Neter et al., 1990) the regression analysis just uses Equation 7.3a for the analysis. However, Equation 7.3a was modified to fulfil Equation 7.3 which was:

\[ y = (c + bx) ind + d \] \quad \ldots \ldots \ 7.3b

where \( ind = 1 \) for \( x \leq z \) \quad \& \quad \( ind = 0 \) for \( x < z \)

Determining the \( z \) term in Equation 7.3 will identify the maximum distance that a thermocouple could be from the artificial layer. The \( z \) term was known and specified in the examples used by Neter et al., (1990) and Eye and Schuster (1998). However, the \( z \) term needed to be determined. Therefore, a modified 'fixed-point iteration' by Burden and Faires (1997, p.58) was used to determine \( z \) term which is shown in Algorithm 7.1.
Algorithm 7.1 – Iteration procedure to determine z in Equation 7.3

AIM: To find a solution to z given an initial approximation x₁ from the discrete experimental data.

INPUT initial approximation x₁ from the discrete experimental data (xⱼ,yⱼ); maximum number of iterations N₀.

OUTPUT approximate solution z

Step 1 Set i = 1
Set zᵢ = x₁

Step 2 While i ≤ N₀ (N₀ < number of experimental data points)
Do Steps 3-6

Step 3 Set ind = 1 for xⱼ ≤ zᵢ & ind = 0 for xⱼ > zᵢ (Equation 7.3 b)
Compute piecewise regression analysis from Equation 7.3 b

\[ z = \frac{d-a}{b} \] (from Equation 7.3)

Step 4 If zᵢ = z or xᵢ has been used before in Equation 7.3 b

then

OUTPUT z (Procedure completed successfully)

STOP

Step 5 i = i + 1

Step 6 If z is an experimental xⱼ data value then
Set z = xᵢ
Set zᵢ = xᵢ (update zᵢ)

Else find closest value in the experimental xⱼ data to z
Set xᵢ = closest value in the experimental xⱼ data to z
Set zᵢ = xᵢ (update zᵢ)
Finally, a comparison was made of the gradient (derived from the regression analysis of the experimental data) with the theoretical gradient shown in Equation 7.2 (i.e., using Equation 7.1) for the two different cycle times. However, the experimental set up was three-dimensional and and the steady state analytical solution (in three dimensions) to a periodic point source that dissipates heat at a rate of \( \rho C_p e^{i\omega t} \) (Carslaw and Jaeger, 1959) is shown in Equation 7.4.

\[
T_{@(x,y,z)} = \frac{1}{4r \pi \kappa} \exp \left\{ -\frac{\omega}{2\kappa} \sqrt{r^2 + i\left( \omega t - \frac{\omega}{2\kappa} \right)} \right\}, \quad ...... 7.4
\]

where: \( r = \sqrt{(x-x')^2 + (y-y')^2 + (z-z')^2} \) and the periodic source is at \( x', y', z' \); \( \rho \) is density; \( C_p \) is specific heat; \( \omega \) is angular frequency; \( t \) is time; and \( i \) is the imaginary part of the harmonic.

Consider a point in the experimental block \((x,y,z)\) from the origin point, then 'r' would represent the direct distance to the origin, as in Equation 7.5.

\[
r = \sqrt{x^2 + y^2 + z^2} \quad ...... 7.5
\]

Representing \( x, y, z \) in simplified terms and to aid in the practical use of the equation would be to consider the heat to transfer in all directions in equal terms (i.e., \( x, x, x \)). Then, the result of Equation 7.5 would be Equation 7.6.

\[
r = \sqrt{3x} \quad ...... 7.6
\]

Now compare Equation 7.1 using Equation 7.6 with the amplitude of Equation 7.4 (refer to Equation 7.7), which are similar. It should be noted that the modified Equation 7.1 (using Equation 7.6) is not strictly a three-dimensional model.

\[
A_{@(x,y,z)} = \frac{1}{4r \pi \kappa} e^{-\frac{\omega}{2\kappa} r} \quad ...... 7.7
\]

Therefore, the simplified Equation 7.1, with Equation 7.5, will be used to compare the experimental data analysis results in determining a practical formula for the maximum distance that a thermocouple could be placed from the unwanted adhered layer.
7.3 Modification of theory to experimental set-up

The theory in Section 7.2 was related to calculating the temperature amplitude from a temperature probe that was a specific distance away from a known periodic source value for a one-dimensional solid as shown in Figure 7.3. For the experiment that was conducted, the artificial layer reduced the total heat input into the experimental die block through the heating and cooling of the artificial layer, as shown in Figure 7.4. Therefore, the effect of the artificial layer on the temperature amplitude at a specific distance from the artificial layer, as shown in Figure 7.4, is measured by the 'Mean temperature amplitude without artificial layer' \((A_0)\) minus 'Mean temperature amplitude with artificial layer at a distance \(r\) from the thermocouple' \((A_r)\), as shown in Figure 7.5.

\[
A_3 = A_0 e^{-\frac{x_3}{T_\lambda}} = A_1 e^{-\frac{(x_3-x_1)}{T_\lambda}} = A_2 e^{-\frac{(x_3-x_2)}{T_\lambda}}
\]

From Equation 4.3 (rearranged Equation 7.1)

*Figure 7.3 – Theoretical schematic of the decay in temperature amplitude as a function of distance from the periodic heat source.*
Figure 7.4 - Experimental set-up of the temperature amplitude decay as a function of distance from the artificial layer.

Figure 7.5 - Diagram highlighting the effect of the artificial layer on the original temperature amplitude
Chapter 6 highlighted that the most stable method for detecting the artificial layer was through the examination of temperature amplitudes (i.e., maximum cycle temperature minus minimum cycle temperature), with and without the artificial layer. However, as also highlighted in Chapter 6, the steady state temperature amplitudes before the artificial was placed at the thermocouple positions were different for the different thermocouple positions (refer to Figure 6.23 and Figure 6.24). Therefore, to compare the effect that the artificial layer had on the temperature amplitude for the different thermocouple positions, it was necessary to normalise the temperature amplitude readings, as shown in Equation 7.8.

\[
\frac{A_o - A_r}{A_o} = \ldots \ldots 7.8
\]

The experimental arrangement, as shown in Figure 7.4 had to be represented as described in the theory, as in Equation 7.2, in terms of the temperature amplitude. Then the impact of the artificial layer from the temperature amplitude on the steady periodic temperature amplitude should be as in Equation 7.9. However, this verification of the experimental results with the theoretical is only relevant when there is a change in temperature amplitude in a positive manner as described in Equation 7.10.

\[
\frac{A_o - A_r}{A_o} = e^{-\frac{\pi}{r \tau}} + \frac{\text{Noise}}{A_o} \ldots \ldots 7.9
\]

\[
A_o - A_r > 0 \ldots \ldots 7.10
\]

7.4 Comparison between mathematical model and experimental data

The data were separated into the two cycle times of 40 and 80 seconds. The experimental data used for the regression had to comply with Equation 7.10. Those experimental data values are shown in Figure 7.6 and Figure 7.7. Both Figure 7.6 and Figure 7.7 show the general theoretical trend as shown in Figure 7.2. The regression analysis for the intersection point \((z, \text{determined from Algorithm 7.1})\) for the two cycle times are shown in Table 7-1 and Table 7-2. Refer to Appendix G for an example of Algorithm 7.1. The iteration process could not be fully completed because the experimental values were discrete.
Figure 7.6 – Experimental data (with a 40 second cycle time) together with the general theoretical trend

Figure 7.7 – Experimental data (with a 80 second cycle time) together with the general theoretical trend
Table 7-1 – Summary output from the regression analysis for 80-second cycle time

The regression equation, for \( z_i = 0.0267 \) where \( z \approx 0.0261 \), is:

\[
y = -4.26 + (3.70 - 142x)\text{ind}, \quad \text{where ind was defined in Equation 7.3b}
\]

Analysis of Variance

<table>
<thead>
<tr>
<th>Source</th>
<th>Degrees of Freedom</th>
<th>Sum of Squares</th>
<th>Mean Squares</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>2</td>
<td>141.710</td>
<td>70.855</td>
<td>275.15</td>
<td>0.000</td>
</tr>
<tr>
<td>Residual Error</td>
<td>94</td>
<td>24.206</td>
<td>0.258</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>96</td>
<td>165.916</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Regression Statistics

- R Square: 85.4%
- Adjusted R Square: 85.1%
- Standard Error: 0.507456
- Observations: 94

Table 7-2 – Summary output from the regression analysis for 40-second cycle time

The regression equation, for \( z_i = 0.01726 \) where \( z \approx 0.0171 \) is:

\[
y = -3.54 + (3.58 - 209x)\text{ind}, \quad \text{where ind was defined in Equation 6.3b}
\]

Analysis of Variance

<table>
<thead>
<tr>
<th>Source</th>
<th>Degrees of Freedom</th>
<th>Sum of Squares</th>
<th>Mean Squares</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>2</td>
<td>136.118</td>
<td>68.059</td>
<td>321.81</td>
<td>0.000</td>
</tr>
<tr>
<td>Residual Error</td>
<td>91</td>
<td>19.245</td>
<td>0.211</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>93</td>
<td>155.364</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Regression Statistics

- R Square: 87.6%
- Adjusted R Square: 87.3%
- Standard Error: 0.459878
- Observations: 91

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The regression analysis in Table 7-1 and Table 7-2 includes an ANOVA table for the overall F-test together with a p-value. The p-value for the two cycle times of 40 and 80 seconds were both zero which is less than $\alpha = 0.05$ so some linear relationship exists between the amplitude parameter and the thermocouple distance from the artificial layer.

From the regression statistics in Table 7-1 and Table 7-2, the $R^2$ values of 0.876 (40 second cycle time) and 0.854 (80 second cycle time) together with the $R^2_{adj}$ values of 0.873 (40 second cycle time) and 0.851 (80 second cycle time) highlighted that the fit was adequate. From the regression equation the intersection of the two linear components of the regression equation are $(0.0171, -3.54)$ for a cycle time of 40 and $(0.0261, -4.26)$ for a cycle time of 80. The iteration process could not be fully completed because the experimental values were discrete.

A comparison between the theoretical gradient and the linear regression gradient (i.e., a theoretical and experimental comparison between the first component of the curve shown in Figure 7.2) is shown in Table 7-3. Equation 7.1 was used for the theoretical gradient and the $\kappa$ value used was $6 \times 10^{-6}$.

The relationship between the experimental value and the modified theoretical one-dimensional model (to have the effect in multiple-dimensional) were not the same for both cycle times (i.e., comparison between Equation 7.1 with Equation 7.5 and Experimental gradient in Table 7-3). The difference between these two values for the different cycle times could have been due to the error in regression analysis for the particular experimental data. However, a primary research object was to determine the maximum practical distance from the artificial layer where a thermocouple could detect the presence of an artificial layer. For this experimental set-up and data the maximum practical distances were approximately 0.017 and 0.026 meters for a 40 and 80 second cycle time respectively.
Table 7-3 – Comparison between the theoretical gradient and statistical experimental gradient

<table>
<thead>
<tr>
<th>Cycle time</th>
<th>Theoretical gradient $x$</th>
<th>Theoretical gradient $\sqrt{3}x$</th>
<th>Experimental gradient</th>
<th>Experimental gradient / theoretical gradient ($\sqrt{3}x$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 seconds</td>
<td>114.4</td>
<td>198.2</td>
<td>209</td>
<td>1.05</td>
</tr>
<tr>
<td>80 seconds</td>
<td>80.9</td>
<td>140.1</td>
<td>142</td>
<td>1.01</td>
</tr>
</tbody>
</table>

The results highlight that the theory pertaining to measurement distance from a periodically heated surface and not the specific temperature and times within a temperature profile of a cycle was the most stable data representation for all experimental variables. This data representation was compared statistically against a modified theoretical equation. The theoretical equation was modified to simplify the 3D effects (i.e., to increase its practical usage) and a noise function was added. The results for the statistical analysis highlight the modified theoretical equation could be used in practical situations to determine the range that a thermocouple could be used to detect the presence of an artificial layer on a die surface. The results also highlight that the artificial layer parameters of width, thickness and material type did not effect the limits at which a thermocouple could detect the presence of an artificial layer.
8.1 Overview

This chapter presents the discussion of the results obtained in this research program which will be related to and compared against previous researchers. This will be discussed, in Section 8.2, in terms of detecting the artificial layer (as analysed in Chapter 7) which will be related back to the detection of the unwanted adhered layer to the HPDC die surface.

8.2 Statistical measurements within a cycle

Chapter 3 highlighted that the HPDC die temperature could have been a factor in the development of the unwanted adhered layer. Therefore, the maximum, minimum and mean temperatures within a cycle were explored in Chapter 6 to detect the artificial layer. However, in Chapter 6 it was noted that, in terms of the experimental rig, the change in average temperature measures with and without the artificial layer were influenced by the gas burner locations. These results from previous researchers on the study on the heat transfer between impinging gas jets and solid surfaces could be observed in the experiments conducted (Refer to Section 5.3).

The turbulent nature of the heat transfer on the experiment die is shown in Figure 6.1 and Figure 6.21, whereby the temperature amplitude, and temperature measures fluctuated from cycle to cycle. The varying heat transfer distribution from the gas nozzles on the experimental die could affect the comparison measures from the change in average temperature measures with and without the artificial layer. Once a peak heat transfer coefficient region (i.e., gas burner position) was blocked through the placement of the artificial layer, then the peak heat transfer coefficient would have disrupted the temperature measures (mainly maximum and minimum temperatures) more than non-peak heat transfer coefficient regions. Thus, a greater decrease in temperature difference would occur between the average temperature measures with and without the artificial layer near blocking the gas burner locations, as shown in Figures 6.13 to Figure 6.18. Finally, the placement of the artificial layer affected the lateral heat transfer coefficient by increase the heat transfer coefficient near the artificial layer at specific positions on the experimental block namely through an increase in temperature amplitude after the placement of the artificial layer, as shown through an increase in temperature amplitude in Figure 6.20. Therefore, the statistical temperature measures could not be used to
detect the artificial layer in this experimental set up due to the irregularities caused by the gas burners.

**8.3 Fundamental theory of periodically heated solid surface**  
**Temperature amplitude reduction analysis**

The change in average temperature amplitude (maximum minus minimum temperature values in the temperature profile), with and without the artificial layer, was determined to be the most stable method, as shown in Chapter 6. As shown in Chapter 7, the maximum theoretical distance that the temperature amplitude analysis could detect the artificial layer was approximately 0.017 metres for a 40 second cycle time and 0.026 metres for an 80 second cycle time.

The change in temperature amplitude (in terms of changes in temperature profile gradients) could be observed in a HPDC process where the casting alloy adhered to the HPDC die surface as shown in Figure 8.1 and Figure 8.2. From the results obtained by these temperature versus time plots, when an unwanted layer built up, the change in temperature profile shape could be observed in both these plots (refer to Figure 8.1 and Figure 8.2). However, these results obtained were from a thermocouple below the HPDC die surface and, as mentioned in Chapter 5, the actual time at which the unwanted layer began to occur was not known exactly. As highlighted in Chapter 5, the HPDC die surface was observed before and after these experiments, which demonstrated the build up of the unwanted layer on the HPDC die surface as shown in Figure 5.4. This change in temperature amplitude (shown in Figure 8.2) was determined to occur in the HPDC process due to the change in gradient as the unwanted adhered layer was building (Tang 2004).
Figure 8.1 – The change in temperature profile shape s highlighting a possible development of the unwanted layer (segment from Figure 5.1)
Figure 8.2 - Temperature profiles highlighting the change in profile shape when an unwanted layer occurs (segment from Figure 5.3)
Temperature readings from a thermocouple that was located 1 mm from the die surface when an unwanted layer does not build up on the die surface were also obtained, as shown in Figure 8.3. The sequence of the temperature profiles were based on every odd numbered casting cycle when the HPDC die temperature was periodically stable. As shown in Figure 8.3, the temperature profiles were not exactly the same and did vary which was consistent with the experimental data shown in Chapter 6. Even though, there was temperature amplitude variation, Figure 8.3 highlights that the temperature amplitudes in HPDC die were consistence and the gradient did not change over time.

In conclusion, the theory pertaining to measurement distance from a periodically heated surface and not the specific temperatures and times with a temperature profile of a cycle was the most stable data representation to detect the presence of an unwanted artificial layer on the die surface.
Figure 8.3 – An example of an odd sequence of HPDC temperature profiles without unwanted layer build up for various times within the casting cycle. a) is from 0 to 40 seconds, b) is from 0 to 8 seconds (Dargusch 2003).
Chapter 9

Conclusion
9.1 Introduction

The research objectives of the research project were to:

a) Detect a localised unwanted adhered layer via changes in steady periodic die temperature readings near the die surface. The die temperature readings used were changes in maximum temperature, minimum temperature, mean temperature and temperature amplitude, with and without the unwanted layer.

b) Change a process parameter and unwanted adhered layer parameters to determine whether the die temperature readings would detect a localised unwanted adhered layer. The process parameter that was varied was cycle time and the unwanted adhered layer parameters that were varied were thickness, width and material.

c) Determine the most consistent method to detect an unwanted adhered layer, with the changes in process parameter and unwanted adhered layer parameters, when the distance from the die temperature readings position to the unwanted adhered layer position increases.

d) Determine the practical distance limits at which the steady periodic die temperature readings would detect the unwanted adhered layer position.

These objectives of the thesis were the first stage leading to a broader objective. The broader objective was to develop a temperature feedback system that could provide the basis for automated detection of anomalies on the die surface or for control system that could improve product quality. However, these objectives go further in the production environment because once the practical limitations of placement of temperature probes was known then the temperature probes could be strategically placed throughout the die to detect anomalies on the die surface.
9.2 Summary of Research Outcomes

The outcomes from the PhD program were:

(i) The localised unwanted adhered layer was detected from changes in steady periodic die temperature readings (i.e., maximum temperature, minimum temperature, mean temperature and temperature amplitude) near the die surface, when comparing changes with and without the unwanted layer. This was discussed in Chapter 5.

(ii) The localised unwanted adhered layer could be detected when the process parameter (i.e., cycle time) and unwanted adhered layer parameters (i.e., thickness) were changed from the die temperature readings (100% using temperature amplitude, as seen in Appendix H, and 100% using maximum temperature for the insulation artificial layer, as seen in Figure 6.8) when it was directly above the thermocouple (i.e., the distance to thermocouple was zero for Figure 6.4 to Figure 6.18 and Figure 6.23 to Figure 6.25).

(iii) Using temperature amplitude readings was the most consistent method to detect the unwanted adhered layer. This was highlighted in Chapters 6 & 7.

(iv) The practical distance limits at which the steady periodic die temperature readings (i.e., temperature amplitude) could detect the unwanted adhered layer position were approximately 0.017 and 0.026 meters for a 40 and 80 second cycle time respectively. The analysis was undertaken in Chapter 7.

9.3 Contributions from Research

It was perceived that a number of contributions of knowledge had been made to the field of HPDC. Specifically these were identified as follows:

(i) An extensive review of research in the field was completed which highlighted the process variables, and their interaction with one another in the pressure die casting process. Once the process variables were identified then the body of research in the area of process improvement was investigated so that directions for this Doctoral research could be determined.
(ii) The research identified and evaluated some of the parameters that were associated with unwanted layer build up on HPDC die surfaces which were unwanted layer thickness, width and material type.

(iii) The research identified and evaluated the process parameter of cycle time that was associated with the detection of the unwanted layer build up on the HPDC die surface.

(iv) A methodology that could compare different detection methods for the unwanted layer phenomenon when it was developed.

(v) It was determined that the possible detection methods noted by HPDC researchers relating to maximum temperature were not feasible for all processes and unwanted layer variables on the experimental apparatus used. This is discussed in Section 9.4.

(vi) The variables affecting the limitations to the maximum practical detection range for the unwanted layer on the surface were identified. The main variables that affected the detection range were cycle time, thermal material properties of the HPDC die and the noise component from the thermocouple readings.

(vii) The maximum practical detection range for the unwanted layer on the surface, based on positions of thermocouples and cycle time, were evaluated.

9.4 Research Limitations

The limitations of the research project were:

(i) The experiments were conducted on an experimental test rig with gas burner flames which affected the maximum, mean and minimum temperature detection method of the artificial layer.

(ii) Only a simplistic HPDC die geometry was analysed for the experiments conducted.
(iii) The unwanted layer was simulated by an artificial layer which had a fixed geometry and was at atmospheric temperature unlike the unwanted layer whose geometry could grow and the temperature was from the normal HPDC process.

(iv) The analysis of the artificial layer via the changes in temperature readings were at two different periodically steady states, which were steady state of the HPDC die and HPDC die with artificial layer, whereas, the unwanted layer might not occur in this manner.

(v) The cycle time for the experiments was consistent throughout the entire experiment (i.e., either 40 or 80 seconds). Whereas, in a HPDC production the cycle time could vary over the entire production time frame.

(vi) The position of the thermocouples were 3 mm from the periodically heated surface and the type (K-type) and thickness (1mm thick) were constant as well.

9.5 Further Research

9.5.1 Overview

There are some areas from this investigation that are recommended for further investigation. One of the items was the need for further analytical results for different shaped solids so that the influence of the shape of the solid could be determined. Some of the areas that need further investigation:

- Validation of results in several HPDC dies, in Section 9.5.2 which would address the limitations of (i) to (iv) in Section 9.4.

- Determining the strength of the noise term in Equation 7.2 for any thermocouple position to detect the adhered layer on the HPDC die surface, in Section 9.5.3 which would address the limitation of (vi) in Section 9.4.

- Determining the limits to the variation in cycle time, in Section 9.5.4, which would address the limitation of (v) in Section 9.4.
9.5.2 Validation of results in several HPDC dies

The results found in this research need to be validated in several HPDC dies with different casting materials, die geometry and cycle time. As highlighted in Chapter 5, the location of an unwanted layer could be approximately controlled but the time that the unwanted adhered layer was formed and the layer's growth could not be controlled. Therefore, a method to determine when the unwanted layer starts to form in the specified location to facilitate comparison of these results with those of other researchers needs to be made.

Alternatively, the change in temperature amplitude could be compared against the current manual method(s) to detect the unwanted layer to determine which technique is more reliable and which detects the unwanted layer at an earlier stage in the HPDC production.

9.5.3 Noise Term in Equation 7.2

The noise term used in Equation 7.2 was evaluated for the experiments conducted, and the thermocouple position from the periodic heating surface was constant at 3 mm. This noise term needs to be evaluated for the HPDC process for: different depths from a periodically heated surface; with different thermocouple types; and different thickness of thermocouples.

9.5.4 Variation in cycle time

If the cycle time does vary then a comparison of temperature amplitudes would be more difficult because for a slightly shorter cycle time, it is expected that a reduction in temperature amplitude will occur. On the other hand, with a slightly longer cycle time, the temperature amplitude increases (refer to Figure 8.4 & Figure 8.5). Therefore, the limits of cycle time variation need to be determined or a method that can consider the cycle time in the analysis as well as the amplitude. A method was highlighted in the literature review (Chapter 3) was the frequency spectrum analysis (Thomson, 1861; and Everett, 1861). As mentioned in the literature review, this method was first used in formulating some of the equations that relate the reduction in temperature amplitude and phase lag with the distance from a periodically heated solid at a surface (Thomson, 1861). Therefore, the limits of the cycle time variation need to be determined for the temperature amplitude to detect the unwanted adhered layer.
9.6 Expansion of concept to further applications

This research determined an alternative detection method (via thermocouples) for the detection of an unwanted adhered layer and the maximum practical distance that a thermocouple could be away from the unwanted adhered layer. The results from this investigation could be used in a number of different ways. These could be in a research or industry environment, whereby, automated systems could be developed to detect the presence of an unwanted layer on a HPDC die surface.

(i) Research environment

From a research point of view, no standard method has been developed to detect the presence of an unwanted layer on the die surface, monitoring and control was manual (Tsuchiya et. al., 1997; and Rogers et. al., 2003). Therefore, this research could be used to monitor the growth of an unwanted layer. For example, the results from this investigation could be utilised in the die or coating development through comparison via the initial time of occurrence and/or the growth of the unwanted layer.

(ii) Industrial environment

From an industrial point of view, the results could be used to develop an automated system in the HPDC process that detects the unwanted layer and informs the operator to clean the die surface or monitor the castings more closely. As highlighted in Section 3.2.6, an automated system could be used to remove the unwanted layer as it was formed. Therefore, the HPDC process could become more automated and possibly fully automated, which could reduce the costs of HPDC operations.

An alternative direction from this project is the use of this technique in other manufacturing process like semi-solid casting and squeeze casting (refer to Chapter 2).
Reference


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163


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Appendix A – List of Publications

Further and specific publications then highlighted in Chapter 1 are listed:

JOURNAL ARTICLE AND CONFERENCE PROCEEDING


CONTRIBUTIONS TO TEXT BOOKS ON PHD RELATED WORK


Appendix B – General Definitions of Casting

The general definitions of casting are provided for clarification of the High Pressure Die Casting (HPDC) process and its background (as discussed in Chapter 2) with respect to the other casting processes.

Metal Casting Category

The classifications in this section were primarily derived from the Anonymous (1997).

The metal casting process involved the placement of molten metal into a cavity or mould and allowing the solidification process to occur so the final cast component became the object whose shape was determined by the configuration of a cavity. There were two broad metal casting processes which were defined as:

- Ingot casting. This process involved the production of final castings (like bars, slabs or billets) which were further processed into the final component shape.

Casting to shape produced the majority of the final component shape but some further processes (such as machining) could still be required to produce the final component shape.

Ingot Casting

The ingot casting process could be separated into three process categories:

(i) *The Static cast ingot process* which involved molten metal being poured into a 'permanent mould' (one that could be reused) and removal from the die after the metal solidified.

(ii) *The Semicontinuous cast ingot process* which involved a permanent mould with a moving base so molten metal could be added on top of solidified metal, which moved down to make room for the molten metal. This addition of molten metal kept on
occurring until the final dimensions of the metal cast was achieved. Then, the casting was removed and the die base moved back to its original position.

(iii) \textit{The Continuous cast ingot process} which involved a similar method to semicontinuous cast ingot process but instead of the base stopping when the final dimensions of the casting was achieved, the output was cut off and removed, thus the process could remain \textquotedblleft continuous\textquotedblright.

\textbf{CASTING TO SHAPE}

The casting to shape process could be divided into five processes:

(i) \textit{Sand Casting}: this involved the use of sand and other materials to make the die for the molten metal to be poured into. The sand casting process had some other process names like shell, carbon dioxide, investment casting, ceramic moulding, and plaster moulding.

(ii) \textit{Gravity Die (or permanent mould or tilt) Casting}: this involved the use of metal to make the die. Therefore, a smooth cavity surface finish and dimensionally accurate die could be made for the molten metal to be poured into. Sometimes the die cavity was coated to increase die life by creating a thermal barrier between the die cavity and the cast metal. Some advantages of the gravity die casting process over sand casting were smoother surface finish, closer tolerances and higher production rates but the process mainly cast nonferrous alloys and cast iron.

(iii) \textit{Low Pressure Die Casting}: this process was similar to gravity die casting but the molten metal was forced into the die cavity at pressures ranging from 20-60 kilo pascals (kPa) (Campbell, 1993).

(iv) \textit{(High) Pressure Die Casting}: this was similar to the low pressure die casting process but the molten metal was forced into the die cavity at higher pressures. Production machines usually cast light metals, such as aluminium, and the typical pressure range was 40-120 MPa (Barresi \textit{et. al.}, 1996). Some of the advantages of the

\textit{Appendix B – General Definitions of Casting}
high pressure die casting process were high production rates, high quality and strength but the process mainly cast low melting point alloys.

(v) *Centrifugal Casting:* this involved the rotation of the die so inertial forces could distribute the molten metal into the die cavity. There were three types of the centrifugal casting process, these being true centrifugal casting, semi-centrifugal casting, and centrifuging.
Appendix C – Data on Infrared Heaters

Data relating to infrared heaters is shown in Table C1 and Table C2 highlight that infrared heaters were not appropriate in terms of heat output for the experimental rig as discussed in Chapter 5. Figure C1 and Figure C2 are schematic diagrams of the different infrared heaters mentioned in Table C1 and Table C2.

![Figure C1 - Common electric-infrared heaters, abstracted from ASHRAE (2000, p.15.3)](image)

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Metal Sheath</th>
<th>Reflector Lamp</th>
<th>Quartz Tube</th>
<th>Quartz Lamp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative heat intensity</td>
<td>2.4 kW/m, 13 mm dia.</td>
<td>125-375 W/spot</td>
<td>3.0 kW/m, 13 mm dia.</td>
<td>3.9 kW/m, 9.5 mm dia.</td>
</tr>
<tr>
<td>Resistor temperature</td>
<td>950°C</td>
<td>2230°C</td>
<td>930°C</td>
<td>2230°C</td>
</tr>
<tr>
<td>In use temperature</td>
<td>840°C</td>
<td>275 to 300°C</td>
<td>650°C</td>
<td>590°C</td>
</tr>
<tr>
<td>Response time (heat up)</td>
<td>180 seconds</td>
<td>A few seconds</td>
<td>60 seconds</td>
<td>A few seconds</td>
</tr>
</tbody>
</table>

Table C1 – Characteristics of typical electric-infrared heaters, abstracted from ASHRAE (2000, p15.3)
**Figure C 2 – Common gas-infrared heaters, abstracted from ASHRAE (2000, p.15.2)**

<table>
<thead>
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<th>Characteristics</th>
<th>Indirect</th>
<th>Porous Matrix</th>
<th>Catalytic Oxidation</th>
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<tr>
<td>Operating temperature</td>
<td>To 650°C</td>
<td>870-980°C</td>
<td>340-370°C</td>
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<tr>
<td>Relative heat intensity</td>
<td>To 24 kW/m²</td>
<td>54-100 kW/m²</td>
<td>2.5-9.5 kW/m²</td>
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<td>Response time (heat up)</td>
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**Table C 2 - Characteristics of typical gas-infrared heaters, abstracted from ASHRAE (2000, p15.2)**
Appendix D – Preliminary Experimental Results

The preliminary experimental results as discussed in Chapter 5, highlight that the artificial layer could be observed 40 mm (width of artificial layer 50 mm, refer to Figure D2) and 20 mm (width of artificial layer 25 mm, refer to Figure D3) away from a thermocouple. Therefore, these artificial widths were not used in the experiments.

Figure D 1 – Artificial layer 100 mm wide and all thermocouples were reduced

Figure D 2 – Artificial layer 50 mm wide thermocouple position 90 was reduced
Figure D 3 – Artificial layer 25 mm wide and thermocouple position 45 was reduced
Appendix E – Statistical measures results for different thermocouple positions

Further experimental results (refer to Chapter 6) from the statistical measures are shown in Figure E1 to Figure E15 which highlight that there was no consistent pattern with the different thermocouple positions (compare Figures E1 to E4; Figure E6 to Figure E9; and Figure E12 to Figure E14 in Appendix E).

Figure E1 – Comparison of the experimental variables for the Tmean temperature measurement located at thermocouple position 90mm

Figure E2 – Comparison of the experimental variables for the Tmean temperature measurement located at thermocouple position 75mm
Figure E 3 – Comparison of the experimental variables for the Tmean temperature measurement located at thermocouple position 45mm

Figure E 4 – Comparison of the experimental variables for the Tmean temperature measurement located at thermocouple position 30mm

Appendix E – Statistical measures results for different thermocouple positions
Figure E 5 – Comparison of the experimental variables for the $T_{\text{mean}}$ temperature measurement located at thermocouple position 15mm

Figure E 6 – Comparison of the experimental variables for the $T_{\text{maximum}}$ temperature measurement located at thermocouple position 90mm
Figure E 7 – Comparison of the experimental variables for the Tmaximum temperature measurement located at thermocouple position 75mm

Figure E 8 – Comparison of the experimental variables for the Tmaximum temperature measurement located at thermocouple position 45mm

Appendix E – Statistical measures results for different thermocouple positions
Figure E 9 – Comparison of the experimental variables for the Tmaximum temperature measurement located at thermocouple position 30mm

Figure E 10 – Comparison of the experimental variables for the Tmaximum temperature measurement located at thermocouple position 15mm
Figure E 11 – Comparison of the experimental variables for the T_{minimum} temperature measurement located at thermocouple position 90mm

Figure E 12 – Comparison of the experimental variables for the T_{minimum} temperature measurement located at thermocouple position 75mm
Figure E 13 – Comparison of the experimental variables for the Tminimum temperature measurement located at thermocouple position 45mm

Figure E 14– Comparison of the experimental variables for the Tminimum temperature measurement located at thermocouple position 30mm
Figure E 15 – Comparison of the experimental variables for the T_{minimum} temperature measurement located at thermocouple position 15mm
### Appendix F - Data obtained from Equation 6.1

**Table F1 - Tabulated data for experiments 1 - 63, using Equation 6.1 with mean temperature used as the 'measure'**

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### Table F1 - Continued

|   | 37 | 38 | 39 | 40 | 41 | 42 | 43 | 44 | 45 | 46 | 47 | 48 | 49 | 50 | 51 | 52 | 53 | 54 | 55 | 56 | 57 | 58 | 59 | 60 | 61 | 62 | 63 |
|---|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
|   | 138.42 | 140.59 | 146.12 | 154.05 | 161.60 | 161.92 | 137.39 | 138.91 | 142.50 | 148.93 | 153.35 | 148.72 |
|   | 137.92 | 140.03 | 145.56 | 153.00 | 160.80 | 161.49 | 134.79 | 136.70 | 140.57 | 149.17 | 154.06 | 149.66 |
|   | 138.79 | 141.37 | 146.65 | 155.17 | 162.49 | 162.23 | 131.29 | 132.74 | 133.93 | 135.50 | 129.11 | 130.34 |
|   | 137.81 | 139.66 | 145.18 | 152.89 | 160.60 | 161.13 | 135.41 | 137.71 | 141.13 | 144.15 | 154.31 | 157.59 |
|   | 138.86 | 140.97 | 146.18 | 153.56 | 160.89 | 161.30 | 135.16 | 138.09 | 141.29 | 147.88 | 157.44 | 158.78 |
|   | 139.10 | 141.47 | 146.69 | 154.76 | 161.88 | 161.53 | 132.48 | 130.29 | 132.79 | 148.15 | 156.72 | 157.85 |
|   | 138.54 | 140.76 | 146.16 | 154.02 | 161.41 | 161.80 | 133.51 | 133.43 | 141.87 | 150.20 | 158.56 | 159.34 |
|   | 136.46 | 138.35 | 143.83 | 151.64 | 159.32 | 159.65 | 128.53 | 134.99 | 143.49 | 152.06 | 159.89 | 160.64 |
|   | 141.99 | 144.35 | 149.91 | 157.01 | 164.14 | 164.39 | 122.96 | 133.50 | 140.41 | 149.01 | 157.55 | 158.67 |
|   | 140.93 | 142.21 | 146.87 | 154.78 | 164.20 | 168.36 | 141.45 | 142.58 | 147.21 | 154.86 | 163.84 | 167.79 |
|   | 140.56 | 142.63 | 147.90 | 155.54 | 162.18 | 161.58 | 139.65 | 142.10 | 145.85 | 153.68 | 157.97 | 153.96 |
|   | 138.97 | 140.20 | 144.86 | 152.81 | 162.39 | 166.59 | 138.44 | 139.15 | 143.72 | 150.22 | 153.36 | 156.26 |
|   | 140.42 | 142.80 | 147.82 | 155.71 | 162.23 | 161.43 | 139.81 | 142.94 | 146.78 | 150.39 | 159.01 | 160.66 |
|   | 137.70 | 138.81 | 143.75 | 151.04 | 159.26 | 160.53 | 138.57 | 140.66 | 145.62 | 152.08 | 160.49 | 161.44 |
|   | 138.41 | 140.47 | 145.47 | 153.19 | 159.78 | 159.24 | 135.58 | 134.83 | 137.80 | 149.58 | 157.14 | 157.82 |
|   | 142.38 | 144.92 | 150.53 | 157.69 | 164.64 | 164.56 | 140.90 | 144.04 | 149.48 | 156.87 | 164.04 | 164.05 |
|   | 136.86 | 138.05 | 143.12 | 150.46 | 158.86 | 160.11 | 125.75 | 133.88 | 142.10 | 149.73 | 158.43 | 159.88 |
|   | 137.69 | 139.84 | 145.24 | 153.38 | 161.13 | 161.34 | 129.33 | 135.91 | 141.11 | 150.03 | 158.45 | 158.94 |
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|   | 143.22 | 145.25 | 150.74 | 158.81 | 167.26 | 169.06 | 143.01 | 145.60 | 151.71 | 161.23 | 170.66 | 180.45 |
|   | 142.03 | 143.80 | 149.32 | 156.88 | 165.49 | 168.71 | 138.85 | 140.83 | 144.67 | 148.79 | 151.40 | 147.36 |
|   | 144.42 | 146.40 | 151.77 | 159.58 | 168.24 | 170.35 | 146.99 | 151.21 | 159.64 | 178.37 | 179.33 | 178.75 |
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|   | 142.97 | 144.91 | 150.71 | 158.57 | 167.19 | 169.38 | 147.72 | 157.76 | 160.02 | 162.27 | 172.21 | 174.15 |
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|   | 144.04 | 145.91 | 151.44 | 159.58 | 167.97 | 169.77 | 151.05 | 151.06 | 155.68 | 162.85 | 170.80 | 172.56 |
|   | 143.50 | 145.38 | 150.52 | 158.40 | 167.08 | 169.40 | 138.41 | 144.88 | 149.26 | 157.06 | 165.81 | 167.97 |

Appendix F - Data obtained from Equation 6.1
### Table F2 - Tabulated data for experiments 1 - 63, using Equation 6.1 with maximum temperature used as the 'measure'

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**Table F2 - Continued**

Appendix F - Data obtained from Equation 6.1

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Appendix F - Data obtained from Equation 6.1
Appendix G – Example of Algorithm 7.1

**INPUT** initial approximation \(x_1 = 0.0182483\); maximum number of iterations 35 (number of different x values in the experimental data); experimental values \(x_j, y_j\) for the 40 second cycle time.

**OUTPUT** approximate solution \(z\)

Step 1  Set \(i = 1\)

Set \(z_1 = x_1 = 0.0182483\)

Step 2  While \(i \leq N_o = 35\)  \(\text{(Yes)}\)

Do Steps 3-6

Step 3  Set \(ind = 1\) for \(x_j \leq 0.0182483\) & \(ind = 0\) for \(x_j > 0.0182483\)

Compute piecewise regression analysis from Equation 7.3 \(b\)

\[
y = -3.53 + 3.58 \cdot ind - 211 \cdot ind \cdot x
\]

\[
z = \frac{d - a}{b} = \frac{-3.53 - 0.05}{-211} \approx 0.017 \quad \text{(from Equation 7.3)}
\]

Step 4  If \(z_1 = z\) \(\text{(No)}\) or \(x_i\) has been used before in Equation 7.3 \(b\) \(\text{(No)}\)

Step 5  \(i = i + 1 = 2\)

Step 6  If \(z = \) an experimental \(x_j\) data value \(\text{(No)}\)

Else find closest value in the experimental \(x_j\) data to \(z = 0.0172627\)

Set \(x_2 = \) closest value in the experimental \(x_j\) data to \(z = 0.0172627\)

Set \(z_2 = x_2 = 0.0172627\)

End of Iteration 1

Step 2  While \(i \leq N_o = 35\)  \(\text{(Yes)}\)

Do Steps 3-6

Step 3  Set \(ind = 1\) for \(x_j \leq 0.0172627\) & \(ind = 0\) for \(x_j > 0.0172627\)

Compute piecewise regression analysis from Equation 7.3 \(b\)

\[
y = -3.54 + 3.58 \cdot ind - 209 \cdot ind \cdot x
\]

\[
z = \frac{d - a}{b} = \frac{-3.53 - 0.05}{-209} \approx 0.017 \quad \text{(from Equation 7.3)}
\]
Step 4 If \( z_1 = z \) (No) \textit{or} \( x_i \) has been used before in Equation 7.3 \textit{b} (Yes)

then

\[
\text{OUTPUT } z = 0.017 \quad \text{(Procedure completed successfully)}
\]

STOP
Appendix H – Temperature Amplitude Results

Further experimental results in terms of measuring the temperature amplitude are shown in Figure H1. The method to obtain the chart was discussed in Chapter 6 which corresponds to 'Method Number'10 in Table 6.1. Figure H1 highlights that the temperature amplitude data representative could detect the artificial layer when the distance to the thermocouple was zero as discussed in Chapter 9.

Figure H1 – Temperature amplitude versus distance to thermocouple position for experiments 1 – 63