The Formulation of Process Variables for the Elimination of Defects in a Semi-Solid High Pressure Die Cast Component.

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Abstract

Semi-Solid Metal (SSM) forming has distinct advantages: strength, near net shape, thick and thin sections and a large scope of materials able to be cast. The aim of this project is to produce a near net shape component using SSM casting with A356 primary Semi Solid Aluminum feed stock from SAG. The selected Short Arm Component was identified as a suitable component for SSM forming, it is used as part of an insulated securing mechanism in overhead pylons, demands high strength and has relatively thick sections. A combination of full and short shot castings from the component and modular die were produced, on the real time shot controlled 62.5 ton high pressure die casting machine, at varying casting parameters of die temperature between 140-250°C, gate velocities of between 1.01-2.87ms^{-1} and a billet temperature of between 578-582°C. To understand fluid flow and locate possible defects, X-ray radiography and naked eye surface observations of the castings were used to locate possible defects and irregularities, which were cross sectioned and analysed using a Scanning Electron Microscope with an Energy Dispersion Spectroscopy module. It was apparent from the current project, as well as from literature, that increases in the die cross-sectional area reduce the shear surface area and increase the viscosity causing undesirable mould filling behaviour.

Table of Contents

List of Diagrams

List of Tables

Chapter 1 Introduction

Semi-Solid Metal (SSM) as the name suggests is metal which is not quite liquid and not quite solid. Under certain conditions metal can be cast in this semi-solid state to produce components that have high internal integrity. In order to accomplish this effectively, the metal's microstructure is modified during solidification to form spherical (globular) grains instead of the naturally forming dendritic microstructure, and may be directly cast (rheocasting) or may be formed into solid feedstock and then reheated and fed into a high pressure die casting machine. The spherical grains improve the fluidity of the SSM by more than an order of magnitude (compared to dendritic grains). The SSM fluid has many advantages over conventional liquid cast or solid forged metal: The semi solid metal may be formed into more complex shapes than conventional forged and cast metal; SSM High Pressure Die Casting displays laminar flow which reduces entrapped gas porosity; and, SSM is partly solidified, so solidification porosity is also reduced. Semi-solid metal forming does, however, also have some disadvantages: the raw material is more expensive and the casting process requires a high level of control and is susceptible to cold shuts, oxide entrapment and porosity defects. To overcome these disadvantages the component must have a high beneficial advantage gained from utilising the SSM process and the process parameters and equipment must be carefully designed and controlled to overcome the defects.

Manufacture of components through casting and forging techniques is a widely accepted and utilised process. This investigation will use the SSM High Pressure Die Casting (HPDC) manufacturing process to produce a high internal integrity component. Only certain components will benefit from, and thus are suitable for, production using the SSM HPDC manufacturing process. The investigation will develop a component selection method and use the method to confidently select a suitable component on which to base the investigation.

A methodical process will be developed to design and manufacture the die and select the machine to produce the component. The SSM HPDC process and die design is very different from conventional HPDC and as a result the investigation will determine the required gate location, geometry and cavity filling behaviour required to successfully produce a high internal integrity SSM HPDC component.

To produce high internal integrity components literature suggests specific fluid flow behaviour and requirements. These requirements and behaviour will be determined by the investigation. Specific solidification criteria must also be met to avoid solidification porosity. The investigation will develop a methodical method to ensure specific solidification behaviour takes place with in the casting during manufacture (casting).

In order to determine the process parameter settings and interactions the whole SSM HPDC system must be considered. The raw material, HPDC machine and the die (mould) process and design parameters must be investigated. To evaluate the raw material this investigation varies the temperature at which the material is cast, the material is from only one raw material supplier and is all from the same batch. The (shot controlled HPDC) machine parameters are evaluated by varying the injection velocity profile. The die design parameters are varied through physical modifications to the die guided by results that will be obtained from a modular die which will be developed to simplify the die cavity. The process parameters of the die are investigated through varying localised cooling of the die cavity surface. This is achieved through the use of cooling channels in specific areas of the die and varying the flow rate of the cooling fluid.

To evaluate the integrity of the components that are cast and to identify defect types and the reasons for their formation, X-ray radiography techniques will be used. The castings will also be evaluated using visual inspection, sectioning, relative density measurement, Scanning Electron Microscopy (SEM) and Electron Dispersive Spectroscopy (EDS) techniques. To evaluate the fluid flow, two dimensional models and castings whose die cavity filling will be interrupted at different percent cavity full values (short shots) will be used.

The approach taken will be to design a die and casting parameters for the selected component based on the recommendations of the Literature Survey. The first castings so produced are evaluated to identify and formulate possible root causes of any defects found. To fully understand the defects' root causes, the fluid flow will be simplified through breaking the component's geometry up into two dimensional planar models. A modular die will be manufactured to cast the different models by utilising removable inserts. The models will be cast and, through their evaluation, will allow for specific flow characteristics and behaviour to be understood. These conclusions will be carried into the formulation of the root causes of the defects. Solutions to the defect's root causes will be implemented onto the original component die.

Then the process parameters of the raw material, machine and die will be investigated. The investigation will optimise the process parameters to produce a high internal integrity component. To achieve this, the investigation will determine interactions between localised cooling of the surface of the die cavity, injection metal velocity and metal temperature. The investigation will determine these optimal process parameters using experimental procedures which enable the effects of the process parameters, which interact with each other and act on the system simultaneously, to be analysed. For this, the Taguchi Experimental method is used. The method is well known and practiced in industry, and will determine the optimum process parameters' level settings at which to run the process at during the manufacture of the component.

To aid the reader a brief summary of the salient objectives is included below in bullet form:

- Develop a component selection method and use the method to confidently select a suitable component on which to base the investigation.
- Developed a methodical process to
    - design and manufacture the die
    - select the correct machine to produce the component
- Develop a methodical method to ensure specific solidification behaviour takes place within the casting during manufacture (casting).
- Investigate the following with respect to part integrity
    - raw material
    - process parameter of both the HPDC machine and the die (mould)
    - die design parameters
- Evaluation of part integrity to identify defect types and the reasons for their formation
- Design a die and casting parameters based on the recommendations of the Literature Survey. Design a modular die to create two dimensional models.
- Use the results from evaluation of these dies' castings to implement changes to the component die
- Use Taguchi Experimental methods to determine optimal parameter values
- Produce high integrity casting in production environment using these process parameters

Chapter 2 Literature Survey

2.1 Introduction to Semi-Solid Metal Behaviour

Semi-Solid metal forming was first discovered by M.C. Flemings in the 1970's. The forming technique uses a "mushy" state of the metal to produce components with much less porosity and therefore higher internal integrity. In order to understand the merits and problems an in depth study of literature in the technique has been conducted.[33]

Semi-Solid Metal is metal which has been heated up to between the alloy's liquidus and solidus point. At this point part of the metal is liquid and part is solid. The amount of solid relative to the amount of liquid is known as the percentage solid or the fraction solid[1,24]. The temperature range through which the metal alloy displays Semi-Solid behaviour depends on the metallography of alloy. To determine the semi-solid range a phase diagram may be used. Diagram 2-1 shows the phase diagram of an Aluminium alloy with Silicon as the major alloying element. The semi-solid range is anywhere between the Liquidus line and Solidus line.

Diagram 2-1[16,22]: Phase Diagram of Aluminium Silicon Alloy

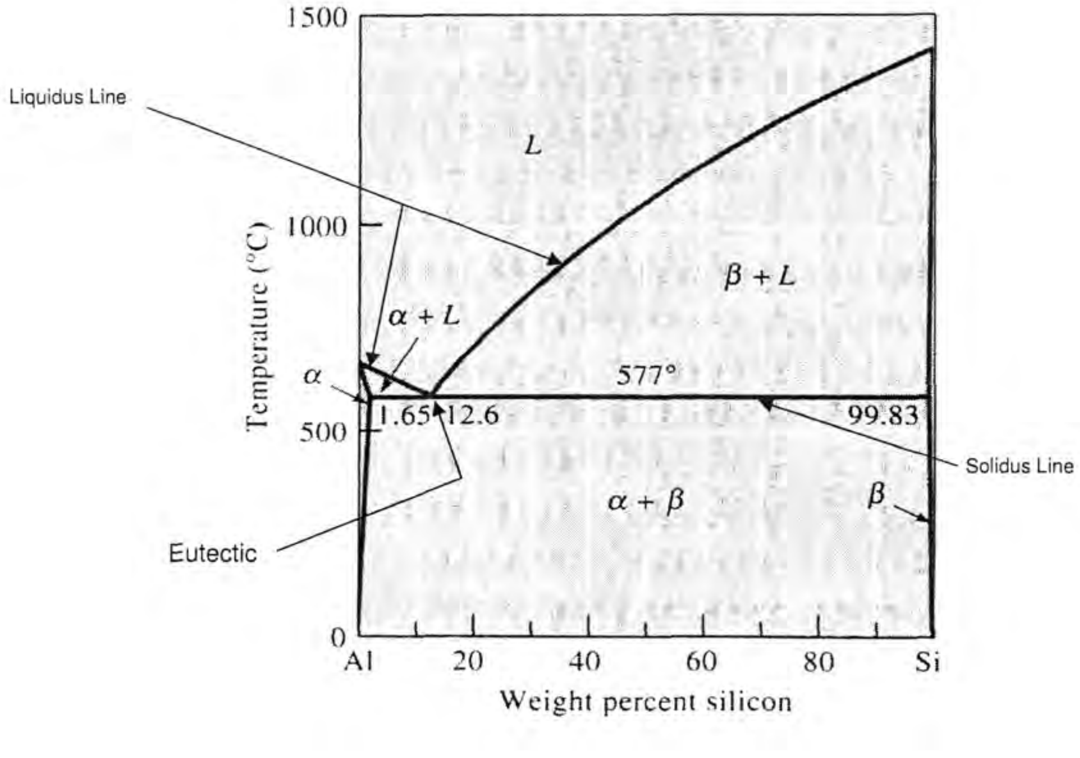


Diagram 2-2 shows the relationship between the fraction solid and the metal temperature in the Aluminium Silicon alloy, A356. The diagram demonstrates the sensitivity of the fraction solid of the metal at a specific temperature to alloy element concentration changes. In the diagram the weight percent Magnesium is shown at two levels, 0.3% and 0.4%. Both are within the specification of the alloy and yet each gives a different fraction solid at the same temperature. It is therefore important to highlight the need to use same feedstock of material when running experiments so as to be able to compare the results of each run of the experiment to each other with confidence.

Diagram 2-2[23] : Solid fraction vs Temp.

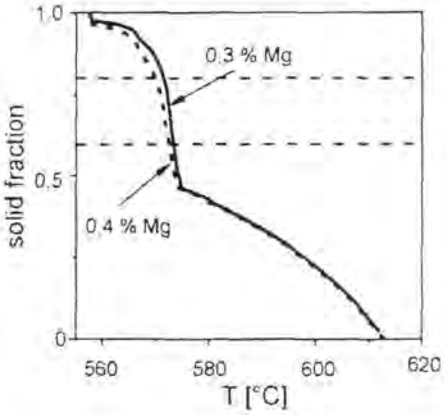
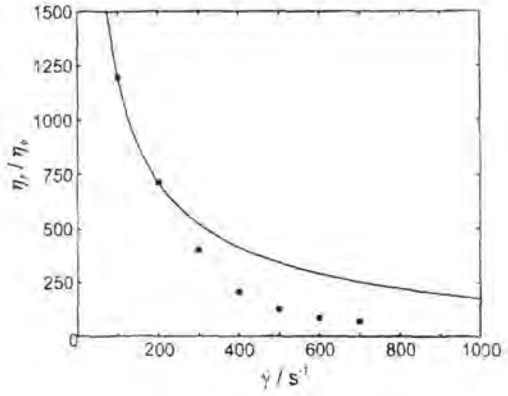


Diagram 2-3[24]: Viscosity vs Shear rate



Semi-Solid Metal forming requires a shear force in order to change the apparent viscosity of the metal and in this manner the metal may be induced to flow[24,1]. Apparent viscosity of an SSM is defined as the combination of three factors on the viscosity. The first factor is the viscosity of the liquid portion of the SSM, η_r. The second factor is the contribution to viscosity of the hydrodynamic drag on individual (non-interacting) particles due to their finite size. The third factor is the drag produced by particle agglomeration or deagglomeration. Diagram 2-3 is a plot of the relative viscosity, η_r/η_o versus the shear rate. The diagram is taken from a paper by Andrew M. Mullis on Particle Dynamic Simulation of Semi-Solid Metal Rheology[24] which uses a Brownian Dynamics model to predict the apparent viscosity η_r of a semi-solid fluid which has solid particles suspended in a liquid of viscosity η_r. The model's prediction is shown in the diagram as the solid line and the square markers are experimental data. The model and experimental data is for a Sn-15%Pb alloy at 0.45 fraction solid. The reason for the discrepancy between the model and the experimental data is due to the model not taking into account the many more solid-solid contacts between particles that occur at a higher fraction solid (the model was designed for fraction solids of below 0.4). Although the diagram and model are for an alloy of Sn-15% Pb it demonstrates the general behaviour of the viscosity of Semi-Solid Metal fluid for different shear rates. The behaviour displayed here is similar for the Aluminium alloy A356 that is used in this investigation.

An existing method to achieve a rate of shear stress on a fluid in order to form it into a specific shape is the High Pressure Die Casting (HPDC) process. It is not too difficult to adapt this process for Semi-Solid Metal Forming (SSMF). However many other forming techniques may also be used. In this investigation High Pressure Die Casting Process was used as the forming method. The decision to use this method was based on the ease and suitability of this method to produce high production volumes and the versatility of the method with respect to the produced component's geometry and multiple cavity die designs enabling more than one component to be produced at a time. Of equal importance is the method's ease of retrofitting a system to feed Semi-Solid Metal into the machine instead of the conventional liquid metal.

2.2 Introduction to High Pressure Die Casting Process

The process utilizes a machine which clamps the two die halves (moulds) together. The die halves are clamped onto two platens one of which is stationary and the other of moves. Diagram 2-4(a) shows a conventional manually ladled die casting machine. The parts of interest of the machine are labelled. The moving platen is called the "moving platen (A)" and the stationery platen is called the "fixed platen (B)". Subsequently the two halves of the die are named the "moving half (C)" and the "fixed half (D)". The machine also has an ejection mechanism which may be utilised to eject the part out of the die. The mechanism is located on the moving platen and so this platen is also referred to as the "ejector (moving) platen (A)" and the corresponding die half which is clamped to this platen is also referred to as the "ejector (moving) (C) die half". The die is a permanent die and is normally made of high strength heat treated tool steel.

The machine also has a hydraulic (some older generation machines used pneumatics) ram which is connected via a plunger rod to the plunger or the metal injection piston. The plunger fills the die cavity with metal under high pressure and at high speed. This is achieved by first filling metal, normally non-ferrous, into the shot sleeve and then the plunger is forced to travel through the shot sleeve in a specific manner to displace the metal out of the shot sleeve and into the die cavity so as to fill the cavity with metal and create a casting. There are two types of High Pressure Die Casting (HPDC) machines, Hot Chamber and Cold Chamber machines. In Hot Chamber machines the Shot sleeve is immersed a heated bath (furnace) containing metal and in Cold Chamber machines the sleeve is located in the air.

Diagram 2-4(a)[22]: Schematic of Conventional Cold Chamber High Pressure Die Casting Process

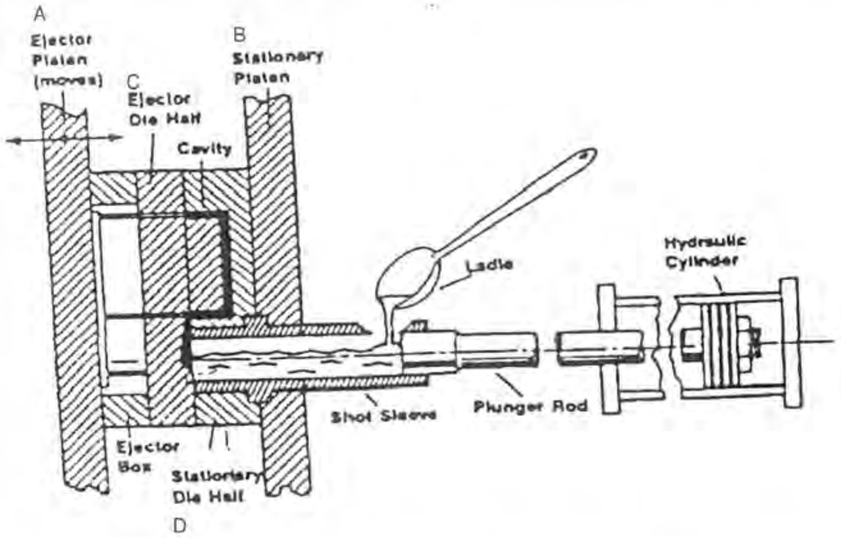
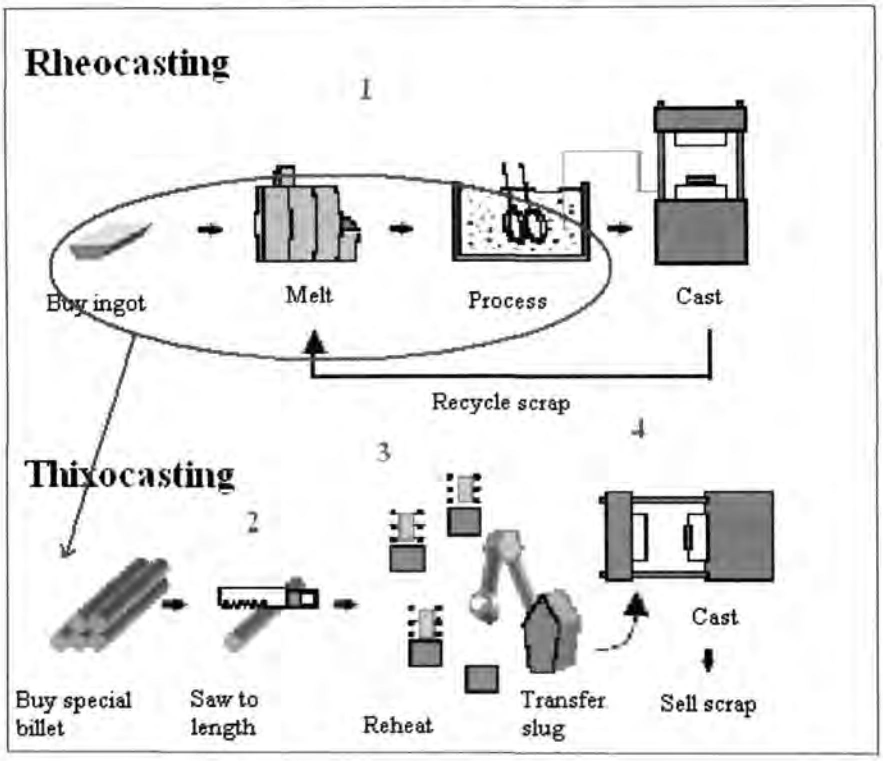


Diagram 2-4(b)[8]:Schematic of Rheocasting and Thixocasting



For the cold chamber machine, metal is ladled into the shot sleeve either manually or automatically by the use of a dosing furnace or an autoladle (an automatic/robotic ladling device). The Hot Chamber machines are not suitable for Aluminium die casting and as a result the cold chamber machine will be utilised and further discussed here.

The metal injection section of the machine is referred to as the shot end or the hydraulic shot end. A schematic of the process is shown in Diagram 2-4(a) and 2-5(a,b,c,d). The specific manner of injecting the metal into the die cavity normally consists of three stages[3,4].

- First stage
- Second stage
- Final Intensification

During the first stage the injection piston (plunger) moves forward at low velocity, less than $0.5ms^{-1}$ through the shot sleeve. This stage uses a low velocity for two main reasons. The first reason is to move the plunger forward enough so as to shut off the pouring hole of the sleeve (in diagram 2-5(a) this is where the ladle is pouring metal through into the shot sleeve). The second reason is to avoid mixing the metal and air in the shot sleeve by displacing the metal slowly until it reaches the runner or gate..

The next phase (second phase) is a high velocity stage where the plunger moves with high velocity to displace the metal into the cavity. The high velocity is necessary to fill the cavity of the die quickly enough so that the cavity is full before the metal has solidified.

After the casting cavity has been filled completely the machine applies high pressure to the metal via the plunger. This high pressure is necessary to feed solidification shrinkage [13,14, 15]. This is the final intensification (3rd) stage.

The biscuit is that part of the casting which is left in the shot sleeve. The runner is the passage way that connects the shot sleeve to the gate. The gate creates specific fluid dynamics to produce a successful casting[7,14,18,32]. The biscuit, runner and gate are not part of the final product. They constitute waste and must be dealt with after casting. First they need to be removed from the casting. To this end the gate plays an important role and is normally thin to aid in removal of the runner and biscuit section from the casting. Once removed the metal in the section must be recycled to reduce costs.

Diagram 2-5[13]: Schematic of the High Pressure Die Casting Procedure

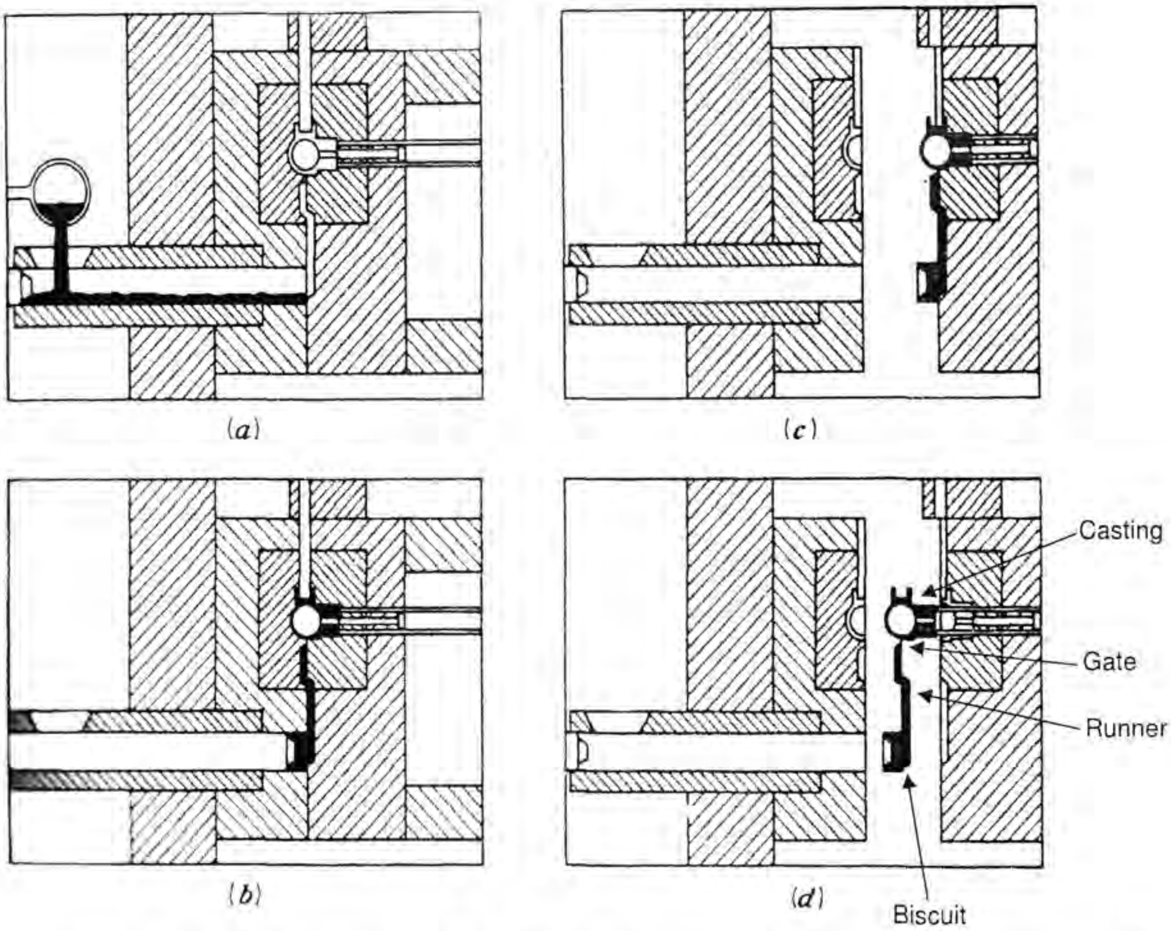


Diagram 2-5(a,b,c,d) is schematic of the casting procedure. Diagram 2-5(d) illustrates the nomenclature of the casting.

The die design must allow for mechanical ejection of the part from the die (diagram 2-5(d)) and as a result the choice of the split line is imperative so as to reduce the number of undercuts that require mechanically or hydraulically actuated moving cores. The design should produce castings as close to near net shape as possible which will reduce the post casting processes. Correct die design is a critical part of successful, economic and high quality, die casting.

After the shot is fired (diagram 2-5 (a), (b)) the die opens (c) and the plunger moves forward and forces the part to remain in the moving die half. The part is then ejected (d), and the plunger retracts. The die is lubricated with die release agent. The die closes and the process is repeated. Cycle rates of up to 180 cycles/hour are possible.

To adapt the HPDC process to SSM forming a method for placing the SSM into the shot sleeve of the machine is necessary. All other requirements are virtually unchanged from the liquid case. The manner in which SSM material is produced is by either, rheocasting (SSM slurry on demand) or by reheating thixotropically prepared billets. The two methods are called Rheocasting and Thixocasting respectively. They are discussed further in section 2.4. Diagram 2-4(b) shows a schematic of the two processes.

2.3 Comparison of Semi-Solid HPDC to Conventional HPDC Process

Semi-Solid Metal (SSM) was first discovered and researched by Dr. M.C. Flemmings at M.I.T. in the early 1970's. SSM forming is an effective near net shape process in which metal is formed in the semi-solid state[1,25]. SSM forming may be done using the high pressure die casting process. SSM High Pressure Die Casting (HPDC) has many advantages over conventional die casting. Complicated shapes with high integrity can be successfully cast and supersede conventional casting quality[26]. Conventionally high pressure die cast Parts are unable to be heat treated however SSM high pressure die cast parts are suitable for heat treatment[26] because of their lack of porosity. It was found by Flemings that if an aluminium alloy is heated to just above its liquidus temperature and then stirred as it cooled to just above its euctectic temperature (diagram 2-1), then the metal showed a profound change in its flow properties[1,25]. Upon further investigation it was discovered that the stirring action modified the typically dendritic microstructure of cast aluminium to a spheroidal microstructure. Diagram 2-6 and 2-7 show the spheroidal microstructure of SSM and diagram 2-8 shows the typical dendritic microstructure both are after casting.

Diagram 2-6 is a micrograph using a Scanning Electron Microscope. It is of a defect region which is discussed later in the Results and Discussion of Results section, diagram 4-13. Diagram 2-7 is a typical spheroidal microstructure from research done by K.C. Sharma[8].

Diagram 2-6: Spheroidal microstructure of defect area of as cast SSM Short Arm Component

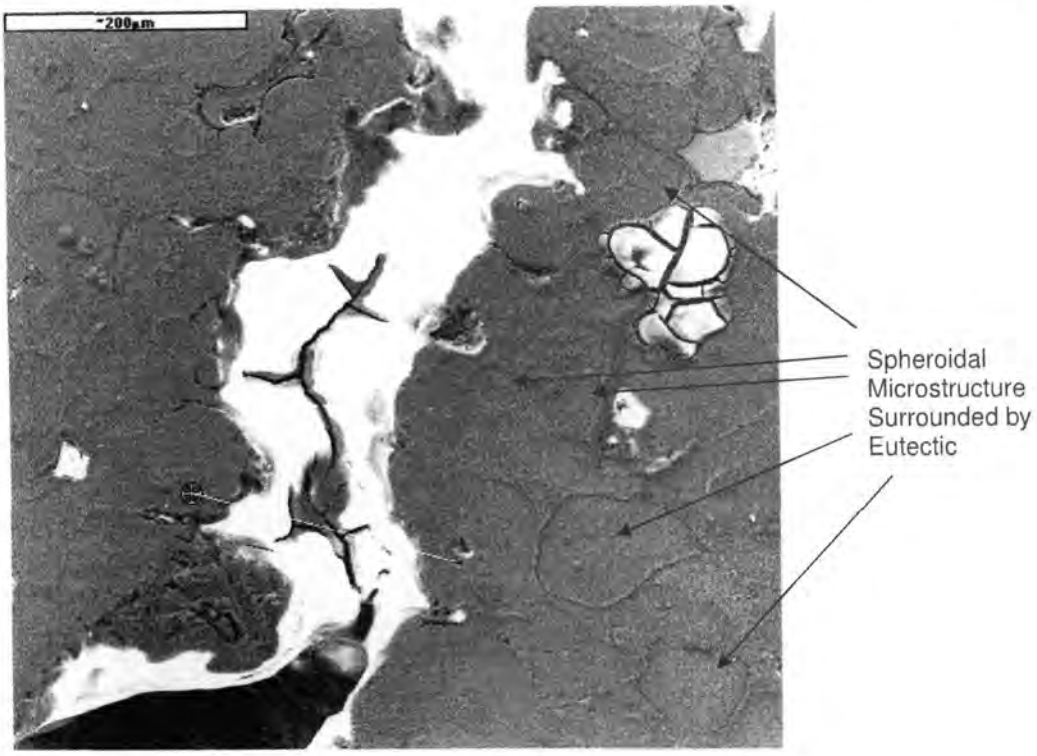


Diagram 2-7[8]: Spheroidal Microstructure

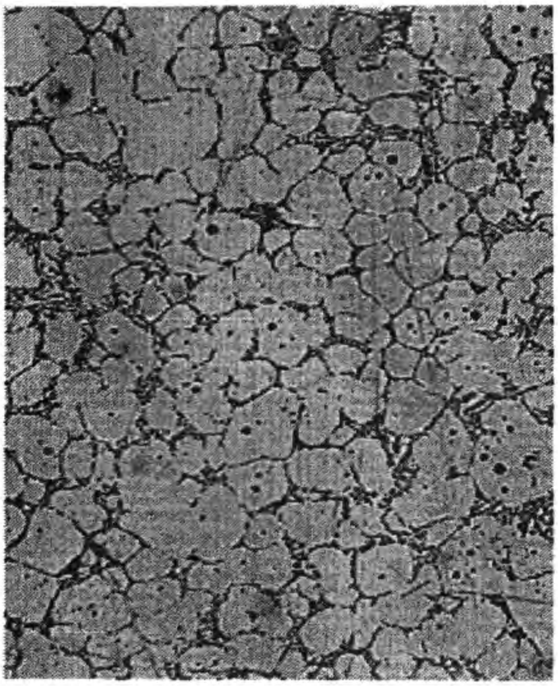


Diagram 2-8[8]: Dendritic Microstructure

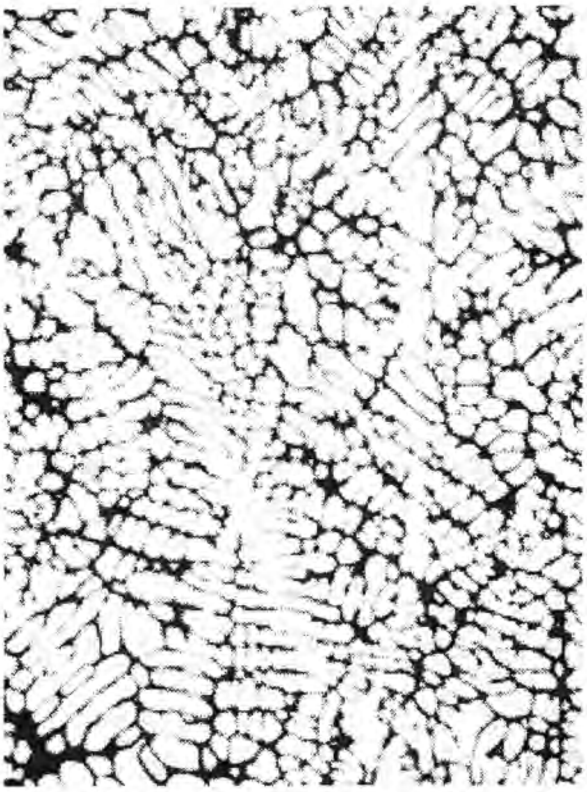


Diagram 2-8 shows the dendritic structure that is formed if the metal is allowed to cool and solidify normally – without any stirring action. When the eutectic melts and the metal temperature is kept within the semi-solid range the dendrites are free to move. Since the dendrites shown Diagram 2-8 have many protrusions it is highly likely that when these solid particles attempt to move they will be restricted by interlocking with each other. This is not the case with the round structures seen in diagram 2-6 and 2-7. When the eutectic melts in these microstructures the round solid particles move easily past each other. The ease of movement of the solid particles has a direct impact on the fluid's fluidity and hence the viscosity of the Semi-Solid fluid. The difference between the resulting fluidity of the two structures is an order of magnitude. According to S. Xing, L. Zhang, P.Zhang, Y. Du, J. Yao, C. Wu, J. Wang, D. Zengand W. Li the mould filling capability of SSM microstructure material is twelve times that of conventional dendritic microstructure material[28].

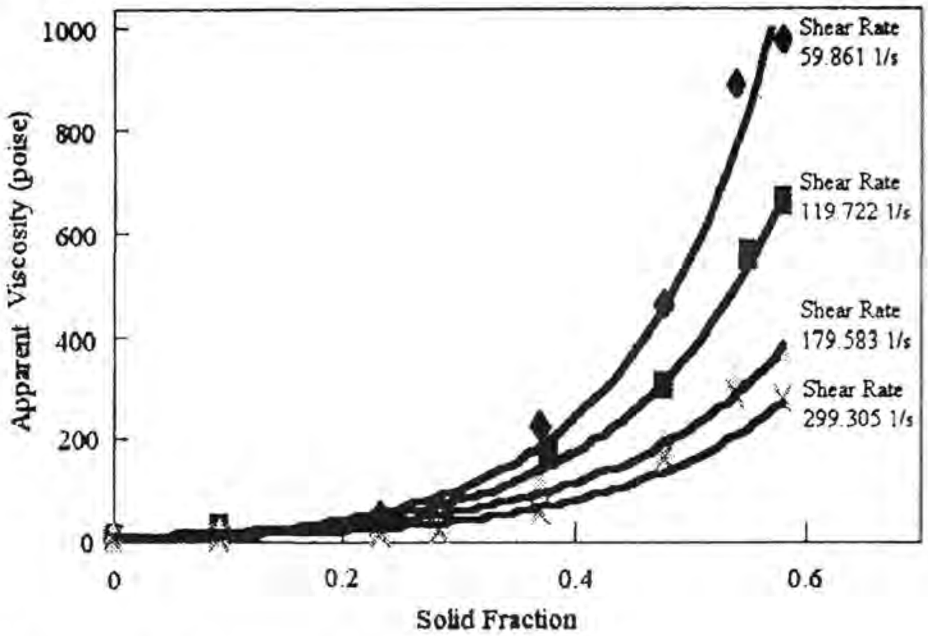
In part 2.1 the impact of the concentration of alloying elements on the semi solid range and fraction solid was discussed and shown diagrammatically in diagram 2-2. The alloy used here is A356, table 2.1 gives the specification of the alloying elements for this alloy in weight percent.

Table 2.1: A356 Specificiation[8] vs Actual Measurements

	Actual Results, wt %				
Element	Specification	Spark 1	Spark 2	Spark 3	Average
Silicon (Si)	6.50 - 7.50	7.15	7.19	7.10	7.15
Iron (Fe)	0.2 (max)	0.137	0.138	0.139	0.138
Copper (Cu)	0.2 (max)	0.008	0.012	0.016	0.012
Manganese (Mn)	0.1 (max)	0.011	0.010	0.010	0.010
Magnesium (Mg)	0.25 - 0.45	0.285	0.287	0.291	0.288
Chromium (Cr)	0 (max)	0.001	0.001	0.001	0.001
Nickel (Ni)	0 (max)	0.002	0.002	0.002	0.002
Zinc (Zn)	0.1 (max)	0.035	0.039	0.039	0.038
Titanim (Ti)	0.2 (max)	0.066	0.063	0.062	0.064
All others	0.2 (max)	0.015	0.015	0.013	0.014
Alumimium	Remainder				

The shear thinning behaviour is shown in diagram 2-3. The viscosity is also temperature dependant with respect to the fraction solid[29]. From the data in diagram 2-9 it is clear that the lower the fraction solid is the lower the viscosity is for a given shear rate. Also from the diagram it is clear that as the fraction solid gets less than 0.2, the fluid acts more like a normal fluid in that the viscosity is less dependant on the shear rate. The converse of this is very evident from above 0.4 fraction solid. The diagram was constructed from experimental data collected using a Couette viscometer for the magnesium alloy AZ91D. It is noted however that similar behaviour is displayed by aluminium alloys. By evaluating diagram 2-9 and diagram 2-2 together the following conclusion may be drawn, for a higher metal temperature the fraction solid will decrease and the apparent viscosity will also decrease which will improve the fluidity of the metal for the same shear rate. For this reason the metal temperature is expected to play a significant role in fluidity of casting of components. Also apparent from diagram 2-3 and diagram 2-9 is that with increasing shear rate the viscosity drops. The shear of the fluid takes place at the interface of the metal with the die cavity surface. The shear rate is directly proportional to the flow rate of the metal. It is thus expected then that at higher flow rates (higher plunger injection velocities) that there will be lower viscosities

Diagram 2-9[29]: Apparent Viscosity wrt Solid Fraction at Different Shear Rates

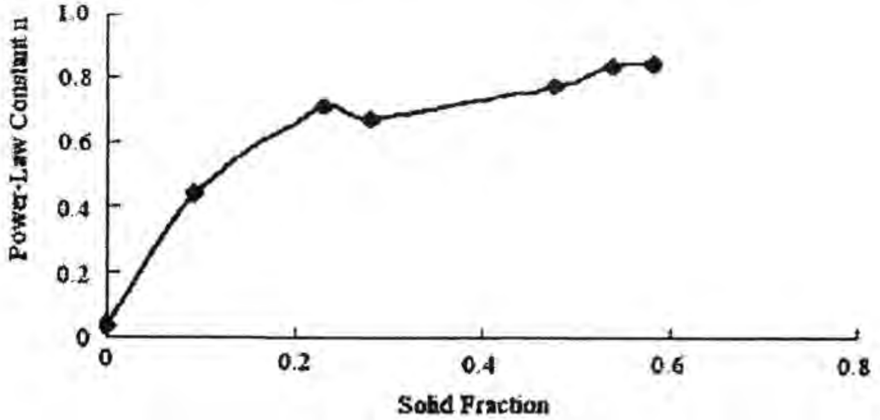


The apparent viscosity can be expressed by Eqn 2-1[29],

$$\eta = K \cdot \gamma^{-n} \qquad \text{Eqn 2-1}$$

Where η is the apparent viscosity [poise], K is a constant, γ is the shear rate [s^{-1}] and n is a constant of the power law. Diagram 2-10 shows the values for n. Again this is derived from experimental data for the alloy AZ91D. It shows however that n is a function of fraction solid, as suggested by diagram 2-9.

Diagram 2-10[29]: Values of n (Eqn 2-1) wrt Solid Fraction



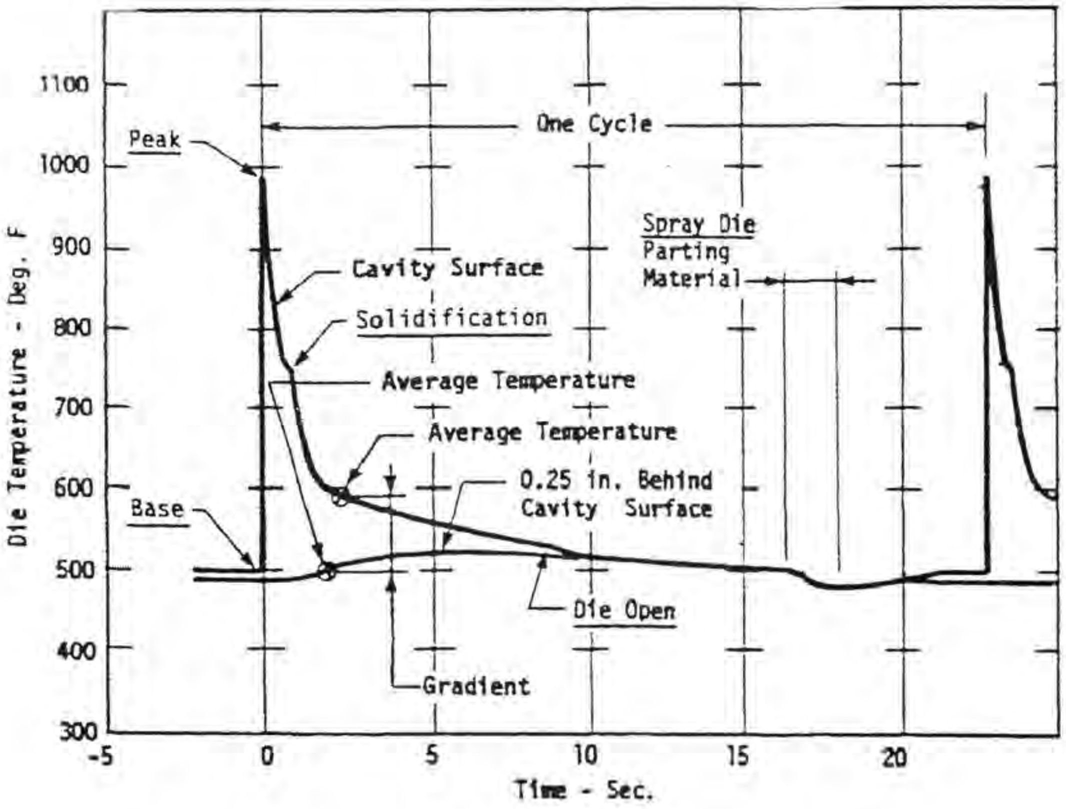
Semi-solid liquid is able to support its own weight (as an upright cylinder 50mm diameter and 100mm length) at a fraction solid of 50% which for A356 is 578°C. The diagram 2-11 shows a free standing SSM aluminium billet being cut by a knife. The action of the knife creates a shear rate which causes a decrease in the material's viscosity and as a result the material peels away from the knife as it is no longer able to support its weight due to the decrease in viscosity.

Diagram 2-11: Photograph illustrating SSM Behaviour [1]

Although SSM material was discovered and researched in the 1970's it was only in the 1990's that commercial interest and emphasis was placed on the processing method. The commercial advantages are substantial as higher demands for quality, weight reduction, geometry complexity and strength are placed on formed components. SSM allows wide variety of alloys to be cast which are normally not possible to achieve successful casting using conventional casting methods. SSM is used to successfully cast high strength, pressure tight, safety critical (high internal integrity) castings containing relatively thick and thin section geometry. SSM also offers distinct advantages such as eliminating air entrapment due to non-turbulent die filling and so achieving parts with high internal integrity and superior mechanical properties[25,30,32,33,34].

Post machining of castings is significantly reduced due to being able to produce near net shape castings with precise dimensions since there is a very small degree of physical shrinkage due to part of the metal already being solidified when casting commences. The SSM has no superheat energy and only the liquid fraction of latent heat. In normal casting methods the metal has its complete latent heat and 70°C to 250°C of superheat added to it before casting takes place. In comparison to normal casting methods, SSM uses significantly less energy to bring the metal to the temperature required for casting. Solidification porosity (also referred to as shrinkage solidification porosity) is also reduced substantially due the metal already being partly solidified. [35,36,37,38,39].

Diagram 2-12[14]: Graph showing the temperature Cycle an Al. Conventional HPDC Die undergoes



There is another significant advantage that SSM die casting has over conventional die casting and that is die life extension. Due to the temperature cycle that the die is subjected to, the surface layer of the die undergoes a thermal induced fatigue cycle. This is caused by the cavity surface of the die heating up rapidly when the molten metal enters the die. This causes the surface to expand. Then the die opens and then the casting is ejected after the solidification time. Thereafter the die cools rapidly in the air and then it is cooled aggressively by the die spray which is water based. This causes the die surface to shrink. The die then closes and the cycle repeats. The cycle time is between 20 and 60 seconds depending on the part geometry and alloy being cast. The metal may be (in the case of Aluminium casting) up to 720°C and the internal equilibrium temperature of the die may be 250°C. So the die cavity surface cycles from 250°C to 720°C every 20 to 60 seconds. This is a considerable thermal cycle and hence a dramatic fatigue cycle for the die steel to withstand. Diagram 2-12 illustrates the die surface temperature changes from die filling at time 0 through one cycle. As the surface heats up (expands) and then cools down (shrinks) the thermal cycle creates tensile and then compressive stresses respectively. These stresses eventually cause the surface of the die to form tiny cracks which slowly grow bigger with every cycle. These cracks on the die are referred to in the industry as heat checking. Because the metal is at a considerably lower temperature the heat checking is greatly reduced. SSM dies last four to five times longer than conventional die casting dies. [26] Die casting dies make up a large part of the fixed cost of high pressure die casting, so to reduce this by four to five times by increasing the die life, is a considerable cost saving.

2.4 Selection of Components

There are many forming techniques available. All these techniques have specific advantages as well as disadvantages. To ensure that a component is in fact suited to SSM forming it is necessary to evaluate the suitability of the casting with respect to the casting's specific requirements and characteristics against each forming technique. For the purposes of this investigation it is necessary to select a component which is suited to SSM high pressure die casting.

The advantages of SSM forming have been discussed in the preceding section. From this discussion it is clear that it is a specialised process. The economics of the process have not been discussed at length, however, to fully understand and appreciate the benefits and repercussions of using the process, a brief discussion of the economics is necessary.

The feedstock must be prepared specially for SSM processing. This may be done by utilising two methods, Thixoforming or Rheoforming. Diagram 2-4(b) illustrates the two methods. Thixoforming which was the first commercially adapted method, involves fully melting the metal and then casting the metal into billets while continuously stirring the billet as it solidifies. Once the billet has solidified it is reheated to the required fraction solid and the forming may take place. Rheoforming is a more recent process. It involves heating the metal to above the liquidus temperature and then casting the metal either directly into the vessel from which it will be formed or into a transfer cup. The metal is not allowed to solidify fully and its temperature is allowed to gradually decrease until the required fraction solid is reached. While the metal partly solidifies it is stirred or it is interfered with in some other manner so as to prevent dendritic microstructures forming. Then when the metal has reached the required fraction solid, it is formed.

This extra step of processing is costly and often needs a high level of control and accuracy to be able to achieve the desired feedstock at the desired fraction solid. The temperature control required for most alloys is +-1°C. In industrial applications this is a challenging and costly exercise. However once the preparation work has been done the benefits of SSM forming become apparent both in cost and in quality and production rate. It is stressed here though that if the benefits available from using the SSM process are not suited to or not relevant to the part being formed then these extra costs cannot be recovered and so the process cannot be justified.

To evaluate whether the part will benefit sufficiently from the SSM forming process for it to be economically viable to use the process, all the alternate forming processes should be considered. There has not been a large amount of research done on this to date. The North American Die Casting Association (NADCA) produced a useful set of standards and specifications for SSM Die Casting[40]. The set of standards includes a set of tables which rates sixteen different forming processes with respect to a comprehensive set of factors. The tables are broken up into the following categories, strength and integrity factors, dimensional complexity factors, machining and tooling factors, casting factors and economics of process and product cost factors. These tables have been utilised together with a weighting value representing the importance of each factor to the specific component being evaluated. This process is discussed at length in the Results and Discussion of Results Chapter.

By using these tables, (Results and Discussion of Results Chapter contains the tables modified with the weighting value) an acceptable study may be reliably and efficiently carried out to achieve a quantitative result easily comparable to each forming process. This process will enable the most suitable forming process to be chosen with confidence[17,40].

2.5 Die Casting Machine Parameters

The parameters of the die casting machine are widely variable over a large range. The parameters also have a large direct impact on the quality of the casting. These parameters also have a direct relationship to the properties of the SSM. The correct setting and selection of the parameters is therefore paramount to achieving a successful high quality casting.

2.5.1 Injection Profile

The injection profile is the profile followed by the injection plunger with respect to pressure and velocity over its injection stroke. The injection velocity has a major impact on the cavity fill time and flow characteristics of the metal within the die cavity. The injection pressure causes pressure in the metal and this is critical to assist with directional solidification "feeding" and ensuring complete cavity fill. [7,10,12,18,26,32,41]

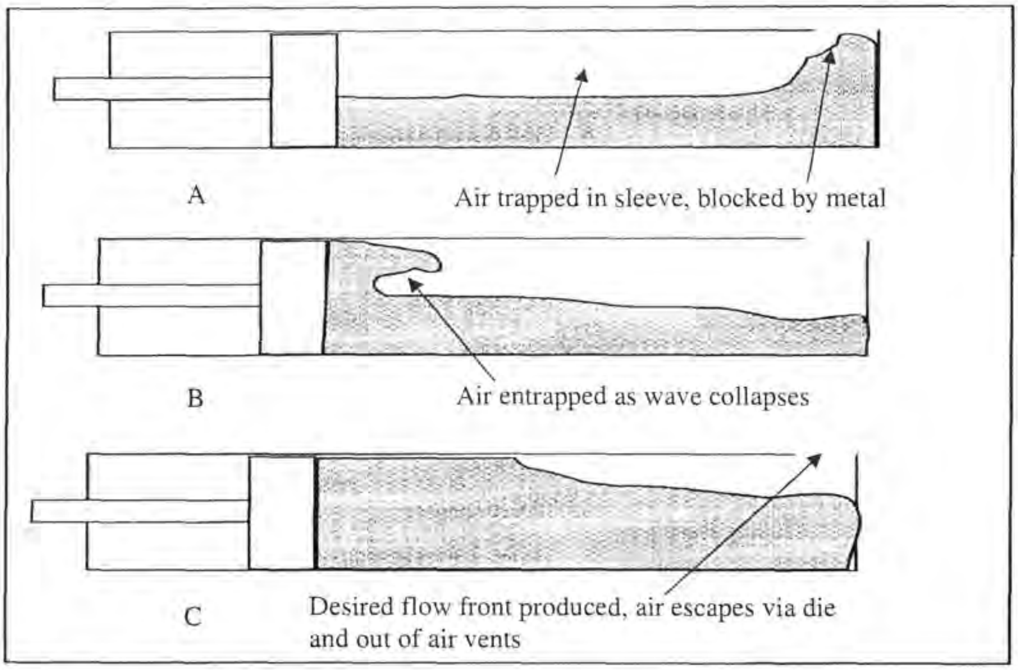
2.5.2 First Phase

The first phase is the initial stage of the injection displacement profile. The objective of the first stage is to remove as much gas from the shot sleeve and die cavity, to move the metal to as close to the gate as possible without entrapping any gas or causing excessive heat loss from the metal. As mentioned in section 2.2 the first stage is required to ensure the pouring hole of the sleeve is closed effectively by the plunger moving forward correctly, without any metal being displaced out the pouring hole for safety and good housekeeping reasons. To seal off this hole the plunger must move slowly since if it moves fast it will upset the metal in the sleeve and cause the metal to spill out through this hole before it is shut off. The second reason why the plunger should move with a low velocity is to avoid the metal becoming turbulent. The critical metal fluid velocity is that velocity whose internal kinetic energy is equal to its surface tension energy. Above this velocity the flow of metal in the casting process will become turbulent. For fully liquid Aluminium this velocity was shown to be approximately $0.5ms^{-1}$ by experiments done by Professor John Campbell at the University of Birmingham[31]. The fluid should not become turbulent since if it does, it will mix with the air in the shot sleeve and runner before it has even entered the cavity of the casting.

The first stage therefore displaces the metal until the shot sleeve is 100% full and in some cases even displaces the metal up the runner to the gate. By displacing the metal to this point in a slow laminar manner there is an extremely low likelihood of the metal mixing with the gas (air) which was originally in the shot sleeve and runner system. This air has been replaced by metal and has exited through the die cavity via the air vents[14].

To understand the above two paragraphs a diagram is useful. Diagram 2-13[8] is a section through the shot sleeve after metal has been ladled into the shot sleeve. The diagram contains three scenarios, A, B & C. Scenario A shows the case when the liquid metal has been accelerated too much and is moving at too high a velocity and banks up against the end of the shot sleeve. The associated problem with this scenario is that the air is trapped inside the shot sleeve. This is because the passage way into the die which then leads the air out to atmosphere via air vents is blocked by metal[8]. The trapped gas will become entrained in the metal and cause porosity as described below. Scenario B shows the case when the plunger is moving too slowly. Here a wave forms and due to the low speed it collapses. When it collapses air is entrapped inside the metal. This entrapped air becomes entrained in the metal either as a gas bubble or as dissolved gas in the metal. The gas bubble will show up in the solidified casting as porosity (entrapped gas). Upon solidification the gas that dissolved will come out of solution and create a pore, porosity (entrapped gas).

Diagram 2-13[8]: Section through Shot Sleeve Showing 1st Stage of Injection



Scenario C shows the desired metal movement through the shot sleeve. The piston speed is such that a wave forms which does not collapse and the shot sleeve becomes full of metal as its volume decreases due to the moving plunger. The metal moves by a continuous solid wave front driven by the moving plunger. The last place to fill is the passage way into the die. In this manner all the air in the shot sleeve is pushed out of the sleeve and into the die and then out the air vents in the die. In this manner no gas is entrapped due the first phase injection movement of the plunger. This critical speed is specific to the plunger diameter and sleeve size and the volume of metal in the shot sleeve being cast.[42,43]

The next important step is to get the metal to the die cavity quickly enough so that not too much heat is lost and the metal drops to below a suitable casting temperature. This means that the 1st stage speed cannot be too slow. It also means that the passage way leading the metal to the die cavity should have a high modulus (volume to surface area in contact with the die ratio).

In the case of Semi-Solid little research has been done on the 1st stage injection process. However it is clear from the above discussion that Semi-Solid Metal will be very much less vulnerable to entrapped air problems due to its much higher viscosity. However since the metal is cast with no superheat it is vulnerable to heat loss resulting in the metal temperature and resultant fraction liquid dropping past the temperature suitable for successful casting. For this reason it is necessary for the modulus of the passage way leading to the die cavity to be higher than that required for conventional high pressure die casting.

2.5.3 Second Phase

The second phase of the injection profile is normally at a considerably higher velocity than the first stage. The ideal point to change from slow to high velocity injection is when the metal is at the entrance (gate) of the die cavity. By doing this the maximum amount of air has been expelled from the system. The reason why it is desirable to remove as much air as possible is because if this air mixes into the metal it becomes dissolved or remains as an air bubble inside the flow and when the metal solidifies the air comes out of solution and the air bubbles form voids in the cast component which are absent of metal. These voids are known as porosity and are normally undesirable since the strength and other desirable factors of the casting are detrimentally affected[2,5,6,14,15,16].

The velocity required is determined by the cavity fill time required. The cavity fill time can be calculated for typical conventional high pressure die casting and is a function of: die temperature, casting wall thickness, metal temperature at gate of casting, minimum flow temperature of the metal and the allowable solid fraction required by the caster[14]. The relationship is shown in equation 2-2.

$$\text{Cavity Fill Time} = \frac{k(T_g - T_f + C \cdot Z) \cdot t}{(T_f - T_d)} \qquad \text{Eqn. 2-2}^{[14]}$$

Where:

C	is the allowable solid fraction that the caster requires
T_f	Minimum flow temperature
T_g	Metal Temperature at the Gate
T_d	Die Temperature
Z	Unit conversion Factor
t	thickness of the casting
k	general constant

For conventional high pressure die casting of normal Al-Si hypoeutectic alloys,

$C \approx 0.1$
$T_f \approx 580^\circ C$
$T_g \approx 600 - 650^\circ C$
$T_d \approx 250 - 330^\circ C$
$t \approx 0.2 - 10$ [mm]
$Z \approx 200$
$k \approx 0.05$

Diagram 2-14: Graph of Eqn. 2-2, cavity fill time w.r.t. thickness of the casting

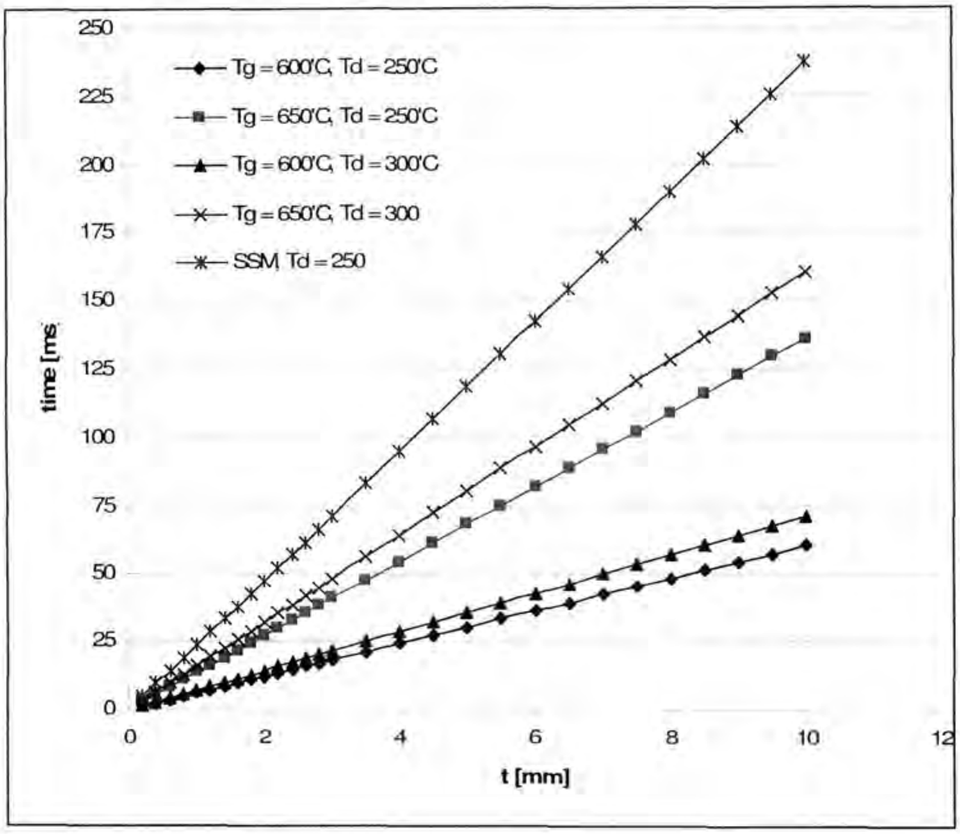
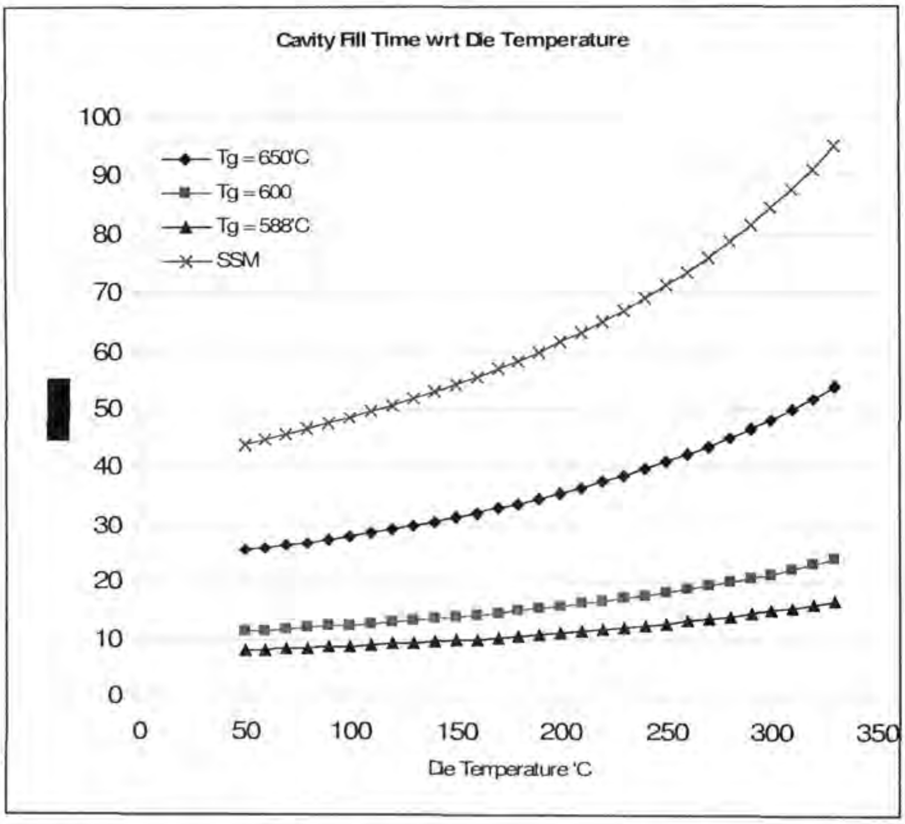


Diagram 2-14 shows the linear relationship between the thickness of the casting and the cavity fill time for different metal temperatures and die temperatures (T_g ,T_d). The formula loses its accuracy for very thick or thin castings (refer to [14]) where Chvorinov's rule[16] is more accurate. However for the normal range of geometry and process variables of HPDC components the formula is useful. We can adapt the formula to Semi-Solid Die casting by adjusting the variables suitably for the alloy of interest, A356. In Semi-solid die casting the maximum allowable fraction solid can go as high as 0.7, the minimum flow temperature can go as low 570°C, the metal temperature at the gate can be 582°C and the die temperature the same as for conventional high pressure die casting. The graph for SSM in diagram 2-2 shows us that SSM can tolerate a longer cavity fill time due to its ability to still be fluid at a lower fraction liquid (higher fraction solid) and a lower metal temperature. It is clear that the latent heat is the dominating factor in the equation. This is shown by comparing the SSM graph to the others, where even though conventional die casting is cast with superheat, the higher fraction solid tolerated by SSM enables the fill time to be longer.

In diagram 2-15 equation 2-2 is illustrated this time with respect to varying die temperature. Again the dominating effect of the latent heat is illustrated by the graph for SSM showing longer cavity fill times.

Diagram 2-15: Graph of Eqn. 2-2, cavity fill time w.r.t. Die Temperature



The second stage velocity of the injection plunger must ensure that the metal fills the entire die cavity within the required cavity fill time. The resulting metal flow rate is extremely high. The high flow rate results in turbulent metal behaviour during cavity filling. The turbulent cavity filling results in increased gas and oxide entrapment which together reduce the internal integrity of the casting.[8,14,15,42,43,44] If the velocity is halted at a point during the injection a short fill shot (short shot) may be produced. An example of a short shot is shown later in the text (diagram 2-18).

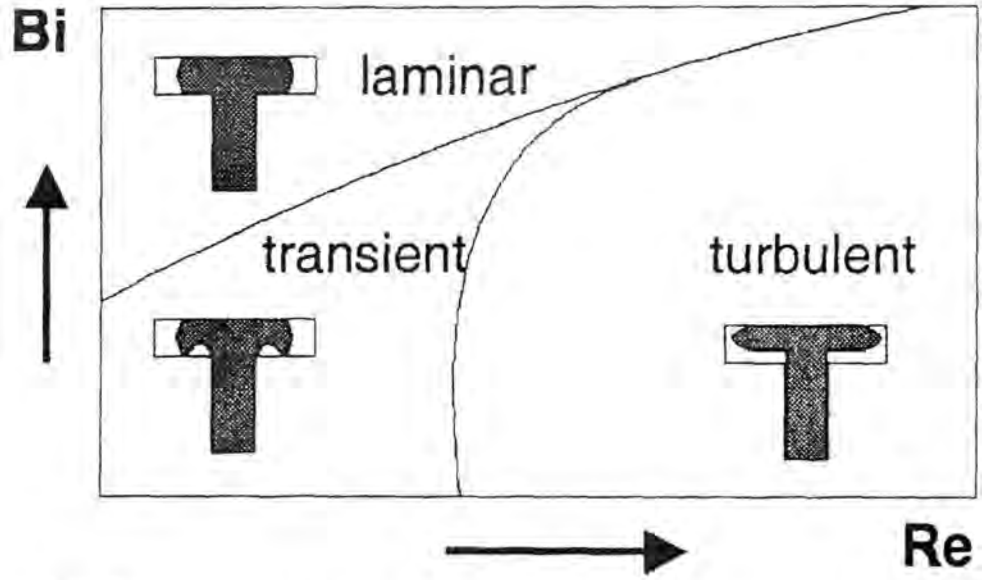
The second stage velocity (flow rate) affects the surface finish of the casting[45]. The higher the metal flow rate, the better the resulting surface finish is. However the higher flow rate will result in more turbulence and normally more entrapped air and worse internal integrity. Also the higher speed and hence momentum of the metal when it collides with the die surface will create an increase in the erosion of the die. A higher speed can also cause a phenomenon called soldering. This happens when the die surface is overheated and the metal solders onto the die as the die surface layer of die release agent is removed and the die steel is heated up sufficiently to allow the aluminium to penetrate a very thin layer of the die steel and so solder onto the die steel. Increasing the metal speed, metal temperature and or the die temperature aggravates this phenomenon. The soldered aluminium takes time to remove from the die face and this decreases the cycle rate substantially and severely reduces profitability.

From the above discussion it is not possible to satisfy all the conflicting requirements to achieve a perfect internal integrity part with the best surface finish. One must be traded off for the other in conventional die casing.

As mentioned already, for components to be made economically out of SSM, they must require the superior qualities that only the more expensive SSM process allows for. For the SSM process to produce these superior results the SSM flow must be non-turbulent. [7,18,32]

R. Kopp and H. Shimahara [47] have looked at the dimensionless Bingham and Reynolds number and modified them for Non-Newtonian flow behaviour. They have found that there is a relationship between the two which makes a process window, diagram 2-16. They have also shown that the desired part of the process window is in the laminar section. The experiment used to obtain the process window, was the T-die experiment which was carried out by researchers at RWTH Aachen University in Germany in 2001, these authors did not publish the numbers on the graph in diagram 2-16. However it is a fascinating area and one which will help the die and process designer of new SSM cast components to be cast successfully. Kopp and Shimahara found that the progression of the borderlines for different flow behaviour shown in diagram 2-16 were independent of specific metals.

Diagram 2-16: Flow Contour diagram with Dimensionless Bingham and Reynolds number, modified for Non-Newtonian flow behaviour[47]



$$\mathrm{Re} = \frac{\rho \cdot v^{2-n} \cdot D^{n}}{\kappa \cdot k} \qquad \text{Eqn 2-3}$$

$$Bi = \frac{\tau_0 \cdot D^{n}}{k \cdot v^{n}} \qquad \text{Eqn 2-4}$$

Where

ρ	Density of the fluid
κ	fraction of solid particles agglomerated
τ_0	initial shear yield stress
v	velocity of the injection plunger
D	Diameter of the inflow section
k,n	parameters of flow curve, (simplified in eqn 2-1)

A.N. Alexandrou, P. Le Menn, D. Apelian and G. Georgiou [49] found that for a square gate section the Reynolds and Bingham numbersa are given by,

$$\mathrm{Re} = \frac{\rho \cdot U_0 \cdot H}{\eta} \qquad \text{Eqn 2-5}$$

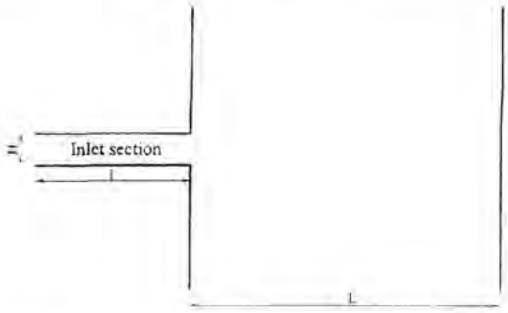
$$Bi = \frac{\tau_0 \cdot H}{\eta \cdot U_0} \qquad \text{Eqn 2-6}$$

Where

ρ	Density of the fluid
τ_0	minimum shear stress for deformation (also known as the yield stress)
H	Inlet Region Height
U_0	average inlet velocity
η	apparent viscosity

The fluid flow was modelled using the Bingham constitutive model, modified to avoid the numerical difficulties of the discontinuous results by approximating the rheological behaviour of the material to be valid at all stress levels[49]. The geometry modelled is shown in Diagram 2-17.

Diagram 2-17: Schematic of the Geometry of the two dimensional cavity for modelling[49]



A die was also made to verifiy the results predicted by the model. A set of results at the Bi and Re numbers at levels where unstable flow becomes apparent is shown in diagram 2-18. A number of different flow patterns were observed in the filling of the 2D cavity. With H=1 and l=5 (of diagram 2-17). The patterns which resulted from different Re + Bi numbers are shown in diagram 2-19.

In diagram 2-20 a line is drawn which separates the square markers (representing the bubble pattern) from the rest, triangular with apex up, triangular with apex down and circular markers. The research showed that the bubble pattern observed in 2-19(d) was an unstable flow pattern. The result from experiments of such a flow pattern is seen in diagram 2-18. This is clearly undesirable flow. The research showed that of the patterns showed in diagram 2-19, the bubble pattern (d), leads to unstable jet behaviour but the shell (a), disk (c) and mound (b) remain stable. The transition case (e) normally leads to stable jet profiles but not always. The numerical results obtained explain why experimental results of the bubble pattern are uncommon – it is unstable. Diagram 2-21 is a graphical representation of the numerical model predicting the formation of a bubble which is given a small disturbance as is normal in the real case. The disturbance is only applied for time t=0 to t=1.5.

Diagram 2-18: Short Fills of SSM castings showings unstable flow[49]

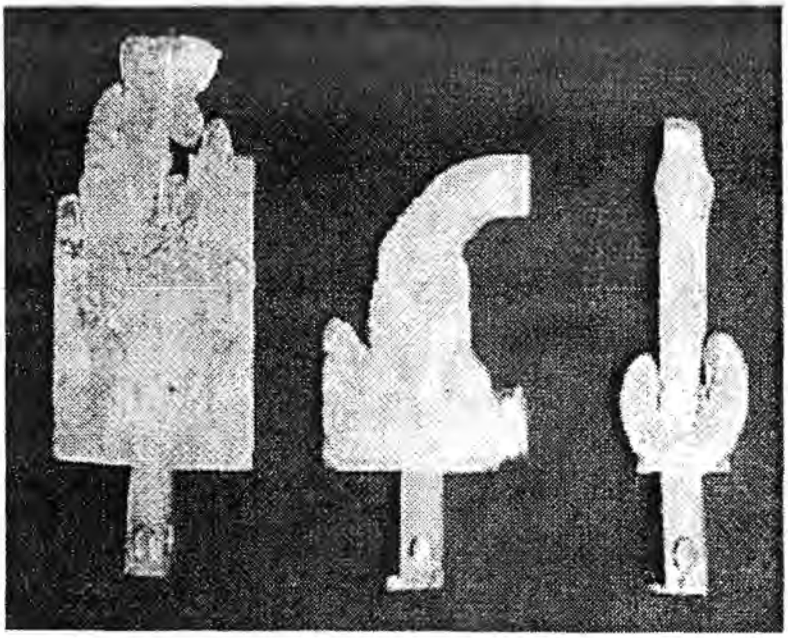
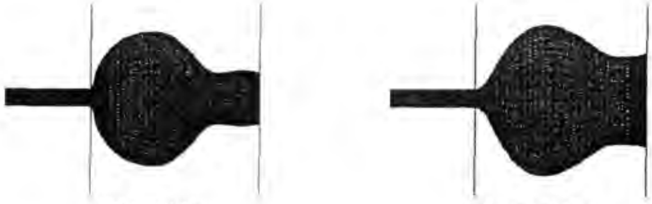


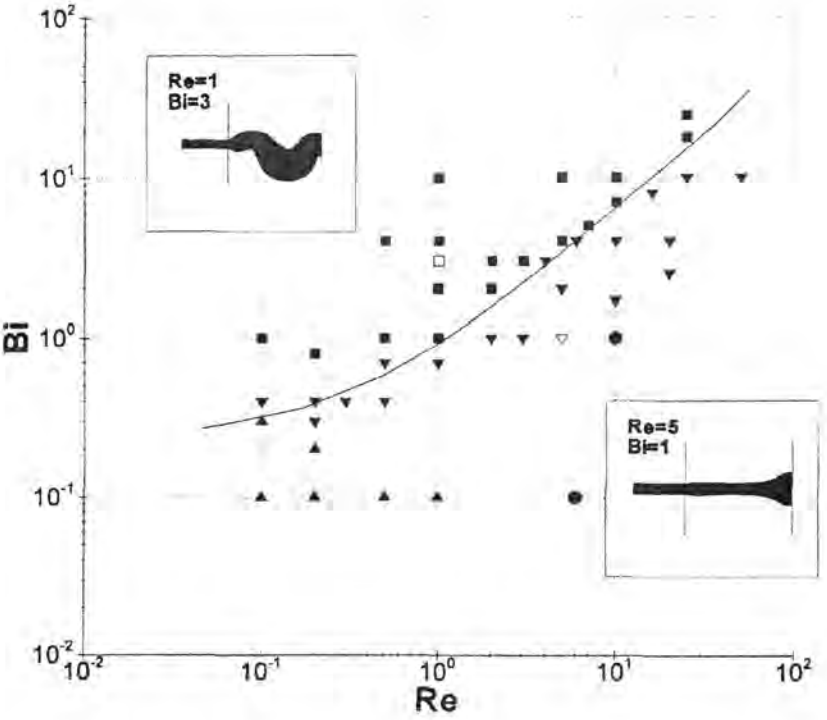
Diagram 2-19: Summary of flow patterns from the 2D model[49]

(a) shell (b) mound (c) disk



(d) bubble (e) transition

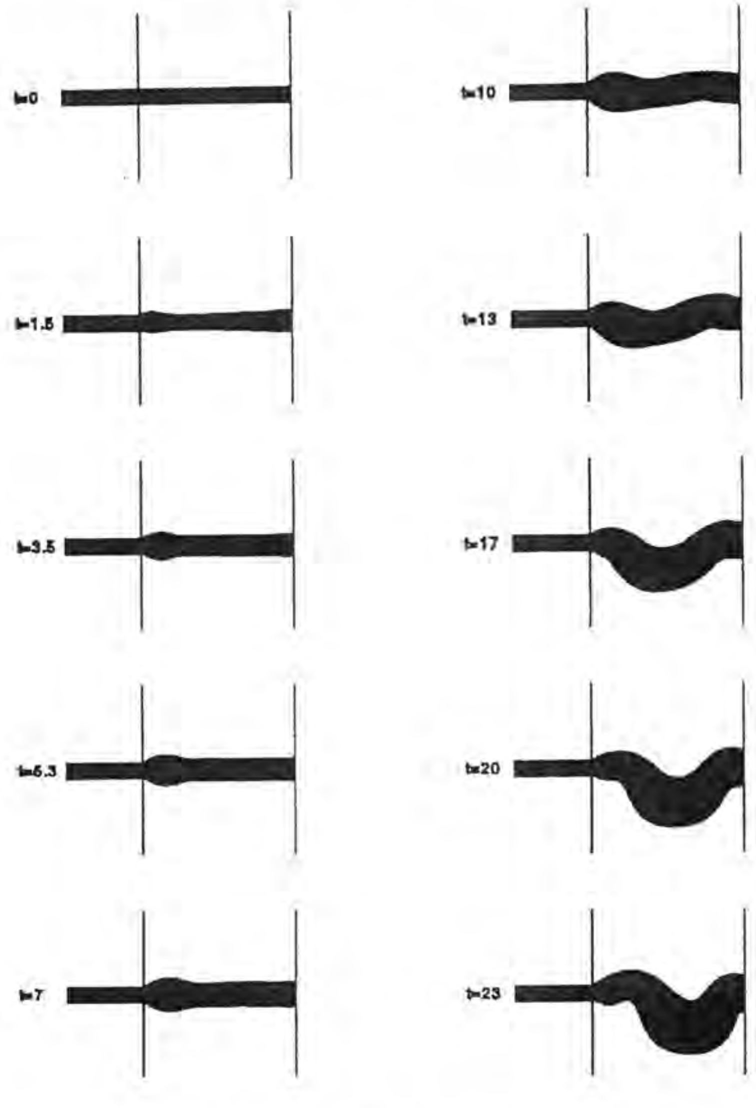
Diagram 2-20: Plot of the Jet Behaviour[49]



The simulations by A.N. Alexandrou et al show that by using simulation techniques it is possible to avoid instabilities of the flow by properly selecting the operating conditions (process window). [49]

The research clearly demonstrates that there is a critical velocity above which the flow of SSM becomes turbulent. S.P. Midson, L.E. Thornhill & K.P. Young showed that for a given consistency SSM material a gate speed of above 5ms^{-1} will result in turbulent filling. J.C. Lee, H.K. Seok and H.I. Lee showed this to be 2.5ms^{-1}. The discrepancy is explained by the different parameters (initial material parameters) each researcher used in their experiments and the different gate geometries. The important point to note is that the critical velocity should not be exceeded. Since the SSM is not a Newtonian fluid the speed at which the flow becomes turbulent is very difficult to predict and for this reason numerical modelling techniques are necessary to simulate fluid flow during die filling in order to establish the speed at which the fluid flow will become turbulent.[24,49]

Diagram 2-21: Simulation of the Formation of an unstable Bubble Flow Pattern[49]



K.C. Sharma[8] showed that at a speed above 3.5ms^{-1} the castings produced had porosity. It is noted however that only two levels of the flow rate were chosen and so the actual critical flow rate must be somewhere in between these two values. The two injection plunger velocities chosen by K.C. Sharma resulted in gate velocities of 1.75ms^{-1} and 3.5ms^{-1}. In the research by both Midson et al and Lee et al the various other parameters which are critical to SSM fluid dynamics were not investigated and so because of this it is not curious that they all achieved different critical gate speeds. K.C. Sharma also did not investigate different gate geometries but did use differing fraction solids in his research. K.C. Sharma also points out that the critical velocity for SSM metal casting is unique to the process parameters as confirmed by the research and results from the modelling done by A.N.Alexandrou et al[49].

To obtain the critical velocity one may carry out numerical simulation or one may carry out experiments both with the die and process parameters set at values required for the casting[48]. To achieve a result from using the experimental method a large enough range of process parameters must be included in the experiments so as to ensure that both scenarios of (desirable and undesirable) fluid flow are included. For the area of discussion this means that the second stage velocity is of paramount importance to the quality of the casting and a reasonable range must be investigated. The result that is sought from selecting the correct second stage velocity is a casting which has no irregularities caused by incorrect fluid flow or premature freezing. When a value for the second stage velocity has been achieved which satisfies this then this value may be considered a usable value. It is noted also that many other process parameters influence this usable value. For this reason it is necessary to design the experiments and analysis of the experiments so that effects of multiple variables at the same time can be taken into account. So as to choose a set of process variable settings with confidence.

2.5.4 Intensification

Intensification is a very important part of high pressure die casting[14,15,27]. The intensification is an increase in metal pressure which is exerted in the metal of the casting during solidification. To achieve an increase in metal pressure the plunger's force acting on the biscuit is increased (by an increase of hydraulic pressure from the intensifier circuit of the hydraulics).

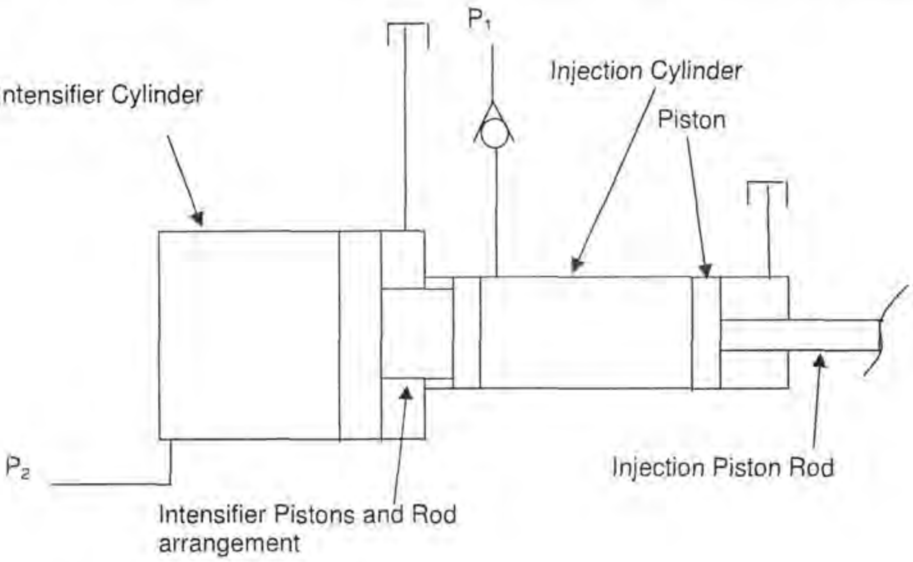
During die casting the liquid metal solidifies on the surface of the die first. This thin solid layer forms a crust which is held in place during solidification by the metal pressure. Therefore any change in the metal pressure will have an effect on the casting. For this reason it is necessary to understand how the metal pressure comes about and where it is formed.

The metal pressure comes from the force exerted over the area of the end of the plunger in contact with the metal. The movement of the plunger is due to the rush of hydraulic fluid which flows into the injection cylinder from the accumulator. The accumulator is a hydraulic spring and it stores potential energy in the form of hydraulic fluid under pressure. To do this the accumulator is a fixed volume pressure vessel and is charged with nitrogen gas normally at about 12MPa. There is either a bladder or a flying piston (piston with no rod) which separates the nitrogen gas from the hydraulic fluid. The hydraulic fluid is pumped into the vessel normally at 2MPa higher pressure than the gas pressure. To do this the hydraulic pump is regulated to 14MPa. The energy to fire the high velocity second stage comes from the potential energy stored in the accumulator. When the plunger reaches the point when the die cavity is completely filled it creates a water hammer effect. This effect creates a pressure wave inside the hydraulic injection cylinder as well as inside the metal itself (as both are fluids). The pressure waves may interact with each other and could reach alarming values at resonance. In reality the friction inside the cylinder and the die, damp this wave and it does not last long and does not normally reach very high values. The water hammer however is further enhanced by the compressibility of the nitrogen in the accumulator. For this reason a non-return valve is fitted on the fluid path back to the accumulator from the injection cylinder.

Consider the metal inside the die. As soon as it is injected into the die it cools and begins to solidify, on the interface of the die surface first. The metal within the centre of the casting will solidify last. The metal pressure will push the metal against the crust formed by the solidified metal on the interface of the die. When the water hammer effect takes place there will be an increase in the metal pressure instantaneously and then the pressure will drop to below the original pressure. This drop in pressure while the metal solidifies will create pores in the metal because when the wave returns from its reflection with the plunger the pressure will increase again but it will be too late for those areas of the casting that have already solidified in that small amount of time and they will not be able to fuse with the molten metal next to themselves that was temporarily moved away during the drop in pressure . Each time the wave travels forward and backwards and the pressure rises and falls so the casting will form more pores. This is clearly an undesirable situation. To overcome this, the non-return valve is critical but not enough. An increase in hydraulic pressure is needed to counteract the pressure drop set up by the water hammer effect.[15,46]

To achieve a higher pressure an intensifier is used. The intensifier is a larger diameter cylinder which has a piston inside it which operates onto the smaller diameter cylinder in front of it and so increases the pressure in this smaller cylinder. In diagram 2-22, P_2 is only pressurised when the hydraulic circuit detects the large increase in pressure in the injection cylinder due to the water hammer effect. The time with which the intensifier hydraulic circuit reacts to this increase in pressure should be minimal so as to reduce the effects discussed above.[14,15]

Diagram 2-22[15]: Schematic Part of Hydraulic Circuit of High Pressure Die Casting Machine



The intensifier pressure also assists in forcing new molten metal to "feed" the casting as it solidifies. When the casting solidifies its volume decreases. Since the surface of the casting has solidified first and formed a crust which is held in place by the internal metal pressure, the reduction of volume can only take place inside the casting by the formation of voids. These voids are called shrinkage porosity. A way to avoid these voids forming is to "feed" new molten metal to the solidifying metal. This method is known as directional solidification [13,14,15,27]

In high pressure die casting directional solidification is assisted by the high pressure exerted by the injection plunger onto the metal. This high pressure and force, forces the metal to move into the voids before they form. This is possible for as long as there is a passageway of molten metal connecting the centre of the casting to the biscuit[32]. The biscuit acts as a reservoir of liquid metal and must therefore solidify last. To ensure that directional solidification takes place a modulus study is necessary. The modulus study uses Chvorinov's rule to predict the order of solidification of each section of the casting. By calculating each section's volume and surface area and taking the ratio of the two it is possible to predict the order of solidification of the sections. Chvorinov's rule is explained further in section 2.5.5 and in the Test and Experimental Methods Chapter.

For SSM Midson et al[32] claim that a metal pressure of 1000kg/cm^2 or more will ensure adequate feeding and eliminate both macro and micro-porosity. The higher the metal pressure is the more strain is placed on the die and machine and both will have reduced mechanical life. The present investigation will experiment with lower injection pressures for this reason and ascertain whether they give acceptable results.

The intensification pressure has a very serious impact on selecting an appropriate machine to cast the component on. This is because the metal pressure acts on the projected area of the split line of the component to create a force which acts against the die closing force of the machine. If the force from the metal pressure and the projected split line area is larger than the force of the machine holding the dies together, the die will open and metal under high pressure will escape at a resulting high velocity into the lower pressure of the atmosphere, this occurrence is known in industry as flashing. This is clearly an undesirable occurrence from a part quality and safety consideration. The part quality is adversely affected since when the die parts the metal pressure will be reduced. The situation is very dangerous since the hot metal travelling at high speed will cause serious burns and injury to any person or object in its path.[15] To overcome the flashing, a machine with a die clamping force large enough must be selected which overcomes the force from the metal pressure. The larger the machine the more expensive it is. For the reasons discussed above it is desirable to run the die with the lowest intensification possible to produce a casting of the required quality level.

2.5.5 Die Temperature and Cavity Fill time

The temperature of the die affects the rate of heat flow from the metal into the die. Since the die is cooler than the metal the heat flow is in the direction described above. The rate at which the heat is removed by the die is directly proportional to the amount of time required for the casting to solidify and cool to a temperature suitable for removal from the die.

The temperature at which the casting is able to be removed from the die is determined by a number of criteria. The casting must have solidified fully or in the case of very thick castings to such a degree so as to allow the casting to maintain its shape in the face of the extraction method and action effected on it to remove it from the die. The casting must have benefited fully from the directional solidification assistance given by plunger. That is the casting should not be removed until all the desired amount of shrinkage porosity has been reduced by feeding new metal via the pressurised biscuit to the casting. The last criteria is that the casting should be safe for it to be removed from the die. For the casting to be safe it must be solid enough to to be handled. The casting should also have solidified to a point which allows the casting to withstand the internal metal pressure without exploding or losing its original shape. The die acts as a shell to maintain the castings shape and dimensions until the casting is able to maintain these on its own.

For a given die temperature each different casting geometry requires a different cavity fill time. Also each quality requirement of a casting requires a different cavity fill time. Thus a specific casting geometry and quality requirement will have it own specific cavity fill time which will achieve the best results. The geometry affects the cavity fill time due to the amount of heat stored in the casting and the rate at which this heat may escape. Chvorinov[16] showed that the time taken to solidify for a given system with different casting geometries was determined by the casting's modulus. The modulus is the ratio of the castings volume to its surface area which is in contact with the die surface. A detailed account of Chvorinov's rule is given in the Test and Experiment Methods Chapter.

E.A. Herman and North American Die Casting Association [14,27] claim that equation 2-2 determines the cavity fill time. However equation 2-2 does not take into consideration the modulus of the casting. The only term which is partly taking the modulus into account is done specifically for the case of conventional high pressure die casting which displays turbulent die filling. The correct answer may not be obtained adapting the equation to SSM as done in section *2.5.3*. This is because SSM forming is predominantly laminar fluid flow. [14,49]

Equation 2-2 and diagrams 2-14, 2-15 show the impact that the temperature of the die has on cavity fill time in conventional die casting. For the case of laminar die filling characteristics displayed by SSM it is necessary to use Chvorinov's[16] rule and calculate the modulus of the whole casting and use experimental data to obtain the coefficients for the SSM die cast case for equation 2-7.

$$t_s = B\left(\frac{V}{A}\right)^n \qquad \text{eqn. 2-7}$$

Where t_s = Time for the section of the casting to solidify

V= Volume of the section

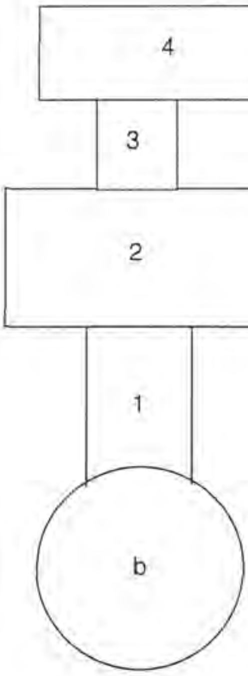
A = Surface of section in contact with mould

B and n = constants depending on the mould and metal characteristics

Changes in die temperature have been shown to have little effect on the porosity level in castings when cavity fill the time has been kept constant[20,50]. If the porosity present in a casting is caused by the shrinkage and solidification process then this means that during this process the casting was not fed with new metal as described in section 2.5.4. To avoid this happening there must be a passage way through which the molten metal may move so as to take up the voids so formed as the metal solidifies and shrinks.

Consider diagram 2-23 and assume that the thickness is constant. Let S_n, V_n be the surface area of each section in contact with the die surface and the volume each section respectively with n=b,1..4. From the simple geometry the descending order of magnitude of the ratios of V_n/S_n can be worked out by inspection and will be, section b,2,4,1 and then 3. From Chvorinov's rule then this will be the descending order of the solidification times, that is section 3 will solidify first, then 1, then 4, then 2 and lastly b. Section 4 is connected to section 2 via section 3. Since section 3 solidifies before section 4, the liquid metal in section 2 is unable to move towards section 4 since it is blocked by the solid metal in section 3. After section 3 solidifies no new metal may be able to take up the voids it created during section 4's solidification and the section will contain shrinkage porosity[13,16]. The same will happen to section 2 as it is blocked off from section b when section 1 has solidified.

Diagram 2-23: Theoretical Casting to illustrate shrinkage and solidification techniques



Chvorinov's rule assumes the mould conditions to be the same through out the mould (die). One way to achieve a better result is to either heat the die in areas where a longer solidification time is required or cool the die in areas where a shorter solidification time is desired. In the case of diagram 2-23 the desired combination would be to heat sections 1 and 3 and cool sections 2 and 4. The degree of heating and cooling would be critical to achieving no shrinkage and solidification porosity in the casting.

N. Tsumagari, J.R. Brevick and C.E. Mobley [20] showed that by altering the normal temperature of the die and by the use of external heating or cooling thereby setting up a specific and favourable temperature gradient to encourage a pathway of molten metal to all areas of the die, the porosity of the casting was significantly reduced. In this manner the specific temperature of the die face at different areas plays a significant role in the outcome of the quality of the casting.

The die temperature also affects the surface finish of the part. Since the surface of the die is responsible for the heat removal and the difference in the temperature of the surface and the temperature of the metal being cast is responsible for the rate of this heat removal. A very low die surface temperature will cause the there to be a very rapid solidification on the surface of the die which could result in cold shuts and or flow marks being formed on the corresponding surface of the casting. The thinner the casting wall thickness is the more apparent is this problem and the more a low die temperature will impact on the quality of the casting[52]. To compound the matter further the thinner wall section will also have less heat capacity to heat up the die and so this area of the die will always be colder than the rest of the die and as a result the casting quality in this area will always be poor under normal operating conditions. To compensate for this many die casters simply cast the metal at a higher temperature so that only this small section benefits and fills correctly. The problem with this approach is that the die will have to withstand an even higher temperature and so be more susceptible to heat checking and so shorter die life. A far better alternative is to maintain this section of the die at a hotter temperature either by using as external heating device in this area or by simply cutting a scalup into the back of the die behind this section to reduce the heat flow out of the die in this section and into the platen of the machine thereby maintaining this section of the die surface at a higher temperature.

Too hot a die temperature causes a different kind of problem. When the metal flows across the die cavity surface, at a very high temperature the surface of the metal solders onto the surface of the die. Also a very hot die temperature is not suitable for most die release agents and as a result they do not perform the function they are meant to carry out, which is to form a layer between the die and the cast metal which allows for easy release of the casting from the die. Soldering is undesirable and affects productivity adversely as mentioned in section 2.5.3. [51]

The die temperature can be a major asset in quality control of castings. It can also be a major cause of defects if it is not controlled correctly. It is a significant variable for castings with specific geometries.

2.5.6 Shot Sleeve Temperature, Geometry and Transfer Time

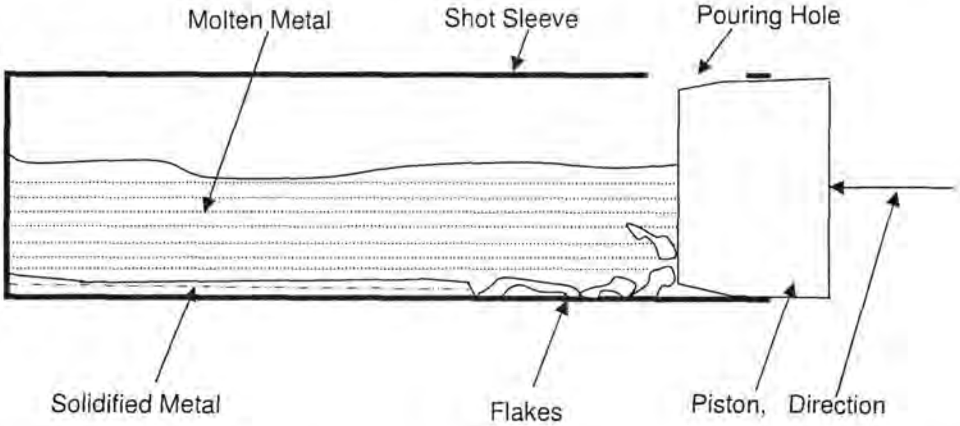
The shot sleeve temperature in die casting is normally not taken into consideration by most die casters as a process variable which is critical to the quality of the casting. An important note here however is that if production has not run for a few hours using that shot sleeve, then the sleeve must be pre-heated before it is used. This is a safety and dimensional consideration. The plunger is cooled with water but the sleeve is not. The tolerance of the plunger and sleeve is very close to a size for size fit in that the difference in diameter is only 0.05mm. Any slight misalignment will cause the plunger to seize and any foreign matter or temperature differential between the sleeve and plunger could cause the movement to seize. A seized plunger is a very undesirable situation and causes serious amounts of downtime which adversely affect production. Also since the plunger is cooled with water there is a possibility that water may be present in the sleeve. If water is present and metal is poured on top of it an explosion due to the water forming steam at a rapid rate and increasing in volume which will cause the metal to be thrown upwards, some will come out of the pouring hole of the sleeve and can injure any person or object which comes into contact with it. Another more serious consideration is that if the metal is aluminium and is at a high enough temperature the water causes an exothermic chemical reaction with the aluminium. [22]

$$3\ H_20 + 2\ Al \quad \rightarrow \quad 6\ H + Al_2O_3 + Heat$$

The hydrogen is absorbed into the molten aluminium and upon solidification it comes out of solution and causes porosity[22]. The shot sleeve therefore must be maintained in a clean dry and constant temperature situation Before production starts the sleeve must be heated up so the clearance increases to around 0.1 to 0.15mm which is a still small enough clearance not to allow molten metal to seep between the plunger and sleeve. [15,27]

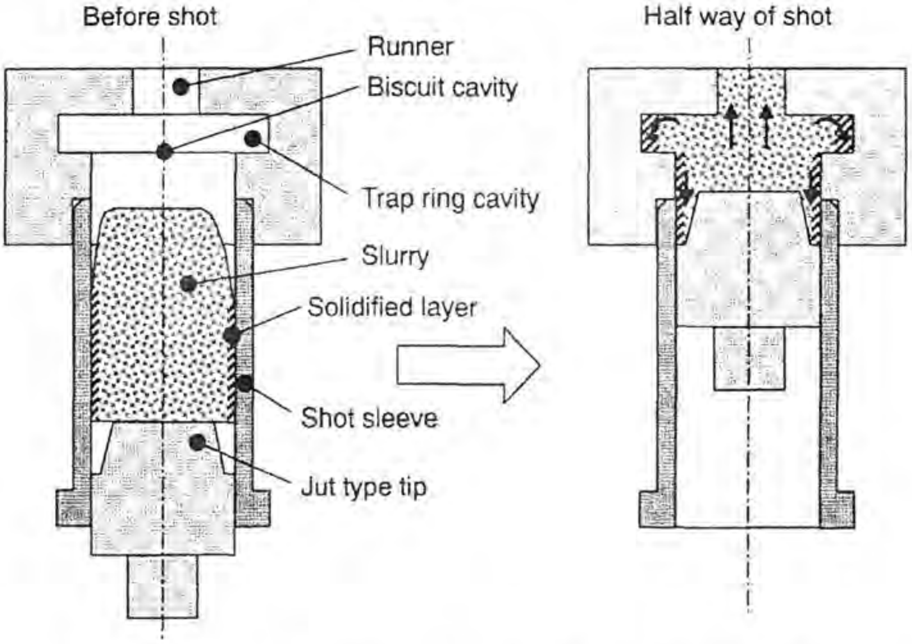
During casting the temperature of the sleeve can cause adverse conditions if it is too cold. A problem often associated with too cold a shot sleeve or molten metal temperature is "flaking". Flaking is caused by a reasonable thickness of molten metal solidifying while it is in contact with the colder shot sleeve, before the plunger begins its injection. If the solidified metal is not remelted when it is removed from shot sleeve surface by the action of the plunger moving forward, then this solid metal may cause defects in the following two manners. The solid particles may create a log jam at the entrance to the gate of the casting and so restrict the flow and so cause undesirable flow characteristics during cavity filling. Another defect that this could cause, are cold shuts in the casting. Since the solid particles will normally not allow metal to fuse with themselves, the area surrounding themselves will not be homogeneous with the rest of the structure[53]. Diagram 2-24 illustrates the flaking problem. The problem is most acute when the molten metal temperature is low and the shot sleeve is cold. The effect of these flakes or Externally Solidified Product (ESP) as T. Liang and C. Mobley[63] refer to them is a reduction in tensile strength and fatigue life.

Diagram 2-24: Schematic of a Section Through the Shot Sleeve Showing Metal Flaking in Conventional HPDC



A study by UBE Machinery Corporation showed that in SSM HPDC a solidified skin forms on the surface of the SSM billet as soon as it is placed into the shot sleeve of the die casting machine. This solidified skin can cause cold shuts if it makes its way into the casting. The skin should be removed by use of a trap in the shot sleeve or runner system. Diagram 2-25 shows the trap ring and a tapered plunger. Both the tapered plunger and the trap prevent the solidified skin from entering the component part of the casting. [54]

Diagram 2-25[54]: Showing the Trap and Plunger Tip for Removing Skin



The transfer time is the amount of time taken to move the SSM from the place of preparation, reheat furnace/SSM rheocasting machine, into the HPDC machine's shot sleeve. K.C. Sharma investigated the effect of having a 5 second time delay from the time the SSM is taken from the place of preparation and placed into the sleeve and the injection process started. He investigated two level settings, immediate (+-0.5second delay) and a 5 second delay. The results showed very little influence on the casting due to the time delay. Since the transfer of SSM from the preparation section into the die cast machine is done mechanically over a reasonable distance with fairly complicated movements, there will always be some delay. A five second window for this process is more than adequate. [8]

Since SSM metal is cast at a significantly lower temperature than conventional die casting metal, it was postulated by K.C. Sharma[8] that the shot sleeve temperature may be a significant variable in SSM die casting. Upon research of this it was found that the shot sleeve temperature had very little influence on SSM castability. For this purpose it will not be considered to be a significant variable in this study.

2.5.7 Cycle Time

The cycle time is the time taken for a part to be produced and the machine and die to be ready for the next part to begin being produced. That is, it is the average time to produce a part. The best way to establish the cycle time in industry is to time the time taken from when the cycle starts until when twenty parts have been manufactured and the cycle is about to start to produce the twenty first part. To get the average cycle time the time is divided by twenty. The cycle time or (also referred to as) shot rate determines the rate at which new hot metal is introduced to the die. For this reason the shot rate will have an impact on the mean die temperature.[14,27]

Each time new hot metal is brought in contact with the die to make a casting the latent heat and superheat is dissipated into the die and the die casting machine. After the first five casting have been produced the die reaches steady state[27]. So long as the cycle rate remains constant and the amount of die release agent applied to the die is the same each cycle the mean temperature of the die will not vary. Diagram 2-12 shows the average temperature of the die 0.25" [6.25mm] behind the surface of the die and on the cavity surface. A higher shot rate (lower cycle time) will increase the heat input rate into the die and hence the average temperature of the die will increase.

From the discussion in section 2.3 the life of the die with respect to heat checking is dependent on the temperature differential between the die and the metal. Running the die at a higher shot rate increases the temperature of the die and so reduces the temperature differential. By reducing the differential in temperatures the fatigue loading is reduced and the die life is extended [14].

The faster the shot the more economical the process becomes as the fixed costs are reduced by the increased volume from the higher shot rate. For this reason to it is desirable to run the process at the highest possible shot rate. In die casting the fixed cost is a significant portion of the total cost of each part. A saving of a few seconds of cycle time can reduce the cost per part substantially.[13,15]

In some instances a high shot rate may cause certain parts of the die to become excessively hot (examples are thin core pins and deep recesses). In bad practice the shot rate is reduced so as to avoid problems in these hot areas of the die. This is the wrong approach and the shot rate should be maintained at the highest rate possible based on the cooling time of the casting. These problem areas of the die should be cooled by external means. In so doing certain areas of the die are regulated so as to obtain the correct die temperature and hence the highest shot rate possible. Another advantage of a higher die temperature is shown in figure 2-14 and 2-15. A higher die temperature reduces heat checking and increases the cavity fill time which reduces the injection speed. Running the machine and die at a lower injection speed increases the life of the die and machine[14]. The cycle time can be controlled by controlling the temperature of the die.

2.5.8 Shot Weight

The shot weight of the casting is the weight of all the metal that was used to make the casting. This includes the parts of the casting that do not form part of the desired component. The shot weight effects the casting in three ways,

1. The thickness of the Biscuit
2. The filling degree of the Shot sleeve
3. Yield of the Casting

The thickness of the biscuit is changed by the amount of metal that is used to create the casting with the given die. More metal will cause a bigger biscuit and less metal will cause a smaller biscuit. The biscuit is used as a reservoir of molten metal to assist directional solidification. The modulus must not be smaller than the runner otherwise the pressure assisted directional solidification described in section 2.5.5 will not be possible[13,14,27]. Another consideration in the size of the biscuit is that the injection piston must not reach the end of its stroke before it has completely filled the die cavity..

The degree of fullness that the shot sleeve is when it is initially filled with metal is termed the percent full or the filling degree. The higher the filling degree the more metal is in the sleeve and the consequence is that less air needs to be removed from the sleeve. The higher filling degree also increases the modulus of the metal in the shot sleeve and in so doing reduces the heat loss into the sleeve. The lower the filling degree the less metal is in the shot sleeve and the more air is needed to be removed. The modulus is lower for a lower filling degree. The percent full that is normally recommended for conventional die casting is 60% to 75% full. The filling degree also determines the critical first stage velocity to create a solid wave front. [14,55,56]

Taking the above into consideration it would appear the larger the shot weight the better. This is not true however since a larger shot weight for the same size component means that more metal is used to create the casting. The component weight is the same for a small or large shot weight thus the extra weight is in the non-used part of the casting. This part of the casting must be recycled. The yield is defined as the ratio of the weight of the component cast and the weight of all the metal used to produce the casting.

The recycling process is a cost. The metal must be remelted. During melting energy is used and losses occur due to oxide formation and melt loss through burn off. For this economic reason the yield should be as low as possible, after taking into account the above requirements for a good quality casting. For SSM forming it is an even higher cost to recycle due to the special preparation needed for SSM. SSM forming as a result is under more pressure to reduce the shot weight and increase the yield of the casting.

2.5.9 Die Release Agents

A die release agent is a substance that is applied to the die cavity surface to provide an interface between the cast metal and the die steel. The interface can act as an insulating layer. It can also act as a barrier to stop soldering and chemical attack of the die steel. The main use of the die release agent is however to assist in the ease of removal of the casting from the die. Die release agents are also sometimes called die lubricants. Another area where lubricants are used is to lubricate the shot sleeve. There are four broad categories of Die lubricants/release agents, Water Based esters, Graphite based lubricant (colloidal suspension in water), Oil based lubricants and Graphite powder lubricants.

Water based Esters are widely used in aluminium conventional die casting. They give an excellent surface finish. There are minimal toxic fumes released. Also the amount of gas (although dependant on the lubricant used) is normally much less than that of oil lubricants. However high concentrations will release relatively more gas and could create porosity problems. They also do not discolour the casting. There is virtually no build up of the lubricant on the die. This is important and allows the die to be run for extended periods of time, it is not uncommon for a die lubricated with a water based ester product to run for three weeks, 24hours a day without any cleaning of die being necessary. Another important reason why build up of die lubricant is undesirable, is that the lubricant blocks the air vents. Air vents are a critical part of the die and should they become blocked the porosity of the casting is severely increased (as the gas is not allowed to escape and instead becomes trapped inside the casting). The air vents are only 0.2mm deep and as a result can clog very easily. The release agent is water based and so assists with cooling of the die. The esters will burn off if the die temperature is too high, conventional ester lubricants can only operate at die temperatures below 270°C. Above this they are ineffectual. For this reason it not uncommon to see the operator of die casting machine with a badly designed die, spraying the die with lubricant for 45seconds or more and the die to be drenched in lubricant. This is done by the operator in an attempt to cool the die enough so that the esters do not burn off as much and can provide the release action needed. This is obviously not correct and the die should rather be maintained at a lower temperature or a different die lubricant should be selected. The spray may be directed (with the use of nozzles) to specific areas on the die which require extra cooling and lubricant. It is noted however that the cooling action is very limited and localised as a result only cores and other separated parts of the die are successfully cooled. If parts of the die itself are attempted to be cooled by the application of lubricant the result is not satisfactory. This is because the large heat reservoir in the mass of hot die steel will heat up the die again within a short period of time, normally before the next shot is even fired. Die lubricant can cool localised areas only but for best results proper external die cooling means are required. The esters in the lubricant do not provide a significant insulation on the cavity-metal interface. [57,27]

Graphite based lubricants are normally colloidal suspensions in water. Graphite is however also sometimes in an oil base as described in the next paragraph. Graphite based lubricants are very powerful release agents. The graphite is very fine and forms a layer on the surface of the die when it is sprayed onto it. A bonding agent is normally used in the lubricant to assist the graphite in bonding to the steel of the die. The most commonly used bonding agent is Sodium Silicate or "water glass". The Sodium Silicate dissolves in the water and forms Sodium and Silicate ions and assist the graphite to bond onto the steel die face. To perform the release action there must be at least two layers of graphite particles on top of each other. Since the particles are so fine this is nearly always the case as long as the concentration is sufficient. To action the release the cast metal sticks to the top layer of graphite, it parts with the bottom layer of graphite and the part is released. This is obviously the theoretical case; in reality no graphite may remain on the cast metal or none on the die. This is a positive action for release and thus the graphite is very effective. The problem with this is that the castings can be discoloured by the graphite. Also over time the graphite builds up on the die face and will cause the geometry of sharp corners and other fine geometries to become rounded and obscured. The Silicate ions can transform into a glass structure and form a very hard build up on the die face which is very difficult to remove. The glass structure can form at die temperatures above 320°C when casting metals at temperatures above 940°C (brass is normally cast at this temperature). The graphite build up and glass formation will lead to blocking of the vents. For this reason the die must be removed regularly and the die faces thoroughly cleaned. The graphite's release action is not hampered by high die temperatures. Lubricant left to stand for extended periods will have bacteria growing in it, the bacteria are mainly hydro-carbon compounds which when the high temperature molten metal comes into contact with, combust and release gases (CO_2 mainly). These gases can cause porosity. The graphite has an insulting effect on the metal filling the die cavity. By so doing the it will ensure the die steel is subjected to a slightly lower temperature and reduces the amplitude of the thermal cycle experienced by the die. This will help to reduce heat checking and prolong the die life. [14,60] It will also increase the cavity fill time.

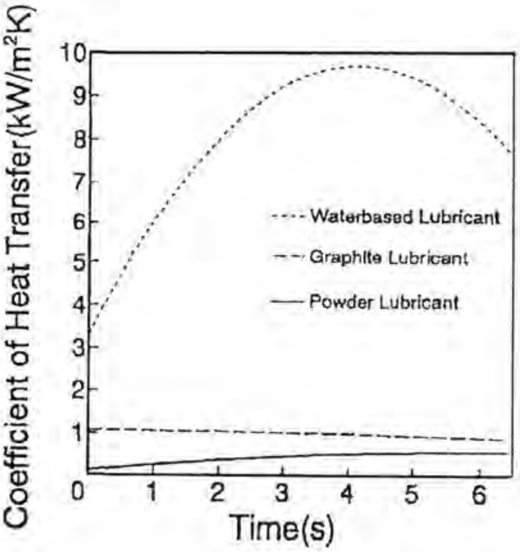
Oil based lubricants combust when the molten metal comes in contact with them. The gases produced are mainly, H_2, H_2O and $C0_2$, and are entrapped in the metal and form porosity when entrained into the casting. If oil based lubricants are used the amount used must be minimised so that the amount of gas released is minimised. Oil based lubricants are generally not used any more in industry for the associated quality problems as well as the noxious fumes released. Oil based lubricants are restricted to die preparation and plunger lubricants. PA111 from Kluber is such a lubricant (die preparation agent). It is used widely in industry only to form a "patena" on new dies and dies that have not run for extended periods. The "patena" forms a layer which provides a better adhesion surface for the release agents and a smoother surface. The first shot fired after the application of this oil lubricant is discarded since it will contain porosity and is normally discoloured as well[9]. Another area where oil based lubricants are commonly used is to lubricate the plunger and shot sleeve. A product called Isolat 208SP from Fochem is such a product.

Care must be taken not to apply too much lubricant to the plunger. Also the lubricant should be applied onto the plunger when it is in the retracted position. The lubricant must not be applied inside the shot sleeve. The reason for this is that excess oil in the sleeve will cause combustion when the molten metal is introduced to the shot sleeve. This combustion releases gases which are entrapped in the molten metal and will result in porosity of the casting should they be entrained into the casting. A better way to lubricate the shot sleeve is using graphite since there is less combustion. Isolat 208SP is in fact graphite in a thick oil base[9,58,59]. The oil in Isolat 208SP will combust and lead to porosity. The best way to lubricate the sleeve is to apply graphite only, this is not practical in most circumstances. Another alternative is described below.

A better method is to use dry lubricants, these are graphite or esters that have been not been suspended in liquid. The difficulty with these is their application and storage. Their use is limited in industry. However the dry graphite lubricant has been successfully used by elctrostatically charging the die and particles and so causing the bonding action required[61]. A method for lubricating the shot sleeve uses graphite contained in a waxy substrate. The mixture is normally 15% graphite and the balance is an ester. The mixture is manufactured into small beads. The wax allows the graphite to be transported evenly over the shot sleeve. When the beads enter the sleeve they melt and move by capillary action up the walls of the sleeve. This forms a thin layer for lubricating the plunger's movement. Although the graphite is responsible for the lubrication it is necessary to have the wax substrate. The wax substrate will combust when molten metal comes in contact with it. The combustion reaction forms gases which, in large enough volumes, cause porosity. It is important to limit the amount of beads used to a minimum. [59]

Research done by M. Tashiro, S. Aoyana and K. Sakaota showed that powder lubricants display extremely good insulation. Diagram 2-26 is taken from their work and illustrates the insulating capabilities of waterbased lubricants (esters), graphite water base and powder graphite lubricants.[61] The insulating property of the die lube is very important in some instances. For example when die casting brass there is rapid heat loss that takes place since the temperature differential between the die and metal is great (die temp. typically 300°C and metal temp. 940°C) and the coefficient of heat transfer of brass (because of the high Copper (60%) content) is very high, for this reason it is often a necessity to utilise a die lubricant that has insulating properties. The insulating properties slow the solidification of the part and so enable the cavity fill time to be slightly longer. By using a slightly longer cavity fill time it is possible to reduce the speed of the plunger which in turn will reduce porosity. This example is from the author's experience in industry with a difficult Brass high pressure die casting which required high internal integrity. In diagram 2-26 the graph showing the coefficient of heat transfer for "water based lubricant" is a water based ester type lubricant. It is clear that, in terms of insulation properties the graphite type is far superior with the powdered graphite form showing the highest insulation properties.

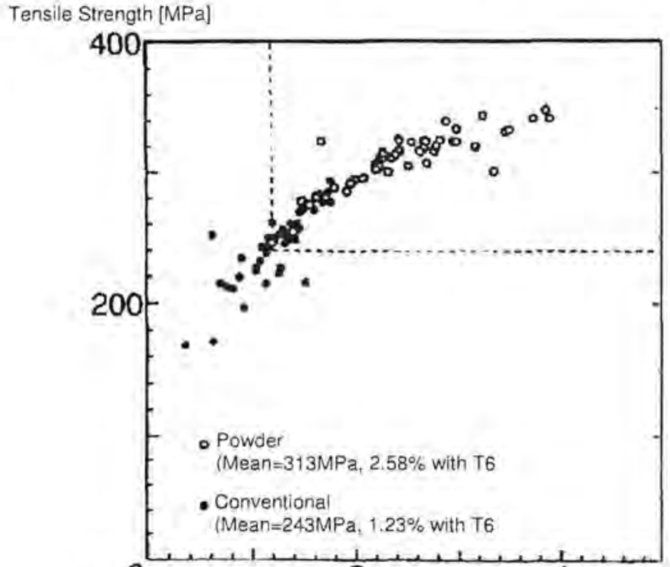
Diagram 2-26[61]: The insulating capabilities of waterbased lubricants (esters), graphite water base and powder graphite lubricants.



Due to SSM being cast with no super heat and reduced latent heat, it is suggested that an insulating lubricant is beneficial to SSM castings[62]. The benefit of the lubricant is specific to each casting. However for the specific case analysed by H.G. Munson and P.J. Pacholke Dumont a clear correlation between the insulation properties of the lubricant and the mechanical strength properties of the casting was evident. A graph from their research is shown in diagram 2-27. The effect of the lubricant shows an increase of 28% in tensile strength and 110% improvement in elongation (refer to [62]). During filling, partial solidification of the metal takes place sometimes, this forms fragments which create mini cold shuts (inhomogeneities) in the casting. This reduces the castings mechanical properties. The graphite reduces the formation of mini cold shuts due to it insulation. [62]

Research done by T. Liang and C. Mobley showed that cold shuts reduce tensile strength and ductility. They also showed that castings with flow marks have reduced tensile strength compared to those with no flow marks. The presence of oxide film features and fragments as described above also decreases the tensile strength. [64]

Diagram 2-27[62]: Tensile Strength of an Aluminium Casting Cast using Different Die Lubricants



From the discussion above it is clear that cold shuts are undesirable and are caused by the cast metal reaching too low a temperature. A method to avoid this is to use an insulating die lubricant to reduce the rate of heat loss from the cast metal into the die. Although it must be noted here that this is not the only method; it may be possible to achieve the same result by strict temperature control of the die through correct die design.

2.6 Die Design

To create a high pressure die casting die the cavity must be machined out of steel (normally) as the "negative" of the component to be cast, this is referred to as the component die cavity. There must be a means to get the metal from the shot sleeve to the entry point of the component die cavity (this part is called the runner). To get the metal to enter the component die cavity in a specific manner so as to successfully fill the component die cavity, an entry point is chosen and a particular cross sectional geometry is machined into the die (this section is called the gate). To allow for gases contained in the die to escape when displaced by the molten metal, vents must be machined into the die. In some circumstances more metal is required to flow through the same area or to be replaced by other metal; to achieve this extra cavities are machined into the die and are filled after the metal has passed through the component die cavity (these cavities or wells are called overflows). Achieving specific temperatures and thus heat flow rates from specific areas of the die to achieve specific solidification patterns in the casting are necessary for production of high quality castings. A method to achieve this is to calculate the heating and cooling requirements and then machine heating or cooling channels into the die. The die design must take into account shrinkage of the part during after and in shot cooling. The split line of the component needs to be designed to avoid undercuts and ensure the machine locking force is not exceeded by the product of the projected split line cross sectional area and the metal pressure. Recycling of material is costly and the die design should aim to achieve the highest yield possible. [7,14,15,18,20,22,27,32,41,54]

2.6.1 Gates and Runners

The runner design must achieve a passageway with attributes which cause the metal to get from the shot sleeve to the gate without any detrimental effects. It must allow for directional solidification as well as a reasonable tendency towards laminar flow[14,20]. The runner must achieve converging flow[14]. A large amount of literary discussion and detail about the runner and gate design is included in the Test and Experimental Methods Chapter as well as in the Results and Discussion of Results Chapter. To avoid duplication it is not discussed in further detail here, a very brief summary of only a few salient points are noted.

The gate for conventional die casting is required to fill the casting with metal which is (normally) highly accelerated as it passes through the gate. This will fill the mould with momentum governing flow. This method gives good part quality for conventional high pressure die casting. In the case of SSM casting the gate should as wide as the section of the casting it fills and should cause converging flow as the metal enters the casting so as to ensure at least three shear faces are present[7].

2.6.2 Directional Solidification

This has been discussed in previous sub sections and is discussed further in the Test and Experiment Methods Chapter and the Results and Discussion of Results Chapter. To avoid duplication a very brief summary is included below.

The degree of directional solidification reduces or eliminates shrinkage porosity [13,14,15,27]. To achieve successful directional solidification the modulus of each part of the casting must be calculated[16]. The gating should be such that the highest modulus section is closest to the gate and the descending order of magnitude of the modulus of each section is also the order of each section's geometrical position with respect to their length of flow path from the gate[13]. Should this not be the case to achieve directional solidification it may be necessary to utilise multiple gating or modify the solidification of different sections with the use of heating or cooling channels[20]. In SSM casting part of the metal is already solidified and so the amount of shrinkage and solidification porosity is naturally reduced compared to the same casting produced from fully liquid metal.

2.6.3 Vents

Air vents are necessary to enable gas (air) to escape from the mould. For the air to escape without building up pressure inside the die, it is necessary to design the cross sectional area of the vents so that they do not choke the flow. To achieve this the speed of the air through the vents should not rise above the speed of sound[46]. The vents should remain open at all times and must not be blocked with foreign matter (eg. die lubricant) at any time. The depth of the vent should not be greater 0.2mm. A depth greater than this will allow molten metal to travel through the vents and escape out the die and into the atmosphere[14,27].

2.6.4 Overflows

Overflows are used to modify the filling pattern. They can also be used to remove metal from the casting and replace this with "new" metal. This is useful if part of the casting always has defective metal found in the same place, examples of this could be cold shuts or oxides[54].

S. Sato, M. Adachi, H. Sasaki, Y. Harada, T. Maeda and N. Ishibashi [54] showed that by using overflows the flow could be altered and defects could be avoided or removed. The component studied by S. Sato et al was called a lower arm, depicted in diagram 2-28. It is a structural part requiring high internal integrity. During filling the cored hole 'C' cold shuts were encountered. This is shown in diagram 2-29(a) and (d). The pictures in the top row are results from simulation and the pictures in the bottom row are actual results from casting.

Diagram 2-28: Solid Model of the Lower Arm[54]

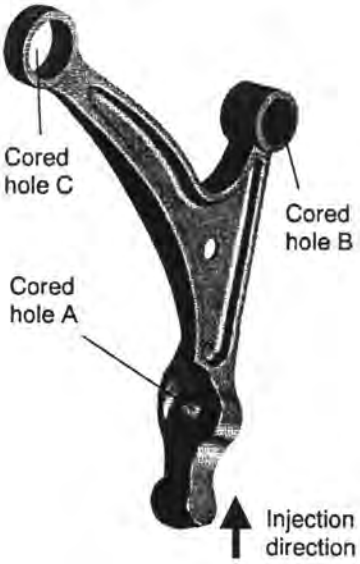


Diagram 2-29: Simulation and Cast Results of Cored Hole "C" [54]

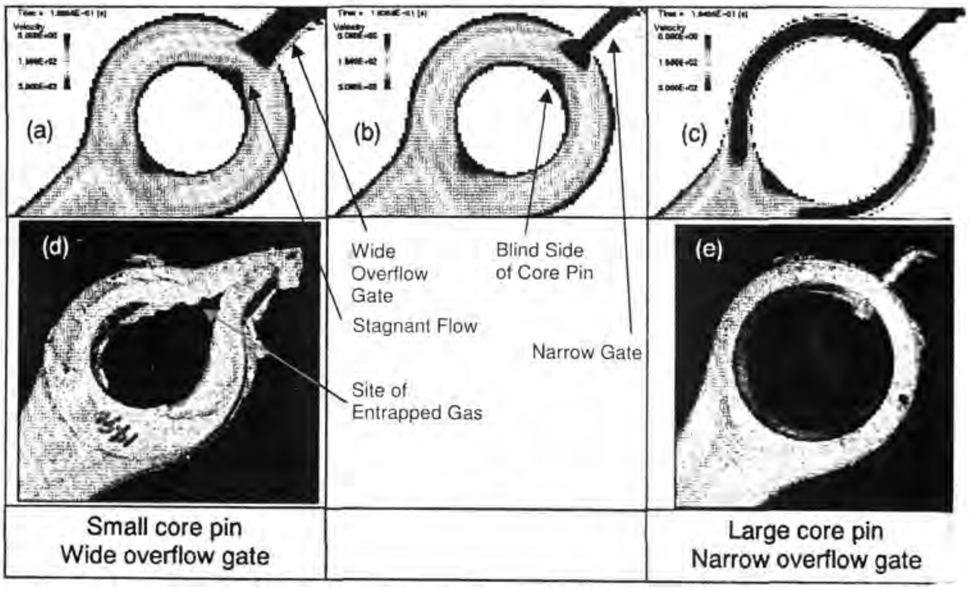


Diagram 2-29 shows the usefulness of overflows to modify the flow pattern. Diagram 2-29(a) and (d) has a large gate leading to the overflow (not shown). There is stagnant flow and hence a discontinuity in the casting at this point shown in 2-29(d). The wide gate into the overflow allows flow into the gate and neglects the portion adjacent the gate. Changing the gate to a smaller size increases the internal metal pressure due to the reduced cross sectional area as a result the flow path is less induced towards the overflow gate and more towards the blind side of the core pin. By inducing the flow to remain in contact with the core pin, there are three shear faces acting on the flow. This gives desirable SSM flow. By increasing the size of the core pin the cross sectional area is reduced further and there is less opportunity for the flow to lose contact with the wall of the core pin. In so doing the number of shear faces are not reduced. This leads to an even better result with the least amount of stagnant flow, shown in diagram 2-29(c) and (e). [7,41,54]

The stagnant areas can easily give rise to cold shuts. Correctly placed and sized overflows can avoid these by either entraining the cold shut out of the component part of the casting or by avoiding the flow geometry causing the cold shut to form. [10,54]

The overflows should be positioned in the area of the die where a flow modification is needed. In this area the overflow's position should also be at the place which is the last to fill[10]. The gate leading into the overflow should be sufficiently restrictive so as to avoid flow being induced into the overflow before the area has been filled [54].

Overflows may be used to avoid problems often associated with the last place to fill in castings. These problems are often, incomplete fill, splash, tearing and premature solidification.[41] Incomplete filling is reduced by an overflow inducing extra metal flow to take place, as the overflow is filled, that would normally not happen should the overflow not have been present. The extra flow causes the metal to continue flowing in areas which otherwise would be stagnant and could lead to incomplete flow.

The SSM can segregate (liquid eutectic separate from the non-eutectic solid) at areas of the die which experience extremely high flow velocities and or shear rates. This segregation is also referred to in severe cases as "splashing". The "splash" is the liquid portion travelling ahead of the normal fluid flow. The areas filled by the liquid (eutectic) only, have substantially different properties to those filled with unsegregated SSM. Segregation is undesirable. A correctly placed, sized and gated overflow will ensure that this segregated material is removed from the component and induced into the overflow. [41,54,64,65]

The site of tearing of the casting during solidification is normally the site of other defects as well. These defects are normally porosity or cold shuts[13]. Defects of gas porosity may be removed by the use of correctly placed overflows. Cold shuts can also be avoided with the use of overflows.

There is one defect however which is not easily remedied by the use of overflows. This defect is shrinkage porosity. An overflow may only be used to feed shrinkage porosity if the modulus of both the overflow and its gate is higher than the section of the component it is feeding, however in HPDC it is often not practical or possible to utilise such a facility. For the overflow to successfully feed the shrinkage to avoid porosity it must be of sufficient modulus to solidify after the section it is feeding. This often means excessive post casting machining and or fettling. Due to the high volume nature of components produced using the HPDC process, the fettling and post machining must be reduced to a minimum. For this reason the gates of overflows should be of as small a cross section as possible so as to utilise easy removal. It is usually more beneficial to design the die with heating or cooling channels to overcome this defect type.

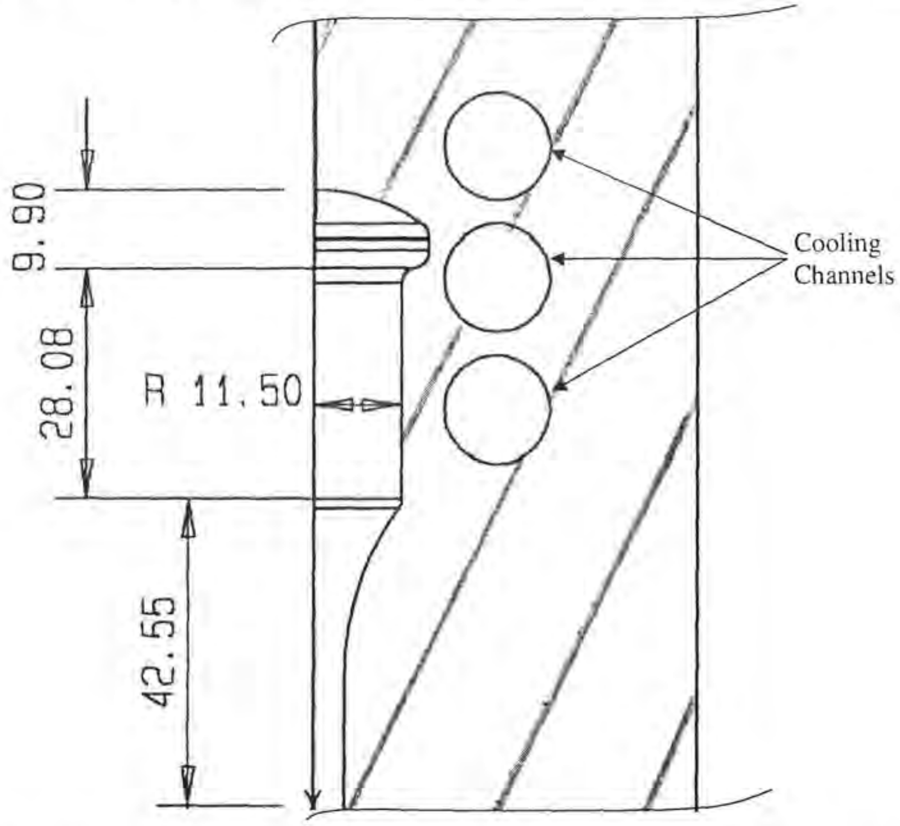
26.5 Heating and Cooling Channels

The use of heating and or cooling channels is a widely accepted approach to controlling the temperature of the surface of the die. It is widely used to achieve directional solidification and to move porosity to non-critical areas or eliminate it entirely. [14,20,27]

Much has been mentioned in the previous sections on die heating or cooling channels and the author will only summarise their application. Examples and applications of their uses have been mentioned in preceding sections.

By cooling and or heating certain regions of a die it is possible to setup and maintain temperature gradients on the surface of the die. These temperature gradients will remain in place even during filling of the metal at high temperatures. Diagram 2-30 is a section view of the Short Arm, back plate die half which is used during experiments for this research. Diagram 4-3, 4-4 in the Results and Discussion of Results Chapter shows the full view of the die. Diagram 2-30 shows the three circular channels in close proximity to the die cavity. The channels were machined by using long series drills. Channels are normally difficult to manufacture. It is necessary to plan the layout of the die cavity very carefully to ensure that it is possible to get the channels to the desired areas of the cavity.

Diagram 2-30: Section View of the Short Arm, Back Plate Die Half- Showing Cooling Channels



The channels shown in diagram 2-30 carry cooling water which cools the surface of the die. Since the rest of the die has no cooling or heating this part of the die cavity will be at a considerably lower temperature than the rest of the die cavity.

Another method is to use fountains in the place of channels. Fountains are useful for localised or spot cooling/heating. A fountain is created by machining a channel perpendicular to the back face of the die. The channel ends about 10mm before the die cavity. A tube of 2/3 the diameter of the channel is inserted down the channel and stops 5mm short of the end of the channel. The exit hole of the channel is plugged in such a fashion so as to allow fluid to travel down the tube and then return back up the channel on the outside of the tube and exit out through the channel's plug.

The benefits of cooling and heating specific areas of the die cavity have been mentioned in the previous sub-sections.

2.6.6 Shrinkage allowance

The internal metal pressure during injection of the metal will ensure that the casting is in contact with the die wall during solidification. However once the casting has solidified it is no longer able to transmit the metal pressure to the surface of the casting. As the casting cools from solidification temperature to room temperature further shrinkage will experienced by the entire casting. The die cavity size must take account of this. In most instances experience has shown that an increase of 1% in the die cavity is normally sufficient to take this into account. For detailed analysis of shrinkage allowance the reader is referred to E.A. Herman, NADCA (North American Die Casting Association) – Designing Die Casting Dies, pg 39-63 [27].

2.6.7 Split line, Metal Pressure and Split line area

The metal pressure has a direct impact on the size of pores due to shrinkage and entrapped gas porosity. For this reason the higher the metal pressure the higher the perceived quality of the casting is. The disadvantage of high metal pressure is that it places the machine and die under high loads and reduces the life of both. The metal pressure is limited by the machine's clamping force and the cross sectional area of the die.

For most aluminium castings a metal pressure of 600 to 700kg/cm^2 is sufficient to form good quality castings[15]. This same metal pressure creates a force acting against the die surface. Consider the plane which is parallel to the split line. The cross sectional area, which the split line creates as it passes through the die cavity, is acted upon by the fluid in the die. This fluid is under pressure and so a force is present acts in the direction to split the die open across the split line. The force must be less than the force holding the die halves together. Equation 3-2 in the Test and Experiment Methods Chapter illustrates the relationship, a worked example is included of the short arm die.

2.6.8 Yield

The yield is defined as ratio of the volume of the used part of the casting (the component) to the total cast weight, in the as cast condition. The yield of a casting is very important for economic reasons. All the raw material that is part of the casting but which is not used in the component needs to be processed back into usable product. This processing step is costly and is driven by variable costs. Thus the volume of unused metal of a casting must be reduced to a minimum. The unused metal is made up of three major parts, overflows, runners and gates. The volume of these should be reduced to the minimum level while still maintaining the required quality of the part.

2.7 Machine Type

There are two broad machine types used in Cold Chamber High Pressure Die Casting (HPDC). They are conventional manually controlled machine and a closed loop injection controlled machine. The latter is commonly known as a shot control machine.

The first machine type to be developed was an open loop controlled machine. In this type of machine the speed and pressure of the injection piston was only controlled by the position of a gate valve which supplied oil flow to the injection cylinder. There are two valves, one controls the flow of oil coming directly from the tank and the other valve controls the flow of oil from the accumulator. The valves are manual valves.

A later development is the Shot Control machine. This machine uses closed loop control utilising feedback from a displacement sensor and a pressure sensor. The closed loop control, controls the velocity and pressure of the injection piston. This is very useful for maintaining a set injection profile shot after shot. The reasons why the profile changes if the valve is simply left on one setting is numerous. An example is lubrication of the plunger, should this vary a variation in piston speed will result. Another example is wear of the shot sleeve and or metal plunger, since this causes a change in clearance tolerance for the sleeve and plunger fit which will influence the resistance offered to the plunger during its injection stroke. This change in resistance will bring about a change in speed should the valves be left in the same postion. In SSM casting the (metal) fluid friction during filling is considerably higher than in liquid die casting. Since the flow is laminar and as the die becomes more full so the fluid friction increases, if the injection system of the machine does not compensate for this the, injection speed will decrease. A change in injection speed will effect many other criteria which have been discussed previously. For these reasons it is desirable to use a Shot Control Machine for SSM HPDC. [8,66]

2.8 Defects, Types and Causes

All the defect types have in fact already been mentioned and many of their causes have also been discussed. This section will serve as a summary and brief explanation of defects and their causes with a view to introducing the next section which will detail key variables which need to be controlled and or designed to avoid these defects.

2.8.1 Gas Porosity

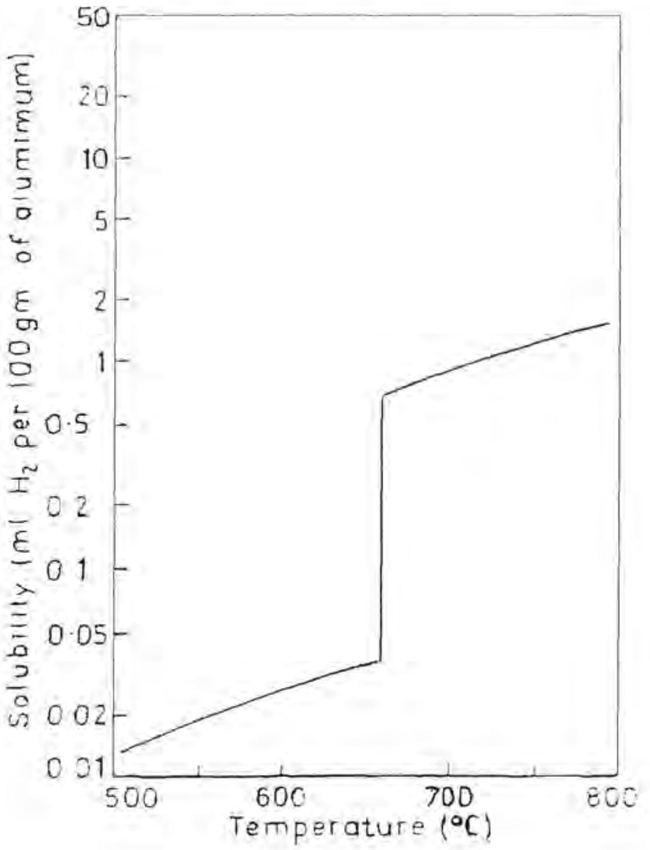
Gas Porosity also known as entrapped gas porosity is caused by inclusions of gas in the metal or by gas which is dissolved in the metal. Gas can be entrapped in the metal through the flow being turbulent. Another way gas may be entrapped is by incorrect filling procedure[14]. Diagram 2-29(d) is such a case. As the two flow fronts meet on the other side of the core pin their momentum keeps them moving in a straight line and the back of the core pin does not get filled. The metal together with the core pin forms barrier which traps the air. As the metal pressure in this area increases the metal will flow into this area and will force the trapped air to become enveloped inside the metal as gas porosity. The second method by which gas porosity may form is when gases which are dissolved in the metal come out of solution when the temperature falls below a point at which the partial pressure of the gas is lower than the metal. The gas produced forms porosity whose size (diameter) is in most cases smaller than the entrapped gas porosity. [22]

Both these types of porosity are easily identifiable by their characteristic shape[13]. They are rounded in shape[22]. To avoid the entrapment of gas correct die design and desirable fluid flow must be used and ensured. This has been discussed in previous sections at length. To avoid dissolved gases one must first identify those gases which have the highest affinity for dissolving in Aluminium. The gas which has an extremely high affinity and is omni present in foundries is hydrogen.

Diagram 2-31 shows the alarming increase in solubility of hydrogen in aluminium at temperatures above 660°C. Diagram 2-31 is from the Aluminium Foundry Short Course[22]. Semi-Solid Aluminium is below this temperature for alloys containing less than 15% Silicon by weight (diagram 2-1). This implies that dissolved hydrogen is not a problem for SSM casting. This is partly true, however to produce SSM material the metal must be melted and in this step it may increase above the 660°C critical temperature. The gas then dissolved will come out of solution during solidification and form gas bubbles which may then float out of the melt into the atmosphere or remained trapped inside the metal. If these gas bubbles remain trapped inside the metal they will form entrapped gas porosity as described above. For this reason it is important that the SSM is well prepared and free of entrapped hydrogen or other gasses.

To summarise entrapped gas porosity must be prevented by ensuring that correctly prepared SSM is used and the correct fluid flow characteristics take place. To ensure correct fluid flow characteristics the suggestions of the preceding sections need to be adhered to, this involves tight process control and correct design of the process. To predict and then avoid entrapped gas porosity simulation and or experimental work is necessary. The author has shown that there are general rules to be followed but they are not a catch all and each casting must be evaluated on its own specifics, requirements and characteristics.

Diagram 2-31: Solubility of H_2 in Aluminium[22]



2.8.2 Shrinkage Porosity

This type of porosity is formed during solidification. In conventional solidification interdendritic porosity can occur especially in castings which form long dendritic arms[16]. Due to SSM's globular microstructure interdendritic porosity is highly unlikely (diagram 2-7). Macro solidification porosity will occur in any area where there is no liquid metal to feed the casting as it solidifies[16]. This was discussed in section. 2.6 Die Design. Solidification porosity is differentiated from entrapped gas porosity in casting samples by the jagged shape associated with formation of the shrinkage voids (pores). [13]

Solidification porosity must be avoided by incorporating directional solidification techniques in the design of the die. As mentioned already this may require specific runner and gate designs as well as special cooling or heating channels. [13,14]

Many suggestions are made in the literature but no specific set of steps and calculations have been found to ensure that the casting made from the die will have no defects. To ensure that the die design is successful in eliminating solidification porosity experiments and or simulation must be carried out on the die. In this investigation a methodical process will be undertaken in an to attempt to reduce the amount of experimental work required to arrive at a successful casting.

2.8.3 Cold Shuts and Entrapped Oxides

Cold shuts are formed when two fluid flow fronts meet and are unable to fuse together[54]. In SSM the flow fronts are normally laminar and form an oxide layer. This oxide layer is solid and will not allow metal to fuse with it. For this reason cold shuts in SSM casting are normally associated with an increase in oxide content at the site of the crack[17] because the cold shut entraps the oxide layer. To detect these defects types and to be able to confidently classify them a Scanning Electron Microscope (SEM) equipped with Energy Dispersive Spectroscopy (EDS) is an established method[17,54].

Undesirable filling has been highlighted in the previous sections and normally results in secondary flow. Secondary flow is a term defined by the author and G.Govender [17] as when a cavity partly fills and then the fluid, from a different flow front passes over the metal surface of the partially filled cavity. An oxide layer is likely to form since there is a time delay between the two surfaces meeting and both are in contact with oxygen in the air. The oxide layer will prevent homogeneous amalgamation (fusing) of the two metal surfaces, since due to its higher melting temperature it is solid. This failure to form a homogenous structure will result in a cold shut[10,17]. The oxide which was on the surface of the flow fronts becomes entrapped and further disrupts the homogeneous metallographic structure.

Secondary flow will only occur if there is formation of another flow front – to form another flow front the internal kinetic energy must be greater than the surface tension energy, this condition must be met for a new flow front to form. The kinetic energy side of the equality involves the flow rate of the metal and consequently shows the importance of the correct setting and control of the flow rate (injection piston velocity) during the injection process. This has been shown by John Campbell [31] who used this principle to calculate, in liquid casting the maximum flow rate a metal could travel before it became turbulent in nature and caused entrapped air and other problems. He is well known for developing and industrializing the Cosworth™ process, based on this principle. Another method by which a new flow front may be formed is if the geometry of the die splits the flow into two or more flow paths. Each flow path will have its own flow front. This is demonstrated in diagram 2-32 and 2-33 by research done by S. Sato et al [54].

Diagram 2-32: Shows Simulation of Die Geometry Splitting the Flow into Two Flow Fronts[54]

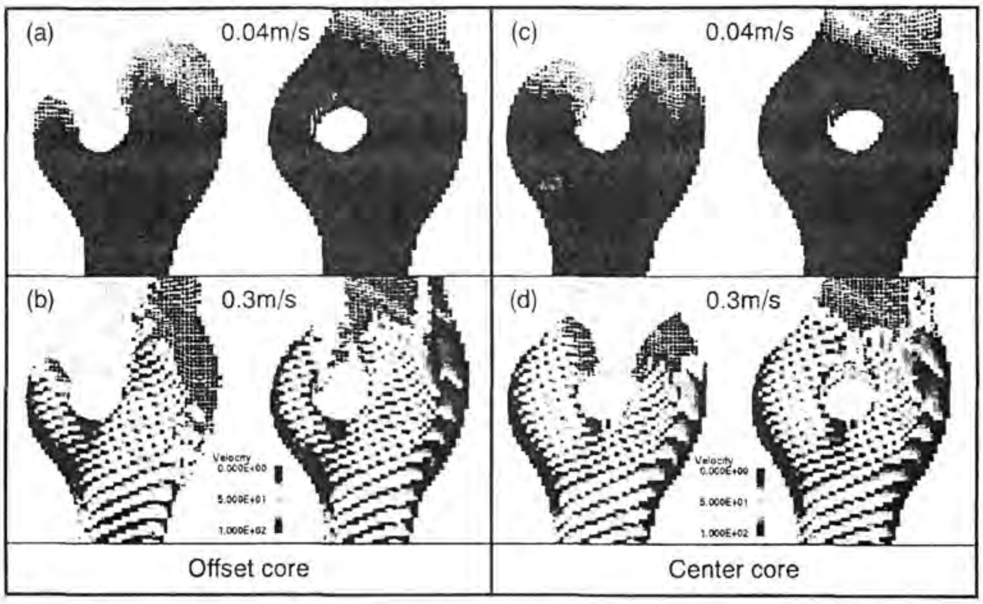
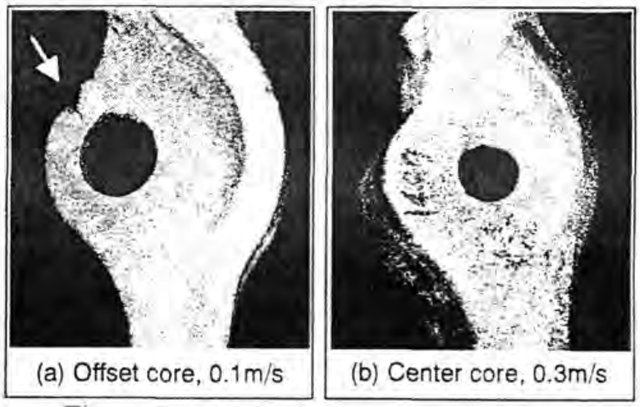


Diagram 2-33: Shows the resulting cold shuts on the left and then after geometry modification to the die the defect is reduced. [54]


(a) Offset core, 0.1m/s

(b) Center core, 0.3m/s

Cold shuts create inhomogeneities in the casting. It was found by T. Liang and C. Mobley [63] that cold shuts reduce tensile strength more than macro, micro porosity or oxide inclusions. It is clear that cold shuts are highly undesirable for high internal integrity and high strength components. This is echoed by S. Sato et al [54].

To avoid cold shuts the literature reviewed in this section as well as previous sections has suggested avoiding flow fronts meeting. If this is impossible to avoid then ensure that the cold shuts do not meet in a stagnant area which will not allow new metal to flow into the original area of the meeting place, this may reduce or eliminate the cold shut. This may be done through the use of overflows or by modification to the component geometry (if this is possible). If the metal of the two flow fronts is too cold the likelihood of cold shuts forming is even higher and the severity of the cold shut is increased.[13,54,64]

As before the die design plays a vital role in determining whether the casting will have cold shuts. To avoid cold shuts the die designer must anticipate where flow fronts are likely to meet. To do this simulation, visual inspection and experimental work is necessary. Once the flow front meeting patterns have been established the die design should be modified to avoid flow fronts meeting. Certain flow front meeting patterns are not practical to avoid. In these circumstances overflows are used to entrain the cold shut out the component and to ensure new metal arrives at the original flow front meeting area and fuses. In this manner cold shuts may be eliminated. Each component is different and so a separate study is necessary for each new component.

This investigation will use the suggestions reviewed to eliminate cold shuts in the component by conducting the necessary study on the component and designing the die accordingly.

2.8.4 Short fill

Short fill is a relatively simple defect to detect. However its causes are not always easily remedied. Short fill is defined as a section of casting which has failed to fill fully. The reason for the incomplete filling maybe due to high pressure gas trapped in an extremity of the die and thus preventing the metal from entering this extremity. Another cause of short fill may be due to a severe cold shut forming and its witness being seen on the surface of the casting. To reduce high pressure gas pockets venting should be sufficient at the extremities of the die. This is however not always practical. Cold shuts must be reduced as discussed in the preceding section.

2.9 Identification of Key Variables in SSM High Pressure Die Casting of Components

The die design determines the fluid flow paths as well as the success of directional solidification. It has been shown that the flow rate influences the manner in which the fluid behaves. The temperature of the metal will impact on the fraction solid which in turn changes the viscosity which also affects the fluids behaviour. Achieving the correct fluid flow behaviour is paramount to achieving a successful SSM casting. All these points have come out of the literature survey.

From the survey it is apparent that the fraction solid (determined by the metal temperature) influences the viscosity and hence the fluid flow behaviour. The most suitable fraction solid for casting is 0.5 to 0.53 and the corresponding metal temperatures, for the alloy used in this study (A356) are 580°C and 575°C respectively [48]. However in this temperature range the literature has not suggested which temperature is the most suitable and instead suggests that different temperatures are suitable for different components. For this reason the metal temperature will be investigated in this study.

The machine parameters are dependant on the die; however, an indication of the gate velocities has been given by the literature which show the maximum and minimum to be within the range 0.8 – 2.4 ms^{-1}. It has been shown however that these values are highly dependant on the specifics of the die geometry and the metal temperature. It has also been shown that graphite die lube gives superior results due to its insulating properties. This investigation will attempt to achieve a homogeneous high integrity casting without the assistance of the insulating properties of the graphite lubricant. This will place more emphasis on the die and process design which is the aim of this study.

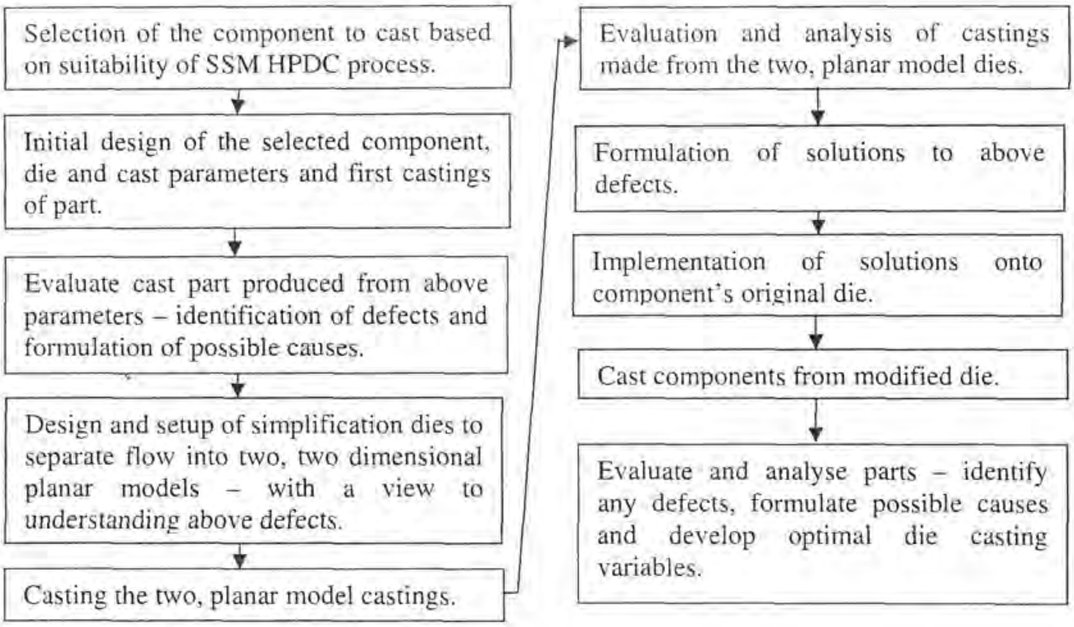
Due to the impact of the die design on the outcome of the casting much of this study will concentrate on experimenting with the die to understand the fluid flow behaviour so developed. Once this has been achieved the die design itself will be investigated and modified to achieve a casting with high internal integrity.

It is apparent from the literature study that all the variables mentioned in the die casting system interact with each other and as a result may not be treated separately in a "one variable at a time" design of experiments. It is instead necessary to design experiments so as to evaluate the variables at all their different levels simultaneously. To do this effectively Taguchi Experimental Analysis will be used[19].

Chapter 3 Test and Experiment Methods

The experimental procedure for this work doesn't follow the classic style, because the objective of the study is to achieve a high integrity SSM high pressure die cast component through optimising the die and process variables. To this end the experimentation process took the form illustrated in the flow diagram below. The process is further explained in the text that follows.

Diagram 3-1: Flow Diagram of the order of the Experiments



Selection of the component to cast based on suitability of SSM HPDC process.

Initial design of the selected component, die and cast parameters and first castings of part.

Evaluate cast part produced from above parameters – identification of defects and formulation of possible causes.

Design and setup of simplification dies to separate flow into two, two dimensional planar models – with a view to understanding above defects.

Casting the two, planar model castings.

Evaluation and analysis of castings made from the two, planar model dies.

Formulation of solutions to above defects.

Implementation of solutions onto component's original die.

Cast components from modified die.

Evaluate and analyse parts – identify any defects, formulate possible causes and develop optimal die casting variables.

3.1 Selection of Component

Not every component is suitable for semi solid high pressure die casting. The following tables have been modified from NADCA Product Specification Standards for Semi Solid and Squeeze processes[40]. Five tables are presented, Table 3-1 to 3-5. In these tables the casting process is measured for its suitability to the component with regards to each factor. In all the tables a 5 represents most favourable and a 1 represents least favourable. The classes of casting processes to which the component is checked for suitability against are, Squeeze Casting, Sand Casting, Permanent mould/Gravity casting, High pressure Die Casting and Forging. Although forging is strictly not a casting class it has been included since forging is often a very competitive process for manufacturing a normally cast component. That is a component which is suited to casting for its manufacture may very likely be suited to forging as well for manufacture. That is why it is important not to neglect forging from the selection of the most suitable method for manufacturing a component.

Table 3-1 - Strength and Intregrity Factors

Production Process	Micro Porosity	Shrinkage Feeding	Pressure Tightness	Solution heat Treatable	Alloy range applicable	MMC Applicable (metal matrix composites)	Surface Integrity	Weldability	Available Strength	Available ductility	Total Short-arm	Total Steering Boss
Squeeze Cast												
Direct	5	5	5	5	3	3	3	5	5	5		
Indirect	5	5	5	5	3	5	5	5	5	5		
SSM	5	5	5	5	2	4	5	5	5	5		
Sand Pocess												
Green	1	2	2	5	5	3	1	4	3	3		
Dry	2	2	2	5	5	3	2	4	3	3		
Cosworth	3	3	3	5	5	1	2	4	3	3		
Lost Foam	1	2	2	5	2	1	1	4	1	1		
Permanent Mould												
Gravity, static	3	3	3	5	4	3	3	4	3	4		
Gravityt, Tilt	3	3	3	5	4	2	3	4	3	4		
Low Pressure	4	4	4	5	3	1	3	4	4	4		
Counterpressure	4	4	4	5	3	1	4	4	4	4		
Cast Forged	4	4	4	5	2	3	4	4	4	4		
Die Cast												
Conventional	1	2	2	1	2	1	5	1	1	1		
Controlled Shot	2	3	3	3	2	3	5	2	2	2		
Vacuum	4	3	3	3	2	3	5	2	3	2		
Forging	5	5	5	5	1	3	3	5	5	5		
Weighting Short Arm												
Weighting Steering Boss												

Table 3-2 - Dimensional and Complexity factors

		Net Shape Capabilities				Dimensional tolerance		Dimensional tolerance		Surface		
Production Process	Part Complexity	Dimensional Repeatability	Machining Allowance	Minimum walls	Linear	Draft	Across Parting	Thickness	Flatness	Finish smoothness	Total Short Arm	Total Steering Boss
Squeeze Cast												
Direct	2	4	1	2	3	1	2	1	5	4		
Indirect	4	5	3	5	5	4	4	3	4	5		
SSM	4	5	4	5	5	5	5	4	4	5		
Sand Pocess												
Green	4	1	1	1	1	3	1	2	2	1		
Dry	3	3	2	2	3	2	3	3	2	1		
Cosworth	4	3	3	2	2	3	2	3	3	2		
Lost Foam	5	4	3	4	3	5	5	5	1	1		
Permanent Mould												
Gravity, static	3	3	2	3	3	2	2	3	3	3		
Gravityt, Tilt	3	3	2	3	3	2	2	3	3	3		
Low Pressure	3	3	2	3	4	2	3	3	3	3		
Counterpressure	3	3	2	3	4	2	3	3	3	3		
Cast Forged	1	4	1	2	4	1	2	2	4	4		
Die Cast												
Conventional	5	5	5	5	5	4	4	4	4	5		
Controlled Shot	4	5	4	5	5	4	4	4	4	5		
Vacuum	5	5	5	5	5	4	4	4	4	5		
Forging	1	4	1	1	4	1	1	1	5	4		
Weighting Short Arm												
Weighting Steering Boss												

Table 3-3 - Machining and Tooling Factors

	Machine		Combined		Tooling							Total	Total
Production	Productivity	Utilisation	Internal	Cast-In	Material	Material	Develop-ment	Life	Manufacture	Change	Multi Cavity	Short Arm	Steering
Process	(cycle time)	(Up time)	Coring	Inserts		Cost Score	Time		Cost	Flexibility			Boss
Squeeze Cast													
Direct	1	2	1	2	Tool Steel	2	4	2	2	1	1		
Indirect	4	3	3	5	Tool Steel	2	1	2	1	1	3		
SSM	5	4	3	5	Tool Steel	2	1	4	1	1	3		
Sand Pocess													
Green	5	5	5	1	Palstic-Steel	5	5	5	5	5	5		
Dry	3	4	5	3	Iron-Steel	3	4	4	4	4	2		
Cosworth	3	4	5	3	Iron-Steel	3	4	4	4	4	2		
Lost Foam	3	4	5	1	Aluminum	4	2	5	4	4	4		
Permanent Mould													
Gravity, static	3	4	4	2	Iron-Steel	3	3	3	3	3	3		
Gravityt, Tilt	3	4	3	2	Iron-Steel	3	3	3	3	3	2		
Low Pressure	2	3	4	3	Iron-Steel	3	4	3	2	2	3		
Counterpressure	2	3	4	3	Tool Steel	2	3	4	2	2	2		
Cast Forged	1	3	1	1	Tool Steel	2	4	2	2	2	1		
Die Cast													
Conventional	5	1	1	5	Tool Steel	2	3	2	1	1	3		
Controlled Shot	4	2	3	4	Tool Steel	2	3	4	1	1	3		
Vacuum	5	1	1	5	Tool Steel	2	3	3	1	1	3		
Forging	3	3	1	1	Tool Steel	2	4	4	2	1	1		
Weighting Short Arm													
Weighting Steering Boss													

Table 3-4 - Casting Factors

Production Process	Metal Flow	Direction-al Solid-ification	Solid-ification Rate	Cavity fill Time [sec]	Cavity fill Time Rating	Solidification Pressure [Mpa]	Solidification Pressure Rating	Die/Mould Temp-erature °C	Die/Mould Temp-erature Rating	Pouring Temp-erature °C * Forge Piece Temp	Pouring Temp-erature Rating	Total Short Arm	Total Stee ring Boss
Squeeze Cast													
Direct	4	2	3	5 - 25	2	103 - 275.8	1	232 - 316	2	704 - 732	2		
Indirect	5	5	5	0.5 - 2	3	103 - 275.8	1	232 - 316	2	691 - 760	2		
SSM	5	5	5	0.1 – 0.5	4	68.9-137.9	2	204 - 260	3	+- 580 alloy	4		
										dependant			
Sand Pocess													
Green	3	2	2	5 - 25	2	Atmos	5	Ambient	5	704 - 760	2		
Dry	3	3	2	5 - 25	2	Atmos	5	Ambient	5	704 - 732	2		
Cosworth	5	3	3	5 - 25	2	Atmos	5	Ambient	5	704 - 732	2		
Lost Foam	4	1	1	5 - 25	2	Atmos	5	Ambient	5	704 - 732	2		
Permanent Mould													
Gravity, static	3	3	3	5 - 25	2	Atmos	5	316 - 426	1	704 - 816	1		
Gravity, Tilt	4	4	3	10 - 30	1	Atmos	5	316 - 426	1	704 - 788	1		
Low Pressure	5	4	3	10 - 30	1	Atmos	5	316 - 426	1	691 - 732	2		
Counterpressure	5	4	3	10 - 30	1	1.4 - 6.89	4	316 - 426	1	691 - 732	2		
Cast Forged	4	2	4	5 - 25	2	Atmos	5	204-316	2	677 - 704	2		
Die Cast													
Conventional	1	2	5	0.04-0.1	5	68.95 - 103	2	149-232	3	635 - 677	3		
Controlled Shot	2	2	4	0.05-0.2	5	41.4 - 82.8	3	204-316	2	663-704	2		
Vacuum	2	2	5	0.04 \- 0.1	5	33.1	3	149 - 232	4	635 - 677	3		
Forging *	1	5	5	0.01	5	275.8	1	149 - 316	3	380 - 400	5		
Weighting Short Arm													
Weighting Steering Boss													

Table 3-5 - Econonmics of Process and Product Cost Factors

Production Process	Overall	Equipment	Tooling	Casting	Processing	Raw Material	Component weight	Near Net shape	Total Short Arm	Total Steering Boss
Squeeze Cast										
Direct	2	2	2	2	2	3	5	2		
Indirect	4	1	1	4	4	3	5	4		
SSM	3	1	1	3	4	1	5	4		
Sand Pocess										
Green	5	5	5	5	1	3	1	3		
Dry	4	4	4	4	2	3	1	3		
Cosworth	4	4	4	4	2	3	2	3		
Lost Foam	5	4	4	5	3	3	1	4		
Permanent Mould										
Gravity, static	4	4	3	4	2	4	2	3		
Gravity, Tilt	4	4	3	4	3	4	2	3		
Low Pressure	3	3	2	3	4	3	3	3		
Counterpressure	3	3	2	3	4	3	3	3		
Cast Forged	2	4	2	3	5	3	3	2		
Die Cast										
Conventional	4	2	1	5	5	5	4	5		
Controlled Shot	3	2	1	3	5	4	4	5		
Vacuum	4	2	1	4	5	4	4	5		
Forging	2	1	2	2	2	2	5	1		
Weighting Short Arm										
Weighting Steering Boss										

The tables were then modified with a weighting factor (each of whose values are assigned and discussed in detail in chapter 4). The weighting factor is used to assign the importance of a factor to the component of interest. The sum of all the multiplications then gives the suitability of the component to that casting class. Two different components were evaluated, the "Short Arm" and the "Steering Boss". The component which had the highest score with respect to the SSM process was selected and this component was used on which to carry out this investigation. We shall from now on refer to the component that was selected as the "Short Arm". Diagram A-1 is a drawing of this component and is contained in Appendix 1.

3.2 - Initial design of selected component's die and cast parameters and the first castings of the component

3.2.1 Aim: The aim of this part is to produce an initial part from a simple die that is able to be modified to suit the recommendations from the subsequent experiments and analysis. The modifications to the die are done so as to avoid and eliminate the casting defects.

3.2.2 Introduction+Apparatus: The short arm part (component) must be examined for castability and a die must be manufactured to high pressure die cast the component.

Diagram 3-2: Picture of SSM HPDC Cell

The component is to be cast on a modified 50ton Edgewick High Pressure Die Casting (HPDC) machine, shown in diagram 3-2. The shot end of the die casting machine has been retrofitted with a computer controlled hydraulic ram which injects the metal through a sleeve and into the mould under pressure. The ram's position and speed is controlled in real time with respect to time using a proportional hydraulic valve which in turn is controlled from the computer in real time. The software was written in Labview incorporating closed loop feedback from a linear displacement sensor mounted on the shaft of the hydraulic ram. The hydraulic pressure h_p of the hydraulic power pack driving shot end is regulated to 24MPa however at the end of the injection stroke the pressure drops to 18Mpa. The maximum pressure in the metal M_p (exerted by the force of the metal plunger onto the metal) is calculated from relationship between the hydraulic pressure, h_p, the cross sectional area of the hydraulic piston h_{da} (area of the hydraulic piston, of diameter, h_d (100mm), less annulus area of diameter, a_d, (25mm)) and the metal plunger area m_{da}, of diameter m_d (47.67 mm):

$$F = h_p \cdot (h_{da})$$

$$F = h_p \cdot \pi \cdot \frac{(h_d^2 - a_d^2)}{4}$$

$$M_p = \frac{F}{m_{da}}$$

$$M_p = \frac{F}{\pi \cdot \frac{m_d^2}{4}}$$

$$M_p = \frac{h_p \cdot \pi \cdot \frac{(h_d^2 - a_d^2)}{4}}{\pi \cdot \frac{m_d^2}{4}}$$

$$M_p = \frac{h_p \cdot (h_d^2 - a_d^2)}{m_d^2} \qquad \text{Eqn 3-1}$$

$$M_p = \frac{18 \cdot 10^6 \cdot (0.1^2 - 0.025^2)}{0.04767^2} = 74.259MPa = 756.98kg/cm^2$$

The initial components were cast at a lower system pressure, 16MPa which then dropped to 14.5MPa after the shot was fired, for these experiments the metal pressure exerted by the hydraulic plunger is

$M_p = 609.789kg/cm^2$

3.2.3 Method

3.2.3.1 Split Line

The first part of the examination is to decide on the split line of the die (mould). The split line must be decided upon so that there is a minimum usage of moving cores to handle undercuts. The short arm has two areas where a possible undercut could occur. This is on either side of the centre section. Where there is an hour glass shaped narrowing. The split line must be through the centre of the narrowing to allow the die to open. Diagram 3-3 and A-1 (in Appendix A) clearly show the component's geometry.

Diagram 3-3: Photograph of the Short Arm Component

3.2.3.2 Machine and Die Compatibility

Now that the spilt line is known it is possible to check the component and machine compatibility. The metal pressure (M_p) should be at least 600kg/cm^2 - [15]. This hydraulic pressure must be retained by die. The die is in two parts determined by the split line. The machine clamps the two die halves together. The machine being used is a 50ton Edgewick machine. Normally for this machine the force holding the two die halves together is 50 tons however this was increased to 62.5tons by running the clamping hydraulic pressure of the machine at 25% higher pressure. In the plane of the split line, the cross sectional area of the cavity, which will be filled with metal under hydraulic pressure M_p, will exert a force attempting to open the two die halves. If the die halves are split open, metal will escape from the die and the metal pressure will drop. This is an undesirable situation. To avoid this equation 3-2 must be satisfied,

$$M_p \cdot A_c < F_{mc} \qquad \text{Eqn 3-2}$$

Where

A_c Cross section area across the split line

F_{mc} Clamping force of the machine

Substituting M_p from Eqn 3-1

$$\frac{h_p \cdot (h_d^2 - a_d^2)}{m_d^2} \cdot A_c < F_{mc}$$

Solving for A_c

$$A_c < \frac{F_{mc} \cdot m_d^2}{h_p \cdot (h_d^2 - a_d^2)}$$

Machine parameters from the 50ton Edgewick machine run at 25% higher hydraulic clamp pressure gives

$$A_c < 62.5 * 1000[kg] / 756.98[kg/cm^2]$$

$$A_c < 82.56cm^2$$

A_c for the shortarm is, 68.1cm^2 which satisfies Eqn 3-2. The clamping force of the machine will be sufficient to cast the short arm.

3.2.3.2 Die Design

The casting procedure design must now be determined. There are two main sections to the casting procedure design, gating and overflow orientation and geometry and machine process parameter setup. Since this is an initial die, the aim here is to make the simplest gate and overflow system possible so that they may be modified later.

3.2.3.2.1 Overflow Design and Orientation

For determining overflows one must consider the following factors – Overflows do not form part of the final component and therefore they are waste. Metal that does not form part of the final component is wasted metal. The yield of a cast component is defined as the amount of metal used, just by the component, divided by the total amount of metal needed to cast the component (this includes the overflows, biscuit, runner and gating system). The higher the yield is, the greater the casting efficiency is. Thus the initial die had no overflows and these could be added later after results from the experiments.

3.2.3.2.2 Gating

The gating system for the initial die must be the simplest possible so that modification can take place later. It was decided to feed the part through one gate only. Two possible gate geometries would be considered. The orientation of this gate came from modulus calculations to give directional solidification of the part. That is the gate must feed the highest modulus section first. This is discussed below.

The first to be investigated would be the small cross sectional area gate. This gate will have a cross sectional area to match the cross sectional geometry of the first section that it feeds. The geometry of the first section is ellipsoid and so the gate is ellipsoid. The dimensions of the gate are elliptical with a minor axis of 14 and a major axis of 30.

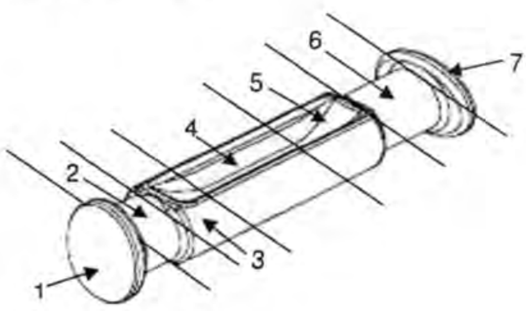
The second gate to be investigated with is a simple cylindrical gate of 25mm which is equal in diameter to that of the large bottom cylinder, which is labelled section 2 in diagram 3-4 and table 3-6. This section was chosen since it has the highest modulus of all the parts and is explained further below.

Modulus Theory has its roots in Chvorinov's theory[16]. The time to solidification of a metal is directly proportional to the ratio of volume to surface area (in contact with the mould surface) of a section, this is called the modulus of that section of the casting. Thus if one assumes that the metal, once it has filled the mould is at a specific uniform temperature, then one can anticipate which sections of the casting will solidify first (the ones with the lowest volume to surface area ratio) and which sections will solidify last (the ones with the highest volume to surface area ratio). As metal solidifies it shrinks, in the case of Aluminum this shrinkage is around 5%. The shrinkage must be "fed" with new molten metal otherwise a cavity will form instead. The desired directional solidification process is to have higher modulus sections feeding the lower modulus sections. The biscuit is normally the highest modulus section and this must then feed the next highest modulus section and so on until the smallest modulus section has been fed.

Table 3-6: Modulus of Sections

Section	Volume	Area	Modulus
1	9974.54	2180.5	4.574428
2	7132.09	1130	6.311584
3	14810	2985	4.961474
4	14619.68	3665	3.988999
5	13719.47	2873	4.775312
6	10317.25	1777	5.805993
7	8043.79	2089	3.850546
Gate	14812	2346	6.313725
Overflows	5901		

Diagram 3-4: Sections of the part for modulus values of each section.



From the diagram 3-4 and table 3-6 it is clear that the order of solidification of the part should be section 7,4,1,5,3,6,2 however it is not practical to gate both section 2 and section "6" since this would require a large runner system of more or the same weight as the casting itself; this would make the yield of the casting very low and it would not be economical during production[14]. It was therefore decided for the initial mould design to gate directly into section 1. The size of the gate was decided upon from directional solidification ensuring that the modulus of the gate section was greater than the section's modulus that the gate is feeding directly into.

3.2.3.2.3 Air Vents

The next important factor in die design is allowing a route through which the air inside the mould can escape. Air vents are used for this. An air vent has a calculated cross section so as to ensure the velocity of the air flow does not reach near sonic speeds (else choking phenomena can occur). The thickness/depth of the air vents must not exceed 0.2mm. This is to prevent metal from flowing down the vents. The vents are located in the last place that the metal will fill. See Diagram 4-3 in the Results and Discussion of Results Chapter, showing a two dimensional (2d) drawing of the die, as seen looking at the die open at the split line.

3.2.3.2.4 Manufacturing the Die

The die was then cut from plastic injection tool steel. (Plastic tool steel was used since this was cheaper than conventional high pressure die casting tool steel in material cost and machining cost, and since a low number of shots were to be made it would suffice to use plastic injection tool steel) the properties of plastic tool steel and high pressure die casting tool steel are very similar. A CAD model of the die was drawn. The Die is cut from two blocks of steel, 400x250x50mm. The blocks are first ground on a surface grinder to ensure all faces are flat and at 90° to each other. Then each is mounted on a CNC mill and the negative of the part is cut into the two blocks as well as the runner, gate and the die section of the shot sleeve. The negative of the part is increased in size by 1% [27] on all dimensions to allow for after casting cooling and corresponding shrinkage. The final block sizes of the die are, for both back plate and front plate, 287x180x50mm

3.2.3.3 Casting the Initial Components

The die is then mounted on the HPDC machine. The machine has heated platens onto which the die is mounted, these platens are heated to 250°C and the dies are clamped shut for forty five minutes so as to obtain an equilibrium temperature. The heaters are made from two silicon carbide elements embedded in the platens. The power of the heaters together is above 3kW. The die surface temperature is stabilized at 250°C. A special penetrative die dressing is then applied to the die, called PA111 from Kluber © lubricants. The dies are then closed for a further five minutes to allow the dressing to penetrate into the tool steel. The die is opened and a waxy water based die lubricant is sprayed onto the die face paying extra attention to the cavity. This die lubricant contains water mixed with fine polyester particles and these particles are the release agent. The die lubricant used is called Isolat 6920TT made by FOCHEM International (Pty) Ltd [57] and is used at concentration of 3% with water. As mentioned in the Literature Study chapter the non insulating die lubricant is selected so as not to distract from the influence of the other die casting parameters on the outcome. The die is now ready for casting.

3.2.3.4 Metal Preparation and Machine Parameters

A billet of 120mm and 50mm in diameter is machined out of the continuous cast A356 semi solid feed stock from Pechiney. The billet is then placed inside an electrical resistance furnace on a cradle which slides on a set of rails. The billet is heated to 580°C, which is close to 50% liquidus. The billet's temperature is measured using a thin thermocouple wire which is inserted 30mm into a pre-drilled hole down the cylindrical axis of the billet.

While the billet is heated the casting parameters of the high pressure die casting machine are set. The computer controlling the high pressure die casting machine is used to set the machine casting parameters. The computer is set to the correct injection speed and pressure at the correct times. The injection speed used is 0.3m/s (this is the speed of the hydraulic ram and subsequently the metal plunger).

Four castings are done including one short shot. The hydraulic pressure used is 16MPa. The profile of the short shot casting is shown in Diagram 4-5. The profile for the full castings is shown in Diagram 4-8. In each diagram the set point is shown by the blue line and circular points. These diagrams are shown in the Results and Discussion of Results Chapter.

The speed is set to 0.3m/s continuously even after the metal is injected into the die and the plunger can no longer move. This is done so as to ensure the proportional flow control valve remains fully open so ensuring full pressure is exerted on the biscuit and translated to the metal inside the die cavity which aids the new metal to be fed to the solidifying metal in the die cavity. The value of 0.3m/s is used for the initial experiment; based on the experiments done by K.C. Sharma et al[8].

When the billet reaches the desired temperature, the dies must be clamped together by a hydraulic piston acting on the moving half of the die, so clamping it up against the fixed half of the die with 50tons of force. The billet is then pushed out of the furnace on the set of rails by a pneumatic ram and lines up the cradle carrying the billet with the shot sleeve below it. The cradle holding the billet is rotated 180° and the billet drops out and falls 300mm and into the shot sleeve below. The billet must be quickly checked to see that it is indeed in the shot sleeve and that it is sitting flat in the shot sleeve. The machine inject button must now be pressed. The machine injects the billet into the die by the plunger on the end of the hydraulic ram moving forward inside the shot sleeve controlled by the computer in real time according to the velocity time profile previously set up.

After the plunger on the end of the Hydraulic ram has moved forward as much as it can until the metal stops it moving since the die cavity is full of metal and there is nowhere further for the metal to move to, the dies must remain clamped together and the plunger under pressure for ten seconds to ensure the billet has fully solidified. After ten seconds the dies are opened and the plunger which is still under pressure pushes the biscuit out of the shot sleeve and the cast component is pushed into and kept in the moving half of the die cavity.

The part is then removed from the moving half die cavity. This first casting is discarded since the PA111 paste is detrimental to the casting causing excessive porosity and discolouration[9] of the part. Another billet is placed in the resistance furnace for heating and the same procedure is followed to obtain another part. This part is then evaluated and analysed.

3.3 Evaluation and Analysis of the Cast Compnents

This section describes the methods used for evaluation, of the cast components as produced from the above die and parameters, and identification of defects and the formulation of possible causes. The main defects that must be checked for are shortfills and cold shuts on the surface and internal porosity and cold shuts inside the part and entrapped oxides[13,14,17].

A cold shut[10,13] is defined as an area on the casting where two or more flow fronts of metal have not fused together correctly. The flow fronts maybe too cold at the time of meeting or there could be an oxide layer on each flow front surface; either separately or in combination both can produce a cold shut. The cold shut is the result of the flow fronts not knitting (fusing) together and a crack is formed. A method to overcome this is to do one or a combination of the following[10,11,12,13], increase the metal temp, increase the speed at which the flow fronts meet, increase the speed of filling the die, increase or modify the flow volume through the die by using overflows. The Literature Survey Chapter has an in depth discussion of this defect type. The brief explanation above is simply to re-iterate the defect type for ease of reading.

The part is examined internally by using an X-ray radiographing machine. The machine must be set to 67 KV and focal distance 100 and power of 8mAs. The part is X-ray radiographed in both planes. The x-ray radiographs are examined. Dark and light areas correspond to less dense and more dense areas respectively. Also areas which are darker correspond to thinner sections of the part and vice versa. Areas where there is an inhomogeneous patch of darkness, that does not correspond to a geometry change to a thinner section, represents undesirable internal integrity of the cast metal (it is less dense here, either due to porosity, cold shuts or both).

The casting must now be sectioned where the inhomogeneous area is. To locate the same area on the casting the scale of the x-ray radiograph to the casting must be calculated. A simple scale is calculated by dividing the known casting measurement by the same measurement on the X-ray radiograph. The scale for each X-ray radiograph must be measured and calculated. The next step to locate the correct area is to measure the position on both x-ray radiograph planes. The measurements from the x-ray radiograph are converted using the scale and then scribed onto the part to mark the position of the inhomogeneity. A sectioning procedure then reveals the inhomogeneous section and the section is mounted in Bakalite powder and then placed in a mounting press and held for the preset time, pressure and temperature to produce a sample suitable for mounting on the Scanning Electron Microscope (SEM) and for performing Energy Dispersive Spectroscopy (EDS). The microscopy is viewed to analyse the inhomogeneous section. By looking at the microscopy of the section it is possible to determine what type of defect it could be, cold shut, hot tear, macro or micro porosity. Then further analysis of the section further may need to be done by performing Energy Dispersive Spectroscopy (EDS) across the inhomogeneous section to check for high concentrations of oxides indicating cold shuts or oxide entrapment. The edges of the defects are of interest to identify the defect type, jagged edges indicate hot tears, round globular pores indicate entrapped gas porosity, jagged edged small pores indicate shrinkage porosity. It is often the case that the defect is a combination of the different types.

It is now necessary to postulate how the defects were created during the casting process. The investigation will concentrate on two main defect classes. The first class of defects are shortfill and

Cold Shuts and the second class is porosity. Porosity is further divided into shrinkage porosity and gas entrapment porosity.

Shrinkage porosity comes about when a section of the casting is not fed with new liquid metal. This can happen if the section is surrounded by solidified metal that is it is cut off from any liquid metal. Since the metal was under high pressure when it was injected into the die and the die surface is steel and relative to the metal is cold, the metal will solidify against the surface of the die. As the metal solidifies further it shrinks and if no new metal is drawn in to take up the void created during shrinkage the void becomes permanent and is called shrinkage porosity. This explanation allows one to check if the porosity was caused by shrinkage, that is if a section of casting is cut off from new metal and there is porosity in that section it is likely that porosity was caused due to shrinkage. To be sure it is shrinkage porosity the casting must be sectioned, mounted in resin and polished with 6um fluid. The sample is then analysed under an optical microscope at low-medium magnification, x5 is normally sufficient. The geometry of the porosity pores are examined and if they have jagged edges then the porosity is caused primarily by shrinkage[13].

Gas entrapment porosity occurs when gas is trapped inside the metal. This can happen during filling the cavity or from when the metal was in the furnace or when the SSM slug was made. Upon solidification the entrapped gas will come out of solution/suspension in the metal and will form pores in the metal. These pores are porosity. The casting is likely to be filled under laminar conditions since the metal is in the thixotropic state which has an extremely high viscosity, it is unlikely that gas is entrapped during this period. While the metal is in the furnace it is solid or thixotropic, below the liquidus temperature and undisturbed so it is unlikely to absorb gas during this period. However when the slug was made gas could have been entrapped. To ascertain between the porosity type (gas or shrinkage) the casting must be examined as described for the case of shrinkage porosity. Since these (gas entrapment) pores are formed by gas coming out of solution/suspension they will be rounded in shape and will have smooth edges[13].

The samples cast are X-ray radiographed to determine the position of the porosity then sectioned and analysed as above to determine if the porosity is caused by shrinkage or entrapped gas.

If the pores are in fact more like cracks, not rounded in shape and longer than 3mm then it must be considered that this could be a cold shut. To further ascertain this, the casting must be sectioned, mounted and polished as described above so they that may be examined on a Scanning Electron

Microscope (SEM) equipped with an Energy Dispersive Spectroscopy (EDS) unit. The SEM's EDS unit must scan across the crack and special attention must be paid to the level of oxygen at the edge of the crack. The oxygen level is important since if the crack is caused by a cold shut then this would imply two flow fronts meeting. These flow fronts would have oxidized since they are in contact with the air in the cavity. If both edges of the cracks show a high concentration of oxygen then this crack is likely to have been caused by two flow fronts meeting that were too far below the liquidus temperature to fuse together. During further solidification these flow fronts break apart further as stress in the part increases as it cools and shrinks.

A cold shut can be avoided by casting the metal at a higher temperature and by using overflows to move the cold shut into an area outside of the casting. The shrinkage porosity can be avoided by feeding the area using a subgate and or heating or cooling sections of die sufficiently to modify the directional solidification to ensure all sections are fed with liquid metal as they solidify. Entrapped gas porosity can be reduced by reducing the injection speed, reducing the amount of die lube applied and reducing the amount of entrapped gas and or hydrogen content of the initial Al slug through better slug manufacture practice. The entrapped gas porosity can also be moved by using overflows. [13,14] . However before any of these steps are taken it is necessary to fully understand the nature of the defect formation. The next section investigates this.

3.4 Set up of simplification dies to separate flow into two, two dimensional planar models

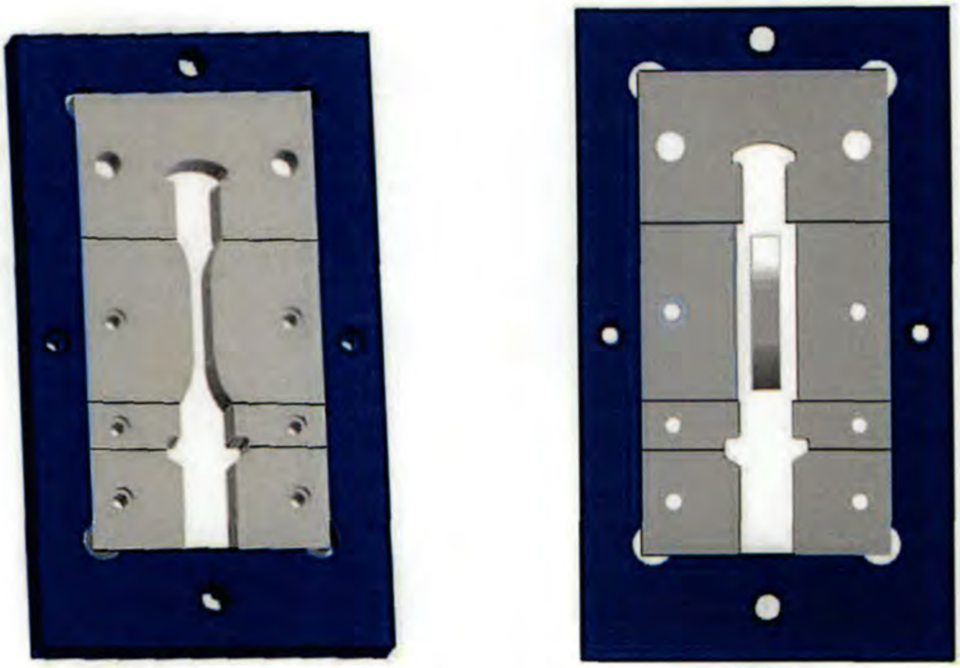
To understand the casting's defects (as found in section 3.3) better, the casting's geometry was examined. It was found that the casting had two axes of symmetry in the Y plane, see diagram 4-17(a) and 4-17(b) in the Results and Discussion of Results Chapter.

The distinctive geometry of each planar section was taken. The thickness used is to give every section the equivalent volume to that of the original casting. By dividing up the casting into the two planar models it would be possible to understand what was causing the defects.

To cast these parts a modular die was made with a bolster with inserts which could be interchanged to produce the desired part geometry. The inserts geometry was designed and then the parts were wire cut out of steel. Appendix 3 contains drawings of all the parts including the bolster. Diagram 4-18 is an isometric solid view showing the modular with a set of inserts to make up the geometry characteristic of diagram 4-17(a) drawing showing. Diagram 3-5 shows drawing of part of the Insert

Die with inserts placed to form the two geometries. Diagram 3-5(a) has the inserts assembled to form the geometry for the plane shown in diagram 4-17(a) and diagram 3-5(b) has the inserts assembled to form the geometry for the plane shown in diagram 4-17(b)

Diagram 3-5 – Showing insert die with two sets of inserts making up the two different geometries.


(a) (b)

3.5 Casting the two planar model parts

Method

The insert die was assembled to create to the first planar model. Six shots were fired into this die. The injection of the shots were interrupted at the six critical areas (short shots) – gate, bottom ellipse, bottom of hour glass, middle of hour glass, top of hour glass and the top ellipse. These short shots are shown in diagram 4-22.

Two full shots were cast. The process parameters for the casting are in table 3-7. The short shots were done stopping the injection plunger at the positions given in table 3-8.

Table 3-7: Process Parameters

Metal Temperature	Die Temperature	Plunger injection velocity	Hydraulic Presssure
580	250	$0.5ms^{-1}$	16MPa

Table 3-8: Injection Plunger halt positions

	Gate	Bottom Ellipse	Bottom hour glass	Middle of hour glass	Top of hour glass	Top of ellipse
Volume #	1	2	3	4	5	6
X [mm]	241.61	257.4	258.6	263	270	279
T [ms]	482.2	514.8	517.2	526	540	558

The injection positions (table 3-8) are calculated from first taking in to account the distance required to move for the metal to come into contact with start of the gate and then second adding the volume of the section as well as the preceding sections to come to the section of interest.

The sleeve length is 341mm including the die plate but excluding the cavity depth (25mm). To move the billet (120mm in length and 55mm in diameter) to the start of the cavity, a displacement of 221 of the plunger is needed.

$$X_1 = 221 + \frac{V_1}{(CrossSectionalAreaOfSlug)} = 221 + \frac{(28)(70)(25)}{\pi(55)^2/4} = 241.61mm$$

$$X_2 = 221 + \frac{(V_1 + V_2)}{(CrossSectionAreaOfSlug)} = 258.6mm$$

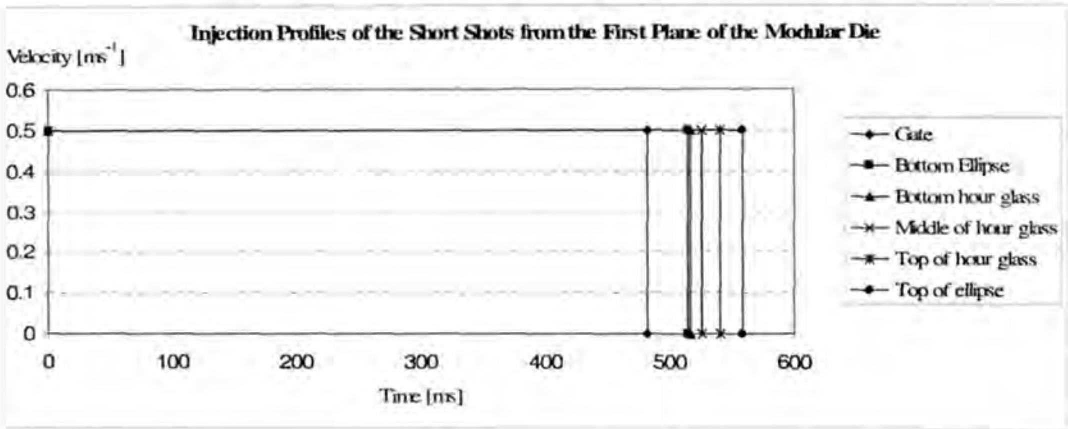
Where X_n = plunger position ; V_n = volume of the section (for dimensions drawings of the inserts are in Appendix 3).

$$T_n = \frac{X_n}{U_n(x)}$$

Where T_n = time to reach position X_n and U_n = velocity function of displacement (x)
U_n is a const for this experiment kept at $0.5ms^{-1}$.

With this information the injection profile maybe set up to produce the short fills,

Diagram 3-6: Injection Profile of short shots

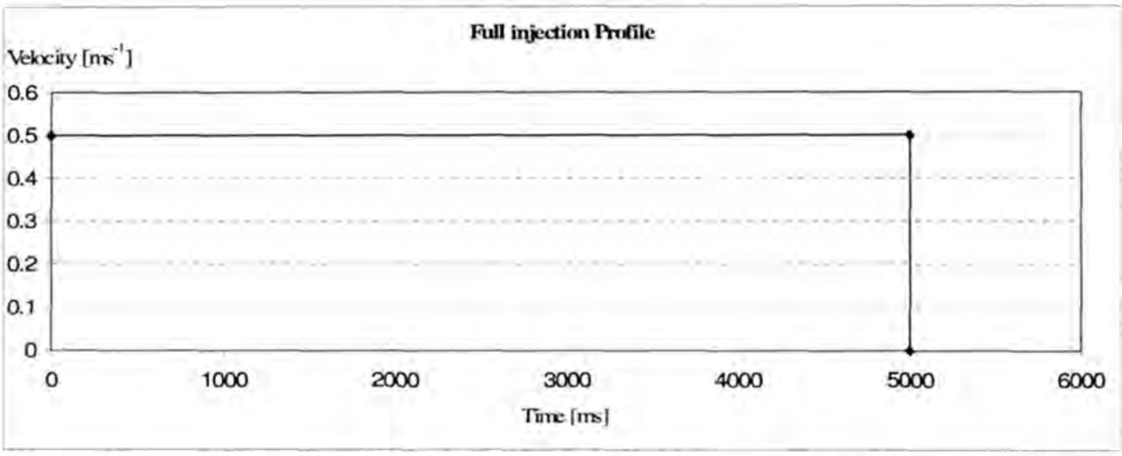


The injection profiles are entered into the computer which controls the modified 50ton Edgewick die casting machine. The die temperature was set and then forty five minutes is needed for the die to reach the set temperature. A thermocouple, mounted in both back plates of the platen onto which each die half is bolted, is used to measure and control the die temperature.

The metal is prepared by preheating a 50mm diameter by 120mm billet, machined from continuous cast A356 semi solid feed stock from Pechiney as described in section 3.2.3.4 Metal Preparation and Machine Parameters. The first injection profile is selected, "Gate". The billet is placed into the shot sleeve and the injection ram is initiated. The injection ram moves according to the selected profile in diagram 3-6. The casting is allowed to cool in the die for 20 seconds and then the die is opened and the casting is removed from the mould. The next billet preheated to 580°C and the next injection profile selected. The casting procedure is repeated. This procedure is done until all six castings have been cast using the six different injection profiles. Thus the six short fill castings are cast.

After the short fill castings have been cast two complete castings were made. Again a billet was machined from the feedstock to the same size and preheated to the same temperature. This time the injection profile in diagram 3-7 was used. An explanation is necessary to understand the profile. The velocity is set to the injection speed of $0.5ms^{-1}$ and then it is held at that speed for five seconds. The injection piston would have reached the end of its stroke by [$0.300mm / 0.5ms^{-1}$] 0.6s but the speed is held at $0.5ms^{-1}$ for longer than this, this is clearly not possible. The piston will come to a dead stop even before this, due to cavity being full and the excess metal in the shot sleeve creating the biscuit and holding the piston stationary. Now since the injection plunger is controlled via an electrically actuated infinitely variable proportional hydraulic valve by closed loop PID (proportional integral and differential) control using the injection profile entered in the computer as reference, what the impossible reference of 0.5ms^{-1} does in reality, is cause the PID control to keep the proportional valve fully open, to try to achieve the 0.5ms^{-1} even though the piston has come to a dead stop due to mechanical constraints and allow full hydraulic pressure to act on the piston and so intensify the molten metal as it cools. The intensifying of the metal assists in forcing metal from the hot reservoir of metal in the biscuit into the casting and aid in feeding new molten metal to areas of the casting still connected to the biscuit via a molten metal pathway as these areas solidify and shrink and so aid directional solidification[13].

Diagram 3-7: Profile of Full Shot



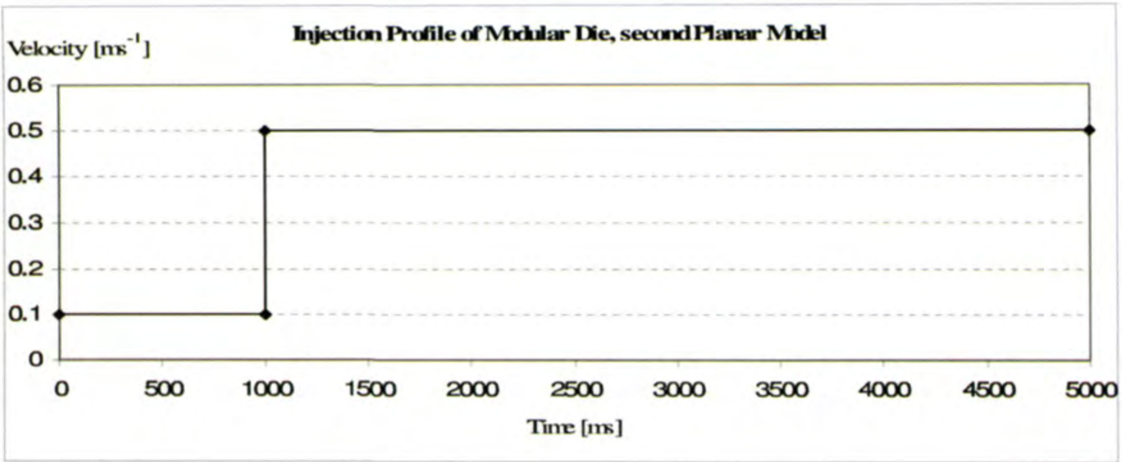
Two castings were done using the injection profile in diagram 3-7. Giving a total of eight castings of the first planar model from the insert die.

The modular die was then dismantled and then reassembled using different inserts to create the geometry to cast the second planar model. A casting produced from the Modular die arrangement for the second planar model (diagram 3-5(b)) diagram 3-8. Four castings were done of the second planar die. Using the injection profile in diagram 3-9.

Again the speed is held constant to intensify the solidifying metal. The slower speed at the start of the profile is to aid in releasing the air from the mould and sleeve. The injection profile is entered into the computer in the same manner as the first planar model. The metal is prepared as for the first planar model at 580°C. The die temperature is set to 250°C. The hydraulic pressure is set to 16MPa.

Diagram 3-8: Casting produced using Modular for second planar model

Diagram 3-9: Second Planar Model Injection Profile



When the metal reaches 580°C it is placed into the shot sleeve of machine and the metal is injected into the die. This was done four times to create four full castings for the second planar model.

3.6 Evaluation and analysis of parts made from two planar model dies – identification of defects formulate reasons/causes of the defects

X-Ray radiography analysis of all the castings produced in section 3.5 is carried out. The castings are X-rayed from both planes as described in section 3.3 at 50kV with a power of 4.5mAs. The same procedure is followed as described in section 3.3 with respect to defect identification and analysis for codl shuts and porosity must. Conclusions about the type of defect must be drawn as described in section 3.3 and formulation of their removal as in section 3.3.

3.7 Formulation of solutions to above defects

From the planar model castings it will be clear that certain defects are characteristic and common to both the initial component castings and the planar model castings. That is the defects in the initial component castings will defects in the corresponding first or second planar casting as per the matching geometry.

These defects have solutions. To apply a solution it is necessary to know whether the defects is due to shortfills, cold shuts and or entrapped oxides on the surface, or if it is due to internal porosity, cold shuts or entrapped oxides inside the part. Once this has been ascertained one must now ascertain whether the porosity is shrinkage porosity or entrapped gas porosity. These conclusions can be drawn from the methods described in section 3.3.

To remove the cold shuts, entrapped oxides and entrapped gases, overflows, venting and or cooling/heating channels are required. The size, location and gating of these is critical to ensure complete removal of the cold shut, as described in the Literary Study Chapter. Shrinkage porosity is caused by certain sections not being fed with new metal during solidification shrinkage. This happens if the section is cut off from the liquid reservoir feeding the casting. For example if a thin section (low modulus) precedes a thick section (high modulus) the thin section cannot feed new metal to the thick section since the thin section has already solidified[13]. For the current component the section where this is likely to occur is predicted by Table M, section four feeding section five and six and section 1 feeding section 2. There are two simple (not necessarily practical) solutions to this, provide a second reservoir to feed sections five, six and two or change the solidifying characteristics of sections five, six and two so that they solidify quicker than the sections feeding them – four and one respectively.

3.8 Implementation of solutions onto part's original die

All the modifications must be considered and calculated.

3.8.1 Overflows

These should be used to flush out undesirable metal containing defects of a cold shut, gas entrapment or oxide nature. To calculate the overflow size and determine their placement and gating the flow during filling must be examined. The area of the casting which contains the defect will have a certain filling mode. By examining the mode it will be possible to determine which part of the section is the last to fill. The gate (connecting pathway between the casting and the overflow) to the overflow must be placed here. This is to ensure that the section is filled completely before the overflow is filled. This will assist in ensuring the cold shut is moved out of the section and into the overflow. If the gate to the overflow is not placed at the last place to solidify then the metal will simply continue filling the overflow with new metal before filling the rest of the section and thereby allowing the possibility of the formation of the defect after the overflow has already filled and thereby not allowing the overflow to remove the defect. The overflow must also be big enough to ensure it can remove enough metal from the defect section so that the defect is also removed. The size is determined by evaluating the results from the analysis and determining the volume of metal which is defective and the volume which will be needed to be removed to ensure all this defect metal is removed including the metal leading to the overflow gate. An overflow also must not choke the flow – a very small thin gate will present high resistance to the flow and can cause the flow rate to change should the speed of reaction of the shot controlled machine not be sufficient[10]. The overflow should also be vented so as to allow air to escape and be replaced with metal the venting of the overflow will also facilitate in removing the air from the casting cavity as well.

3.8.2 Heating and cooling channels

The placement of these and the size of the cooling is determined by the amount and rate of heat needed to be removed by the channels. The amount of heat to be removed is proportional to the volume and temperature of the metal and a function of the distance from the surface of the die to the surface of the cooling channel and the temperature of the median flowing through the cooling/heating channels.

To get section five and six to cool extremely quickly, before section four but after section seven, the area of the die in contact with section five and six must be cooled to a low temperature. Since cooling section five and six would require one set of cooling channels it was decided to place cooling channels for section five and six only, rather than to heat the other sections and then still cool section five and six.

3. 9 Cast original parts from modified Die

Due to improvements necessary to avoid internal inhomogeneities that may be discovered in the castings produced by the preceding methods, modifications are done to the original components die. This experiment casts eight parts from the modified die at four different levels of parameter settings. The aim is to produce parts with no internal inhomogeneities.

3.9.1 Experimental Apparatus and Procedure

A resistance furnace and rheocasting machine was used to produce semi-solid aluminium alloy A356. The modified 50ton Edgewick high pressure shot controlled die casting machine was used to cast the semi solid alloy into the modified die. The die has cooling channels in a critical areas. The die of the short arm, (part of an assembly of a spacer adapter used in high tension over head pylon cable bundles). Three major parameters are investigated in four experiment conditions. Each experiment is run twice giving a total of eight runs and hence components. The parameters and their respective setting levels are given in table 3-9 below.

Table 3-9 Casting Parameter Settings for the Four Experiments

Parameter	**Setting level 1**	**Setting level 2**
Water Cooling	3 litres / minute	0 litres / minute
Injection speed	0.85 m/s	0.3 m/s
Temperature of Semi solid Metal alloy	578°C	582°C

The parameters were chosen by exploring what parameters may effect the entire die casting system. There are three major processes which make up the system, Die, Machine and Metal. Three Die design parameters, eight machine parameters and three metal parameters were considered. Table 3-10 describes the fourteen (3+8+3) parameters' influence on the experimental outcome. Most of these parameters have already been discussed in the Literature Survey Chapter, table 3-10 serves to summarise these for the purposes of developing the experiment's chosen parameters and their respective level settings. An explanation follows each subsection, in the table, as to which are then considered for the experiment shown in table 3-9.

Table 3-10: Description of Parameters influencing the Experimental Outcome

Die	Water Cooling critical areas	Can be used to alter solidification and shrinkage porosity position and size
	Overflows	Can be used to bring about different fluid flow characteristics. Can also be used to flush out cold shuts and or oxides and bring new hotter metal to an area.
	Gates	The size, area and location effects how the metal is fed into the casting. The gate feeds new metal into the casting as it solidifies. The gate position and size can be used to reduce shrinkage porosity and affect certain filling characteristics.
Machine	Injection Speed	Metal speed will cause laminar or turbulent flow. Metal speed is directly proportional cavity fill time. Gate speeds should not exceed 2.5m/s to ensure laminar flow [18]
	Injection second stage position	The second stage position is the change from slow to high speed of the injection phase. This is critical in liquid casting in order to expel the air from the cavity and the sleeve. A change over point that is too early will not expel enough air and one that is too late will increase cavity fill time.
	Intensification	After the metal has filled the die cavity it is subjected to high pressure (intensification). The increased metal pressure assists in feeding new metal into the die cavity to take up the volume created due to the metal volume shrinking during solidification and cooling.
	Metal Volume used	The excess metal will remain in the biscuit. The biscuit is needed as a reservoir from which to feed the shrinkage during solidification. The metal volume effects the second stage position.
	Plunger Diameter	The plunger diameter (consequently the sleeve diameter) and the injection stroke and sleeve length determines the volume of metal that may be cast. The Plunger diameter

		also determines the effective area acting on the metal resulting in the metal pressure [Eqn 3-1]. Varying the plunger diameter will vary the metal pressure and flow rate for a given plunger injection speed and force.
	Cooling time	The length of time the mould is held together and the metal is under pressure before opening and releasing the casting. The casting should be allowed to solidify completely under pressure to allow the intensification opportunity to feed the shrinkage. During ejection from the mould the part may be distorted. It is important to allow the casting sufficient time to cool so as to attain high enough strength to withstand the distortion during ejection.
	Cycle time	The time taken for completing one casting until the next is completed will affect the steady state temperature of the system.
	Die temperature	The die and metal temperature difference allows for heat flow into the die and machine which together act as heat sinks. The magnitude of the difference is proportional to solidification time and cooling rate of the metal. Strength is logarithmically proportional to solidification time [16].
Metal	Metal temperature	A high metal temperature will have a high fraction liquid and vice versa. A higher liquid fraction will have a lower viscosity for the same shear rate and turbulence will occur at a lower flow rate. A high metal temperature has more superheat and latent energy than a lower temperature. Metal at a higher temperature will need a longer solidification time for the same cooling rate. Metal at a higher temperature will have more latent heat and aid amalgamation of flow fronts.
	Modification, Grain size	Grain refiner will reduce the grain size and increases strength[16].
	Modification, Eutectic	The Eutectic structure may be modified so as to reduce

		segregration[8].

Die – Water cooling critical areas

From the modulus study – table 3-6 - it is predicted that the top cylinder (section 6) would not be able to be fed from section 4 and 5 due to section 4 and 5 having lower modulus than section 6 and consequently shrinkage porosity is expected in this area. If this cylinder is cooled quicker than section 4 and 5 which is feeding it then the cylinder may solidify before the hour glass section (section 4 and 5) which feeds it. Time to cool of casting is given by Chvorinov's Rule, equation 3-3[16].

$$t_s = B\left(\frac{V}{A}\right)^n \qquad \text{Eqn 3-3}$$

Where t_s = Time for the section of the casting to solidify

V= Volume of the section

A = Surface of section in contact with mould

B and n = constants depending on the mould and metal characteristics

For this reason water cooling channels in the die were used. The flow rate will be modified to verify results predicted from theory. The settings will be restricted to only two levels cooling or no cooling.

Die – Overflows and Gate

The overflows are cut into the die as described in part 8 and as such will remain constant for this experiment. The Gate has been cut into the die with the same modulus as the castings largest modulus section (table 3-6). The gate will also remain constant for this experiment.

Machine – Injection Speed

The speed will be varied between two levels as suggested described in the table. The speed can have a direct impact on cold shuts and air entrapment. The two levels chosen are high enough to be near the limit of the laminar and turbulent flow and slow enough to be able to get a range big enough to draw conclusions from.

From table 3-6 the total volume of the component is 99 330mm^2. The diameter of the shot sleeve is 47.7mm. To fill the cavity the plunger must move forward by,

$$\frac{99330}{\pi \times 47.7^2/4} = 55.58[mm]$$

Table 3-11 shows the cavity fill times, the gate speeds and the speed change over point for the two speed levels (one (1) and two (2)).

Table 3-11: Machine Parameters

Level		Start	Out of Cup	Out of Cup	2nd Stage Point	At Gate	Cavity full	Injection Stop	Cavity fill time	Intensification
1	Time [ms]	0.0	1200.0	1200.0	1797.5	1797.5	1982.8	31982.8	185.3	30000.0
2		0.0	1200.0	1200.0	1797.5	1797.5	1862.9	31862.9	65.4	30000.0
1	Speed [m/s]	0.100	0.100	0.200	0.200	0.300	0.300	0.300		
2	Speed [m/s]	0.100	0.100	0.200	0.200	0.850	0.850	0.850		
1	Disp [mm]	0.00	120.00	120.00	239.50	239.50	295.08	295.08		
2		0.00	120.00	120.00	239.50	239.50	295.08	295.08		
1	Gate Speed	0.000	0.000	0.000	0.000	0.832	0.832	0.000		
2	Gate Speed	0.000	0.000	0.000	0.000	2.359	2.359	0.000		

Table 3-12: Machine Stroke

Stroke of Machine (and shot sleeve)	300	1
Length of Sprue Bush	29.5	2
Length of Shot Chamber (Sleeve and Sprue Bush)	329.5	3
Length of metal billet	110	4
Disp when metal at Split line	219.5	5
Length of biscuit in back half of die	20	6
Disp when at end of Biscuit (Shot Chamber full)	239.5	7

Displacement when at end of Biscuit (Shot Chamber full and metal at gate) = 1 + 2 – 4 + 6 = 7

The change over from slow to high speed is not varied. The value is kept with the change over point at the position when the metal reaches the gate, when the shot chamber is full. If it is found that the metal is too cold it may be necessary to experiment with second stage position earlier in another experiment. If there is found to be entrapped gas porosity it may be necessary to experiment with the second stage later. Table 3-12 shows the data and calculation of the displacement of the change over point.

Machine – Intensification

The machine intensification hydraulic pressure is set to 24MPa but drops to 18MPa after the injection stroke. The pressure is held for 30 seconds for level one and two (at the resulting 18MPa). This hydraulic pressure creates a metal pressure of 756.98 kg/cm^2 [Eqn 3-1]. This value is not adjusted for this experiment. A higher value will have an impact on reducing pore size due to cold shuts, hot tears and or porosity, but will not eliminate the defect and so for this reason it is held constant.

Machine - Metal Volume

The more or less amount of metal that is used to make the casting will result in a longer or shorter biscuit size respectively. The biscuit size must have a modulus greater than that of the gate, from table 3-6 this is 6.3137.

A biscuit size of length l and diameter d will result in a modulus of

Volume $= \frac{\pi \cdot d^2 l}{4}$

Surface area in contact with die $= \frac{\pi \cdot d^2}{4} \cdot 2 + \pi \cdot d \cdot l - (area\_of\_gate\_in\_contact\_with\_biscuit)$

$$= \frac{\pi \cdot d^2}{4} \cdot 2 + \pi \cdot d \cdot l - 23 \cdot 28$$

Modulus $= \frac{\pi(d^2 l)/4}{\pi(d^2/4)2 + \pi(dl) - (23)(28)}$

Setting d = 48 (Diagram 4-40) and solving for l gives $l = 21.907$mm, this means that the length of the biscuit should not be less than 21.907 in length to ensure that the gate is supplied with new metal during solidification. The biscuit size was set by the cup size used to produce the semi solid metal. This system uses a full cup, 100mm high and diameter 48mm to produce the feedstock. This gave a biscuit size of,

Biscuit size $=$ [Metal Volume $= \pi(48)^2(100) = 180955.7$ mm^3] – [Volume of Part = 99 330 mm^3]

$= 81625.92$ mm^3

Biscuit Length $= \frac{81625.92}{\pi(48)^2} = 45.108$ mm

The biscuit size and metal volume is not varied during the experiment. Table 3-12 uses a value of 110 for the length of the billet the reason for the different value is that table 3-12 takes into account the 10mm washer used to seal the base of the cup. This washer is solid and so will not assist in directional solidification that is why it has been neglected from the above calculation.

Machine – Plunger diameter

The plunger diameter influences the metal flow rate, the modulus of the biscuit and the metal pressure. A plunger size of 47.7 was used and this allowed for the correct amount of metal to be contained in the shot sleeve to produce the part. This was not varied during the experiment

Machine – Cooling time

The casting was allowed thirty seconds cool. This is sufficient for the casting to solidify completely. This was not varied during the experiment.

Machine – Cycle time

The cycle time was kept at as low a value as the production and heating up of the semisolid metal would allow. This was three minutes for semisolid metal preparation and 35 seconds for casting the component. This was not varied during the experiment.

Machine – Die Temperature

The machine is equipped with electric resistance carbide heaters in the platens of the machine. These heat the die via conduction. Thermocouples in the die are used to control the heaters via digital temperature controllers. The die temperature controller was set to 250°C and this temperature was maintained in the die. The die temperature was not varied during casting; other than that caused by varying the fluid flow in the water cooling channels, which has already been discussed.

Metal – Metal Temperature

The metal temperature was varied between two levels - 578°C and 582°C during the experiment. The reason for varying the temperature was to ascertain the effect on the defects and be able to optimise the metal temperature. The Literature Study Chapter suggests that the metal temperature will have an influence on the defects.

Metal – Grain size modification

This can be done by adding Titanium or other grain refiners to the metal which act as nucleation sites and cause small grains to be formed. The grain size was not varied during the experiment.

Metal – Eutectic Modification

This can be done by adding strontium to the metal, this has the effect of causing the silicon in the eutectic to form small rounded particles rather than large plates if allowed to form normally. The eutectic was not modified during the experiment.

Summary

Only the three parameters, water cooling, injection speed and metal temperature are varied during the experiment. To ascertain the influence on the desired outcome, zero internal defects in the casting, a series of castings will be done.

Using the Taguchi method [19] of experimental design all three parameter's influence on the experimental outcome can be quantitatively assessed. This method uses orthogonal arrays to minimize the number of experiments required while still being able to investigate the effects of numerous factors' influence at the same time. Table 3-13 outlines the three parameter settings for the four experiment runs.

Table 3-13: Factor Level Settings

Run# / Factor	Water Cooling (A)	Injection Speed (B)	Metal Temperature (C)	Result
1	3 l/min A_1	0.85 m/s B_1	582°C C_1	Y_1
2	3 l/min A_1	0.30 m/s B_2	578°C C_2	Y_2
3	0 l/min A_2	0.85 m/s B_1	578°C C_2	Y_3
4	0 l/min A_2	0.30 m/s B_2	582°C C_1	Y_4

3.10 Analyse, Evaluate and Rate Components from section 3.9

This section presents the method used to identify any defects through the same procedures already described and then rate the components produced from the experiment described in section 3.9 and thereby allow for the selection of the correct parameters to produce a high internal integrity component repeatability.

The result is the level of inhomogeneity found in the castings. An inhomogeneity in the casting is termed a defect. The defect(s) may be due to a cold shuts, hot tears, porosity or a combination of these. The defects are detected and analysed using two methods.

Method one uses the same manner as described in part 3 and 6; that is X-ray radiography is done on the parts to locate and determine the size of the defects. A rating method is then used to compare each casting to the other based on the castings' defects', size and severity. Method two uses a density measurement. In both methods the part is inspected visually for surface defects. If necessary the casting is also sectioned to examine the defect type and if necessary SEM and or EDM or optical microscopy is done on the section.

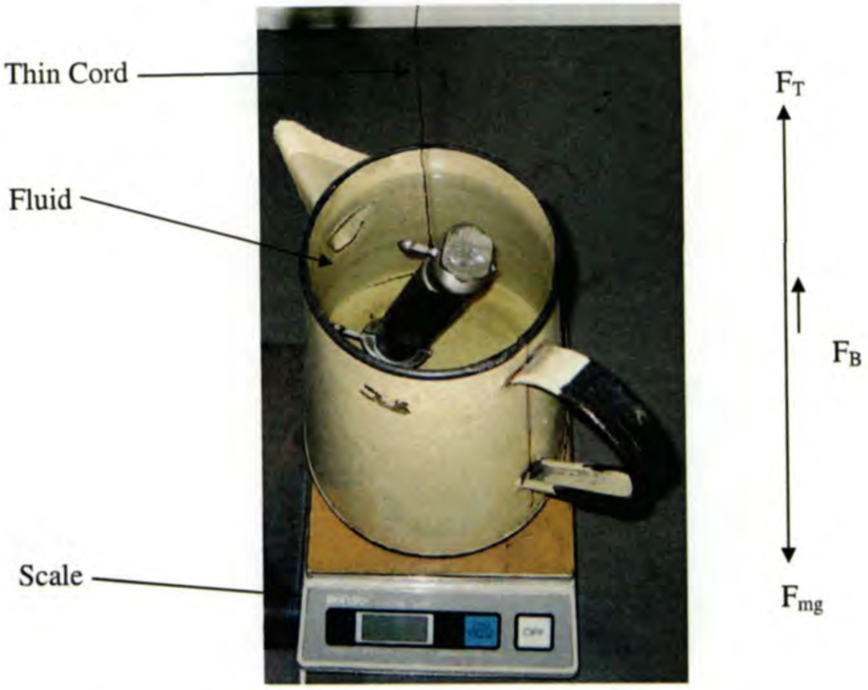
3.10.1 Rating Method

The first method uses the X-Ray radiographs. Each radiograph is examined and the defects are counted. Each defect is given two scores, size and contrast, with 1 being very small for size and very little contrast and 10 being very large and high contrast. The two factors are multiplied together for a final score. Then each casting's defects' final scores are added together to arrive at a final score for that casting. To quantify the size factor 1 is less than $2mm^2$ and 3 is $4mm^2$ and 5 is $6mm^2$ and 7 is $8mm^2$ and 10 is $10mm^2$.

The second rating system uses the density of the component as the method of quantifying the porosity in the casting. Depending on the data a conclusion will be drawn as to which process is giving more meaningful results. To calculate the density of a sample, the sample is weighed in air and then suspended by a thin cord in water and the apparent weight in water is measured. Diagram 3-10 shows the apparatus used to measure the castings density. The procedure above is an accepted method that has been used busy previous researchers [20] to establish a quantitative measure of the level of porosity inside the casting. However it must be noted that for very low levels of porosity the method loses accuracy due to the accuracy limitations of the scale. Also the results would be very close to each other if the porosity level is very low. This will form the main basis for the deciding the meaningfulness of this rating method.

From theory of buoyancy [21], the change in the reading on the scale, when the casting is immersed in the fluid, is equal to the buoyancy force the fluid is exerting on the object, this is shown in Equation B2 . Equation B3 gives the relationship between the scale reading of the casting immersed in de-ionised water and the reading when the casting is weighed in air (normally) on the scale. In this experiment normal water was used which because of ions and other impurities will not have a density of exactly $1000kg/m^3$. If the water used is distilled water then the result of dividing the mass [g] of the casting in air by the apparent mass [g] when weighed in water will give the density in g/cm^3 [Eqn B3].

Diagram 3-10: Apparatus for Density Measurement



Where:		
	F_B	is the buoyancy force of the fluid exerted on the immersed casting
	F_{mg}	is the gravitation pull on the casting
	F_T	is the Tension in the cord

$$\rho_o = \frac{w_a}{V \cdot g} \qquad \text{Eqn B1}$$

$$F_B = w_w = \rho_w \cdot V \cdot g$$

$$\therefore V = \frac{w_w}{\rho_w \cdot g} \qquad \text{Eqn B2}$$

Substuting Eqn B2 into B1:

$$\rho_o = \frac{w_a \cdot \rho_w \cdot g}{w_w \cdot g} = \frac{w_a \cdot \rho_w}{w_w}$$

Where

ρ_o	is the density of the casting
w_a	is the weight of the component weighed in air
w_w	is the apparent weight of the casting weighed in water
V	Volume of the casting
ρ_w	is the density of the fluid (water) the casting is immersed in

$$\rho_o = \frac{m_a}{m_w} \qquad \text{Eqn B3}$$

However since distilled water was not used the result could be slightly higher or lower than the correct density value of the part. Since the same water is used for each casting whose density is calculated in this manner the error will be same for each by the same gain factor and so for the purposes of this study the castings densities may be compared to each other. Another irregularity of the method is volume of the cord which is neglected since it is very small. Again here the same cord was used for every casting density calculation so again the error will be the same on all the castings and so their subsequent calculated density using this method may be compared to each other. To focus on the component part of the casting the overflows, biscuit and gate are removed before weighing the castings.

3.10.2 Selection of the Optimum Level Settings

The results are then tabulated next to each experimental run's parameters, Y_n. This will be done for each of the two methods. Next Taguchi data analysis [19] is done on the result to determine the effect of each parameter on the result. This is done by first plotting the response lines of each parameter or factor at each level in this case level one and two. The graphs are checked for any interactions between the factors. This is done by checking the level of parallelism between the three lines [19]. Then further data analysis is done on the results to establish which factor has the biggest influence on the outcome and which level to set the parameters at to achieve the desired outcome. This is done by using a response table, for this experiment it is shown in table 3-14.

Table 3-14: Response Table

Factor (Parameter)	A – response	B - response	C - response
Level 1	$(Y_1+Y_2)/2 = \underline{A}_1$	$(Y_1+Y_3)/2 = \underline{B}_1$	$(Y_1+Y_4)/2 = \underline{C}_1$
Level 2	$(Y_3+Y_4)/2 = \underline{A}_2$	$(Y_2+Y_4)/2 = \underline{B}_2$	$(Y_2+Y_3)/2 = \underline{C}_2$
Difference between levels	$\underline{A}_1-\underline{A}_2$ = Main Effect A	$\underline{B}_1-\underline{B}_2$ = Main Effect B	$\underline{C}_1-\underline{C}_2$ = Main Effect C

The bigger the main effect is of a factor the more that factor influences the outcome relative to the other factors. Each factors' response at each level is checked and the level chosen that gives the response which is closest to zero for the defect method or the highest value for the density method.

Then a confirmation experiment is done with the factors set at these chosen levels. The castings from the confirmation experiment should have the best desired result. If this is not the case then there is another major factor which has not been included in experiment design in these cases another experiment should be designed to take into account the interactions and or the other major factors previously not included.

The confirmation experiment is done twice so as to obtain two components and the same analysis is performed on them – starting with X-ray analysis and then if necessary sectioning, naked eye, SEM, EDM and or optical microscopy inspection. The two components should both give best result, to ensure repeatability.

Components obtained using the chosen level settings will be of the highest internal integrity possible to be produced with the given system.

Chapter 4 Results and Discussion of Results

The results collected from carrying out the methods and experiments described in Chapter 3 are presented in this chapter. The first section discussed is the Selection of the Component on which to carry out the investigation. Two components are considered and the selection tables, 3-1 to 3-5 are populated with the respective values applicable to each component. Next the initial cast components are presented and the defects and problems associated with them analysed and discussed. Then the results from the modular die are presented and discussed. They simplify the flow and assist in determining the cause and remedies for the defects found in the initial cast components. The results and discussion so presented then predicts improvements to overcome the defects and these are further discussed and then implemented. The improvements are then tested under specific conditions. These final results are presented and the optimum parameters determined. The result is a methodical process which predicts the process parameters and die design in order to repeatably produce high internal integrity components.

4.1 Selection of Components

To establish a suitable Component to be used for this study the system described in section 3.1 of Test and Experiment Methods Chapter was used to rate and ultimately determine the component. Two components were sourced from local manufacturers in South Africa. The first is called a Steering Boss and the second a Short Arm. Both components are to be manufactured from Aluminum. diagram 4-1 shows the Steering boss and diagram 4-2 shows the short arm component.

The Steering Boss is a structural part used by the automotive industry. The part secures the steering wheel to the steering shaft. The requirements are high strength and no internal defects in the part. The manufacturer is looking for a cheaper and more reliable process than currently available. Currently the part is made either from using the gravity casting process or it is machined from billet. The machined option is costly and the gravity option is also costly although less so. The volumes are 1000 per month.

The Short Arm is part of an assembly used in overhead high tension power cables which holds the cables in place over their span. The part must withstand a load which it will experience if a direct short is experienced by the cable. The part must have high internal integrity. Currently it is produced using the squeeze casting method however it has porosity in a section. The porosity is produced during the casting method. A drawing of the component is contained in appendix 1, diagram A-1.

Diagram 4-1 - Photograph of Steering Boss, Gravity casting

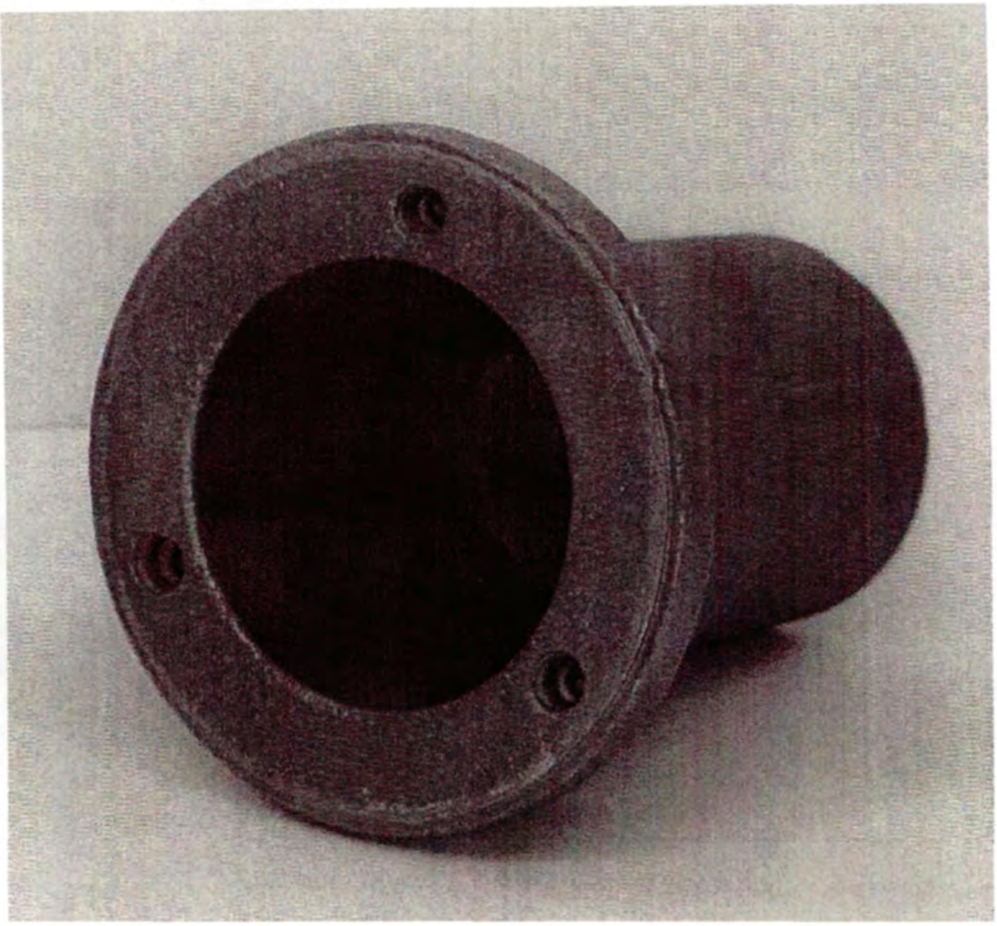


Diagram 4-2 - Photograph of Short Arm

Table 4-1 - Strength and Intregrity Factors

Production Process	Micro Porosity	Shrinkage Feeding	Pressure Tightness	Solution heat treatable	Alloy range applicable	MMC Applicable (metal matrix composites)	Surface Integrity	Weldability	Available Strength	Available ductility	Total Short-arm	Total Steering Boss
Squeeze Cast												
Direct	5	5	5	5	3	3	3	5	5	5	29.5	2.5
Indirect	5	5	5	5	3	5	5	5	5	5	30.5	2.5
SSM	5	5	5	5	2	4	5	5	5	5	29.5	2.5
Sand Pocess												
Green	1	2	2	5	5	3	1	4	3	3	19.5	0.5
Dry	2	2	2	5	5	3	2	4	3	3	21	1
Cosworth	3	3	3	5	5	1	2	4	3	3	23	1.5
Lost Foam	1	2	2	5	2	1	1	4	1	1	12.5	0.5
Permanent Mould												
Gravity, static	3	3	3	5	4	3	3	4	3	4	23.5	1.5
Gravityt, Tilt	3	3	3	5	4	2	3	4	3	4	23.5	1.5
Low Pressure	4	4	4	5	3	1	3	4	4	4	25.5	2
Counterpressure	4	4	4	5	3	1	4	4	4	4	26	2
Cast Forged	4	4	4	5	2	3	4	4	4	4	25	2
Die Cast												
Conventional	1	2	2	1	2	1	5	1	1	1	10.5	0.5
Controlled Shot	2	3	3	3	2	3	5	2	2	2	16.5	1
Vacuum	4	3	3	3	2	3	5	2	3	2	19.5	2
Forging	5	5	5	5	1	3	3	5	5	5	27.5	2.5
Weighting Short Arm	1	1	0	1	1	0	0.5	0	1	1		
Weighting Steering Boss	0.5	0	0	0	0	0	0	0	0	0		

From section 3.1 of the Test and Experiment Methods Chapter, the rating method and tables 3-1 to 3-5 is used and populated respectively as described below. The Steering Boss and the Short arm are evaluated together. The weighting factor for each factor class is discussed. The weighting factor is a number between 0 and 1 with 1 implying the factor is critical to the part and 0 implying the factor is not critical at all to the part. This is a qualitative process. The results are presented in tables 4-1 to 4-6.

Table 4-1 Strength and Integrity factors for Steering Boss.

- Microporosity
    - The Steering Boss must have reasonable internal structure however it over designed in terms of its wall thickness and as a result will not be critical to microporosity. However it is not desirable to have excessive internal microporosity. As a result it is given 0.5 for the weighting factor for microporosity.
    - The Short Arm on the other hand must have extremely low microporosity in all sections as it is designed on the limit of the material strength. The casting is competing with a wrought alloy which is machined to shape, this product has no internal porosity and it is expected, by the customer, that the casting has similar attributes. As a result it is given a 1 for the weighting factor, as microporosity is a critical factor.
- Shrinkage feeding
    - The steering boss as mentioned above is over designed in terms of its wall thickness and as a result will not it is not critical to feed shrinkage porosity. Also the wall thickness is very uniform and as a result there is no need for there to be exceptional shrinkage feeding qualities. The weighting factor for this factor is 0
    - The Short Arm has a very varied thickness, it starts of thick at the oval end and then stays thick during the cylindrical section. Then in the middle hour glass shaped section the part becomes considerably thinner. After the hour glass section the part once again becomes thick again. It will be critical to feed the thicker parts to reduce shrinkage porosity as stressed above. As a result it is given a 1 for the weighting factor for shrinkage feeding.
- Pressure tightness
    - The steering boss does not have any pressure tightness requirement – it is not a pressure vessel of any kind. As a result it is given a zero (0) weighting factor for pressure tightness.
    - The Short Arm does not have any pressure tightness requirement – it is not a pressure vessel of any kind. As a result it is given a zero (0) weighting factor for pressure tightness.
- Solution Heat treatable

  - The steering boss deos not need to be heat treated. As a result it is given a zero (0) weighting factor for solution heat treatable.
  - The Short Arm will require heat treatment since it is competing against a wrought alloy. As a result it is given a one (1) for solution heat treatable weighting factor.
- Alloy Range Applicable
  - The steering boss may be cast from any aluminium alloy since it is over designed and as a result does not have a specific alloy requirement, for strength, corrosion or any other specific needs. The weighting is zero (0)
  - The Short Arm will more than likely have a specific alloy requirement and as a result a range of alloys may need to be experimented with to achieve the required strength. As a result it is given a one (1) weighting factor for the alloy range applicable.
- MMC Applicable (metal matrix composite)
  - The steering boss would not need to be cast from this type of material . As a result it is given zero (0) for the weighting factor
  - The Short Arm would also not need to be cast from this type of material and as a result it is given zero (0) for the weighting factor
- Surface integrity
  - The steering boss is hidden from view also it does not have any special coating applied to it which could necessitate a high surface finish. As a result it scores a zero (0) for the weighting factor.
  - The Short Arm is in full view, it is not coated with any special coating. As a result it is given a 0.5 for the weighting factor.
- Weldability
  - Both Products do not require any welding to be done to them. As a result they both score a zero for the weighting factor.
- Available Strength
  - The steering boss is over designed and as a result does not require all the available strength from the material. As a result it scores a zero (0) for the weighting factor.
  - The Short Arm will require all the available strength from the material. As a result it scores a one (1) for the weighting factor.
- Available Ductility
  - The steering boss will not require all the available ductility from the material as it will not under high stress as it is over designed. As a result it is given a zero (0) for the weighting factor.
  - The Short Arm could perceivably be in fatigue as well undergo high stresses. As a result the product should have high ductility. The weighting factor for this factor is one (1).

Table 4-2 Dimensional and Complexity Factors.

Table DC - Dimensional and Complexity factors

		Net Shape Capabilities				Dimensional tolerance		Dimensional tolerance		Surface		
Production Process	Part Complexity	Dimensional Repeatability	Machining Allowance	Minimum walls	Linear	Draft	Across Parting	Thickness	Flatness	Finish smoothness	Total Short Arm	Total Steering Boss
Squeeze Cast												
Direct	2	4	1	2	3	1	2	1	5	4	7	7.2
Indirect	4	5	3	5	5	4	4	3	4	5	12.7	10.2
SSM	4	5	4	5	5	5	5	4	4	5	15.1	11.6
Sand Pocess												
Green	4	1	1	1	1	3	1	2	2	1	3.9	3.8
Dry	3	3	2	2	3	2	3	3	2	1	8.1	7.1
Cosworth	4	3	3	2	2	3	2	3	3	2	8.4	7.3
Lost Foam	5	4	3	4	3	5	5	5	1	1	12.5	9.9
Permanent Mould												
Gravity, static	3	3	2	3	3	2	2	3	3	3	8.1	7.1
Gravityt, Tilt	3	3	2	3	3	2	2	3	3	3	8.1	7.1
Low Pressure	3	3	2	3	4	2	3	3	3	3	9.1	7.6
Counterpressure	3	3	2	3	4	2	3	3	3	3	9.1	7.6
Cast Forged	1	4	1	2	4	1	2	2	4	4	7.6	7.4
Die Cast												
Conventional	5	5	5	5	5	4	4	4	4	5	14.9	11.3
Controlled Shot	4	5	4	5	5	4	4	4	4	5	14.1	11.1
Vacuum	5	5	5	5	5	4	4	4	4	5	14.9	11.3
Forging	1	4	1	1	4	1	1	1	5	4	6	6.7
Weighting Short Arm	0	0.4	0.8	0	0	0	1	0.6	0	0.5		
Weighting Steering Boss	0	0.7	0.2	0	0	0	0.5	0.7	0.5	0		

- Part Complexity
  - The steering boss's geometry from a casting point of view is very simple. As a result it is given zero (0) for the weighting factor.
  - The Short Arm also not very complex from a casting point of view. As a result it is given zero (0) for the weighting factor.
- Net Shape Capabilities
  - Dimensional Repeatablity
    - The steering boss will a require a reasonable degree of dimensional repeatability [Would need to fit into a jig for hole drilling, and is used to secure the steering wheel in the correct position]. As a result it is given 0.7 for the weighting factor.
    - The Short Arm is over moulded on the two ellipsoid end caps with silicon, the only critical dimension to jigging and fixturing are the two cylindrical section. This product requires a low to medium degree of dimensional repeatability. As a result it is given 0.4 for the weighting factor.
  - Machining Allowance
    - The steering boss has a reasonable amount of extra material that would need to be machined away this is worked into the design of the original part. The restraint therefore on the machining allowance is not very high. As a result the weighting factor is 0.2.
    - The Short Arm is not machined at all after casting it is only pinch trimmed (to remove the flash). There is not any extra material that is required to be removed. This means that the cast part must be ready for use and the casting process must be accurate and near net shape and so the restraint on the machining allowance is high. As a result the weighting factor is 0.8.
  - Minimum walls
    - The steering boss does not have thin walls. As a result the weighting factor is zero (0).
    - The Short Arm does not have thin walls. As a result the weighting factor is zero (0).
- Linearity
  - The steering boss is a cylindrical part and does not have complex geometry. There is no importance for linearity. As a result the steering boss is given a zero (0) for this weighting factor.
  - The Short arm is also a cylindrical part without complex geometry. There is no requirement for linearity and as a result the Steering Boss scores a zero (0) for linearity weighting factor.
- Dimensional Tolerance
  - Draft

    - The steering boss does not have any requirements for minimum draft, it has in fact extremely generous draft angles. As a result it is given a zero (0) weighting factor for draft.
    - The Short Arm also has very generous draft angles as a result of its cylindrical shape. As a result the Short arm is given a zero weighting factor for the draft.
  - Across Parting Line [Dimensional Tolerance across Parting Line]
    - The steering boss is a cylindrical part and it is important that the tolerance across the parting line be maintained at a reasonably high level so as to keep the cylindrical shape and ensure the part meets its jigging requirements. As a result it is given 0.5 for this weighting factor.
    - The Short arm is also cylindrical in geometry and is a requirement so as to avoid electrictral discharge by having smooth symmetrical rounded surfaces. A discontinuity or mismatch in the parting line could give rise to a sharp edge which is not acceptable. As a result the tolerance across the paring line is important and the Short Arm is given a 1 weighting factor for this factor.
  - Thickness [Dimensional Tolerance]
    - The steering boss has very thick walls and requires reasonable tolerance to be maintained for the wall thickness to facilitate jigging and location of the steering wheel. As a result it scores a 0.7 for the thickness tolerance weighting factor.
    - The Short Arm has low thickness dimensional tolerance requirements for the two cylindrical sections where it is clamped during silicon over moulding. As a result it scores a 0.6 for this weighting factor.
  - Flatness
    - The steering boss has two faces , only one has low tolerance for flatness. The two faces are both circular rings and the one face has the steering wheel bolted to itself and the other face buts up against a square section on the sterering shaft.The face which has the steering wheel attached to itself requires low tolerance flatness. As a result the steering boss is given a 0.5 for this weighting factor.
    - The Short Arm does not have any faces with low tolerance requirements for flatness. As a result it is given a zero (0) for the weighting factor.
- Surface finish smoothness
  - The steering boss is hidden from view and as a result does not have a high requirement for surface finish. As a result it scores a zero (0) for the weighting factor.
  - The Short Arm does not require very high surface finish smoothness, however it may not have a rough surface as a rough surface area which can cause an electrical discharge. Therefore the Short Arm is given a 0.5 for the weighting factor.

Table 4-3 - Machining and Tooling Factors

	Machine		Combined		Tooling							Total	Total
Production	Productivity	Utilisation	Internal	Cast-In	Material	Material Cost Score	Develop-ment	Life	Manufacture	Change	Multi Cavity	Short Arm	Steering
Process	(cycle time)	(Up time)	coring	inserts			Time		Cost	Flexibility			Boss
Squeeze Cast													
Direct	1	2	1	2	Tool Steel	2	4	2	2	1	1	10.7	9.05
Indirect	4	3	3	5	Tool Steel	2	1	2	1	1	3	13.4	6.95
SSM	5	4	3	5	Tool Steel	2	1	4	1	1	3	17.4	7.15
Sand Pocess													
Green	5	5	5	1	Palstic-Steel	5	5	5	5	5	5	26.7	19.75
Dry	3	4	5	3	Iron-Steel	3	4	4	4	4	2	18.3	14.7
Cosworth	3	4	5	3	Iron-Steel	3	4	4	4	4	2	18.3	14.7
Lost Foam	3	4	5	1	Aluminum	4	2	5	4	4	4	19.4	14.2
Permanent Mould													
Gravity, static	3	4	4	2	Iron-Steel	3	3	3	3	3	3	17.0	12.45
Gravityt, Tilt	3	4	3	2	Iron-Steel	3	3	3	3	3	2	16.0	11.7
Low Pressure	2	3	4	3	Iron-Steel	3	4	3	2	2	3	15.8	12.25
Counterpressure	2	3	4	3	Tool Steel	2	3	4	2	2	2	14.7	10
Cast Forged	1	3	1	1	Tool Steel	2	4	2	2	2	1	11.7	9.15
Die Cast													
Conventional	5	1	1	5	Tool Steel	2	3	2	1	1	3	14.4	7.85
Controlled Shot	4	2	3	4	Tool Steel	2	3	4	1	1	3	16.4	8.85
Vacuum	5	1	1	5	Tool Steel	2	3	3	1	1	3	15.4	7.85
Forging	3	3	1	1	Tool Steel	2	4	4	2	1	1	15.7	9.35
Weighting Short Arm	1	1	0	0		0.1	1	1	0.25	0	1		
Weighting Steering Boss	0.1	0.1	0.5	0		1	1	0	1	0	0.25		

- Machine Factors
    - Productivity – [Cycle Time]
        - The Short Arm has a relatively large per month volume requirement - >100000 per year. Therefore the productivity rate is important for the successful production of this part from both economic and capacity constraint points of view. As a result it is given a one (1) for weighting factor.
        - The Steering Boss on the other hand does not have large per month volume requirement, the volumes here are <1000 per month. As a result it is less susceptible to economic and capacity constraints and scores one tenth (0.1) for the weighting factor.
    - Utilisation – [Up Time]
        - As mentioned above the Short Arm is a high production volume part. As a result downtime (reduction of Uptime) will adversely affect the successful manufacture of this part. Utilisation is extremely important for the Short Arm thus it is given a one (1) for the weighting factor for Utilisation.
        - The Steering Boss is the converse to this – since it has a very low per month volume requirement. It is given one tenth (0.1) for its weighting factor.
- Combined – [Machine and Tooling Factors]
    - Internal Coring
        - The Short Arm has no internal coring requirement. As a result it scores a zero (0) for this weighting factor.
        - The Steering Boss has no internal coring and only has one large simple static core requirement. As a result it scores half (0.5) for the weighting factor for this factor.
    - Cast in Inserts
        - Both The Short Arm and the Steering boss have no cast in inserts. As a result they both score a zero (0) for this weighting factor.
- Tooling
    - Material [required to manufacture the tooling]
        - The Short Arm with its large volume off take will offset tooling costs as they are a fixed cost. For this reason it is given a low weighting factor for tooling material – one tenth (0.1).
        - The Steering Boss has a small volume per month offtake and so the fixed cost component of the tooling has a large impact on the consideration of a suitable production process. As a result the Steering Boss scores a one (1) for the weighting factor.

- Development Time
    - Both the Short Arm and the Steereing Boss will benefit from quick development time. They are both given a one (1) for the development time.
- Life
    - The Short Arm due to its high volume off take will be very sensitive to tool life. As a result the Short Arm scores a one (1) for this weighting factor.
    - The Steering Boss has a low volume off take and it will not be very susceptible to tool life. As a result it scores a zero (0) for this weighting factor.
- Manufacture Cost
    - The Short Arm is a purpose made product and is high volume part thus the impact of the cost of the tool is offset by the high volume as the tooling is amortised against the castings [the cost per part includes a portion of the cost of the tooling in the ratio of number parts produced in a year]. Due to the high volume the cost of the tool is relatively small and for this reason the weighting factor is a quarter (0.25).
    - The Steering Boss is a small volume part and the amortised cost of the tooling will therefore have a large impact on the total product cost. For this reason it is given a one (1) for this weighting factor.
- Change flexibility
    - Both of these products have no need for changes. Therefore they are both given a zero (0) for this weighting factor.
- Multi Cavity
    - Due to the high volume production required for the Short Arm multi cavity tooling would be very beneficial to the product. The Short Arm is therefore given a one (1) for this weighting factor.
    - The low volume production of the Steering Boss will cause multi cavity tooling to benefit the product less. For this reason the Steering Boss is given a quarter (0.25) for this weighting factor.

Table 4-4 - Casting Factors

Production Process	Metal Flow	Directional Solidification	Solidification Rate	Cavity fill Time [sec]	Cavity fill time Rating	Solidification Pressure [Mpa]	Solidification Pressure Rating	Die/Mould Temp. ℃	Die/Mould Temp. Rating	Pouring Temp. ℃ *Forge Piece Temp	Pouring Temp. Rating	Total Short Arm	Total Steering Boss
Squeeze Cast													
Direct	4	2	3	5 - 25	2	103 - 275.8	1	232 - 316	2	704 - 732	2	12.4	5
Indirect	5	5	5	0.5 - 2	3	103 - 275.8	1	232 - 316	2	691 - 760	2	18.5	6.9
SSM	5	5	5	0.1 - 0.5	4	68.9-137.9	2	204 - 260	3	+- 580 alloy dependant	4	23.5	9.6
Sand Pocess													
Green	3	2	2	5 - 25	2	Atmos	5	Ambient	5	704 - 760	2	18.3	8.3
Dry	3	3	2	5 - 25	2	Atmos	5	Ambient	5	704 - 732	2	19.3	8.8
Cosworth	5	3	3	5 - 25	2	Atmos	5	Ambient	5	704 - 732	2	20.5	9.1
Lost Foam	4	1	1	5 - 25	2	Atmos	5	Ambient	5	704 - 732	2	16.4	7.8
Permanent Mould													
Gravity, static	3	3	3	5 - 25	2	Atmos	5	316 - 426	1	704 - 816	1	15.3	6.1
Gravity, Tilt	4	4	3	10 - 30	1	Atmos	5	316 - 426	1	704 - 788	1	15.4	6.6
Low Pressure	5	4	3	10 - 30	1	Atmos	5	316 - 426	1	691 - 732	2	16.5	7.5
Counter-pressure	5	4	3	10 - 30	1	1.4 - 6.89	4	316 - 426	1	691 - 732	2	15.5	7
Cast Forged	4	2	4	5 - 25	2	Atmos	5	204 - 316	2	677 - 704	2	17.4	7.1
Die Cast													
Conventional	1	2	5	0.04 - 0.1	5	68.95 - 103	2	149 - 232	3	635 - 677	3	20.1	7
Controlled Shot	2	2	4	0.05 - 0.2	5	41.4 - 82.8	3	204 - 316	2	663 - 704	2	18.2	6.2
Vacuum	2	2	5	0.04 - 0.1	5	33.1	3	149 - 232	4	635 - 677	3	22.2	8.1
Forging *	1	5	5	0.01	5	275.8	1	149 - 316	3	380 - 400	5	24.1	9.6
Weighting Short Arm	0.1	1	1		1		1		1		1		
Weighting Steering Boss	0.1	0.5	0.1		0.1		0.5		0.5		0.8		

- Metal Flow
    - The Short Arm is not a complex casting from a casting geometry point of view. It has large thick sections with rounded corners. For this reason the level of fluidity of the metal [metal flow] is not critical and so the short arm is given a tenth (0.1) for the weighting factor for this factor.
    - The Steering boss also has large rounded sections and is thick, 10mm wall thickness. Again there is no difficult casting geometry on this part. As a result the steering boss scores a weighting factor for this factor of a tenth (0.1).
- Directional Solidification
    - The thickness of the Short Arm and the requirement for no porosity requires that directional solidification takes place successfully [13,7]. For this reason directional solidification is critical to the success of the short arm and it is give a one (1) for this weighting factor.
    - The steering boss's internal integrity (porosity requirement) is not as critical as the Short Arm and as a result directional solidification is not critical to this part although reasonable integrity is required especially in those areas where the part is machined. The steering boss scrores a half (0.5) for this weighting factor.
- Solidification Rate
    - As mentioned above the Short Arm is a high volume production part, it is therefore necessary for the amount of time required to manufacture one part to be reduced as much as possible. Therefore the time to Solidify is an important factor and the Short Arm is given a one (1) for the weighting factor.
    - The Steering boss by contrast is a relatively low volume production part and so it is not as critical to have a very low solidification time. As a result the Steering boss is given a tenth (0.1) for this weighting factor.
- Cavity Fill time
    - As above the reduced cavity fill time will benefit a high volume part much more than a low volume part. As a result the Short Arm is given a one (1) and the Steering Boss is given a tenth (0.1) for this weighting factor.
- Solidification Pressure
    - The higher the solidification pressure required the higher the stresses placed on the die and machine producing the solidification pressure. A higher solidification pressure requires a stronger more expensive mould and machine. The Short Arm requires high solidification pressure to facilitate directional solidification (shrink feeding), if the semi-solid metal casting process is used to manufacture the Short Arm. The Short Arm is given a one (1) for this weighting factor.

  - The Steering Boss is far less critical in so far as porosity is concerned and together with its simple casting geometry it does not have a need for very high solidification pressure. The steering boss is given a half (0.5) for this weighting factor.
- Die or Mould Temperature
  - The Short Arm would require a well controlled die temperature to ensure direction solidification takes place. It is given a weighting factor of one (1)
  - The Steering Boss is not very critical to die temperature due to its simple casting geometry and is given a half (0.5) as its weighting factor for this factor.
- Metal Pouring Temperature (for forging this is the billet temperature)
  - Both the Short Arm and the Steering boss will benefit from the lowest metal pouring temperature possible, the Short Arm due to the need for Directional Solidification and slightly more complicated casting geometry than the Steering Boss will require slightly better control of the metal pouring temperature. The Steering boss scores eight tenths (0.8) and the Short Arm scores a one (1) for this weighting factor.

Table 4-5 Economics of Process and Product Cost Factors

- Overall
  - The Short Arm has very large volumes per month and so is more critical to product costs (variable) and less critical to fixed process costs than the steering boss is. It is given a half (0.5) weighting factor for this factor.
  - The Steering boss has low volumes per month and as a result is more susceptible to fixed process costs and less susceptible to product costs (variable). It is also given a half (0.5).
- Equipment (fixed cost)
  - The Short Arm's high volume will reduce the impact of the cost of equipment. It is given a half (0.1) for this weighting factor.
  - The Steering Boss's low volumes will increase the impact of the cost of equipment. It is given a one (1) for this weighting factor.
- Tooling
  - For the same volume reasons as above the Short Arm scores a tenth (0.1) and the Steering Boss scores a one (1) for this weighting factor.

Table 4-5 - Economics of Process and Product Cost Factors

Production Process	Overall	Equipment	Tooling	Casting	Processing	Raw Material	Component Weight	Near Net shape	Total Short Arm	Total Steering Boss
Squeeze Cast										
Direct	2	2	2	2	2	3	5	2	15.4	12
Indirect	4	1	1	4	4	3	5	4	22.2	14
SSM	3	1	1	3	4	1	5	4	18.7	12
Sand Pocess										
Green	5	5	5	5	1	3	1	3	16.5	19
Dry	4	4	4	4	2	3	1	3	15.8	16.5
Cosworth	4	4	4	4	2	3	2	3	16.8	17
Lost Foam	5	4	4	5	3	3	1	4	19.3	18.5
Permanent Mould										
Gravity, static	4	4	3	4	2	4	2	3	17.7	16.5
Gravity, Tilt	4	4	3	4	3	4	2	3	18.7	17
Low Pressure	3	3	2	3	4	3	3	3	18	14.5
Counterpressure	3	3	2	3	4	3	3	3	18	14.5
Cast Forged	2	4	2	3	5	3	3	2	17.6	15
Die Cast										
Conventional	4	2	1	5	5	5	4	5	26.3	17
Controlled Shot	3	2	1	3	5	4	4	5	22.8	15
Vacuum	4	2	1	4	5	4	4	5	24.3	16
Forging	2	1	2	2	2	2	5	1	13.3	10
Weighting Short Arm	0.5	0.1	0.1	1	1	1	1	1		
Weighting Steering Boss	0.5	1	1	0.5	0.5	0.5	0.5	0.5		

- Casting
    - This refers to the variable cost. The cost per part is very important for the Short Arm since it is purely a technical part and requires the lowest cost price to produce. The volumes are large so the variable cost will be a major component of the total cost price. As a result the weighting factor is one (1) for this factor.
    - The Steering Boss is a low volume part by comparison and as a result the variable cost component of the price is low. For this reason it is given a weighting factor of (0.5) for this factor.
- Processing
    - This refers to the work required to be done after the casting solidifies in the mould or die. The amount of processing increases the variable cost substantially. For this reason it is important that the processing is kept to a minimum for a high volume production part that has as a result a large proportion of its price made up of variable costs. The Short Arm is given a one (1) for this weighting factor.
    - The Steering boss on the other hand has low proportion of it price made up of variable costs since it is a low volume production part. For this reason the Steering Boss is given a half (0.5) for this weighting factor.
- Raw Material
    - Raw material makes up part of the variable cost of a part. For the same volume reasons as above the Short Arm is given a one (1) and the Steering Boss is given a half (0.5) for this weighting factor.
- Component Weight
    - This refers to the possibility of reducing the weight of the component by either, the use of thin walls or thinner sections but still offering the same strength and functionality of the part. The main advantage of being able to reduce the component weight is the effect this has on the raw material component of the variable cost, since the lighter the component weight is the less raw material is used and subsequently the lower the variable cost is. For the same production volumes as above the Short Arm is given a one (1) and the Steering Boss is given a half (0.5) for this weighting factor.
- Near Net Shape
    - Near net shape means that once the casting has solidified it is very close the final form, it is near the net (final) shape. This is a large advantage of a process since it dramatically reduces the amount of post casting processing. This in turn reduces the variable cost. For the high volume production Short Arm part this is very important and as a result the Short Arm is given a one (1) for this weighting factor.

Table 4-6: Result of Weighting factors for all Selection Tables

Production Process	Sterngth and Integrity Factors		Dimension and Complexity Factors		Machining and Tooling Factors		Casting Factors		Process and Prodcut Cost Factors		Total Score	
	Short Arm	Steering Boss	Short Arm	Steering Boss	Short Arm	Steering Boss	Short Arm	Steering Boss	Short Arm	Steering Boss	Short Arm	Steering Boss
Squeeze Cast												
Direct	29.5	2.5	7	7.2	10.7	9.05	12.4	5	15.4	12	75	35.75
Indirect	30.5	2.5	12.7	10.2	13.45	6.95	18.5	6.9	22.2	14	97.35	40.55
SSM	29.5	2.5	15.1	11.6	17.45	7.15	23.5	9.6	18.7	12	104.25	42.85
Sand Pocess												
Green	19.5	0.5	3.9	3.8	26.75	19.75	18.3	8.3	16.5	19	84.95	51.35
Dry	21	1	8.1	7.1	18.3	14.7	19.3	8.8	15.8	16.5	82.5	48.1
Cosworth	23	1.5	8.4	7.3	18.3	14.7	20.5	9.1	16.8	17	87	49.6
Lost Foam	12.5	0.5	12.5	9.9	19.4	14.2	16.4	7.8	19.3	18.5	80.1	50.9
Permanent Mould			0				0	0	0	0		
Gravity, static	23.5	1.5	8.1	7.1	17.05	12.45	15.3	6.1	17.7	16.5	81.65	43.65
Gravity, Tilt	23.5	1.5	8.1	7.1	16.05	11.7	15.4	6.6	18.7	17	81.75	43.9
Low Pressure	25.5	2	9.1	7.6	15.8	12.25	16.5	7.5	18	14.5	84.9	43.85
Counterpressure	26	2	9.1	7.6	14.7	10	15.5	7	18	14.5	83.3	41.1
Cast Forged	25	2	7.6	7.4	11.7	9.15	17.4	7.1	17.6	15	79.3	40.65
Die Cast												
Conventional	10.5	0.5	14.9	11.3	14.45	7.85	20.1	7	26.3	17	86.25	43.65
Controlled Shot	16.5	1	14.1	11.1	16.45	8.85	18.2	6.2	22.8	15	88.05	42.15
Vacuum	19.5	2	14.9	11.3	15.45	7.85	22.2	8.1	24.3	16	96.35	45.25
Forging	27.5	2.5	6	6.7	15.7	9.35	24.1	9.6	13.3	10	86.6	38.15

- The Steering Boss being a low volume production will not benefit in the same dramatic manner as shown above by the Short Arm. The variable cost is a low proportion of the final price of the Steering Boss as a result the Steering Boss is given a half (0.5) for the weighting factor for the Near Net Shape factor.

Table 4-6 shows the summation of each score from each table. The table shows that the most suitable process to manufacture the Short Arm by is SSM (Semi Solid Metal) Die casting. This is because it has the highest number, 104.25 the next most suitable process to manufacture the short arm is by indirect squeeze casting, 97.35. Table 4-6 also shows that the SSM Die casting manufacturing process does not suit the Steering Boss since the total score from all the tables for SSM Die casting was 42.85. This is the tenth lowest score for the sixteen different manufacturing processes considered. According to table 4-6 the most suitable manufacturing process for the Steering Boss is in fact Sand Casting using the Green Sand process since this process scored 51.35 which was the highest score the next highest was the Lost Foam process which scored 50.9.

For the purposes of this investigation the Short Arm is selected as the most suitable component on which to conduct an investigation of Semi Solid Die Casting of components.

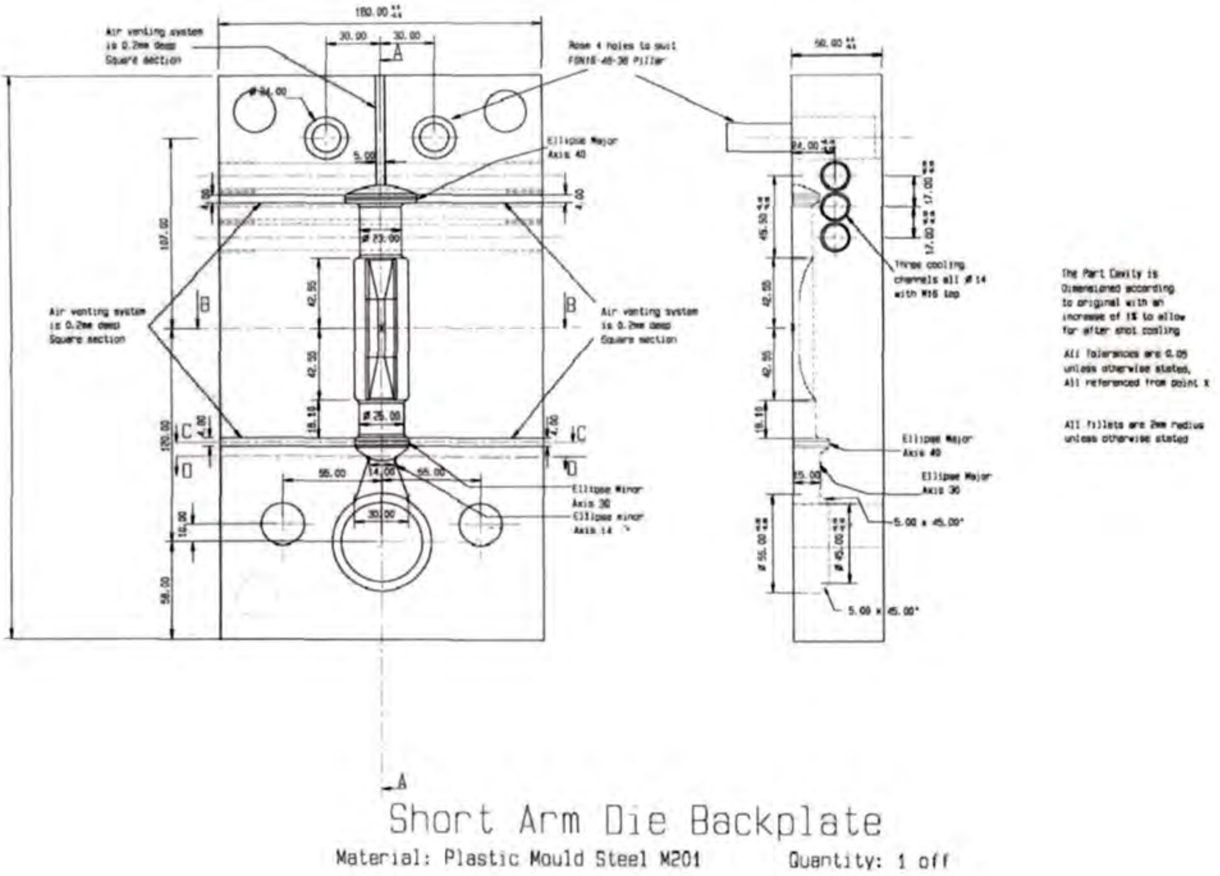
4.2 Initial design of Component die and Initial castings produced.

4.2.1 Die Design

The design of the die as discussed in Chapter 3 enables modifications to be done at a later stage. The modifications expected are overflows, gate geometry changes and cooling and or heating channels.

Drawing 4-2 shows the original die back plate (normally called the ejector half). The die is cut from a Plastic Mould Steel called M201. The plate size is 180mm wide by 320 in height and 50mm thick. The component geometry is cut into the die half with an increase of 1% on all dimensions. The increase of 1% so as to compensate for cooling of the part once it has been ejected from the die[27]. There is a recess at the bottom to form the biscuit. This recess is placed here to collect any oxide layer on the end of the billet[54]. Leading from the biscuit section is the gate this is conical in profile and ellipsoid in section. From the modular study conducted in the Methods section it is clear that there could be a possible problem with directional solidification between the hour glass section and the 23mm diameter cylindrical section. For this reason channels were drilled through the die which could be used as cooling or heating channels in later experiments.

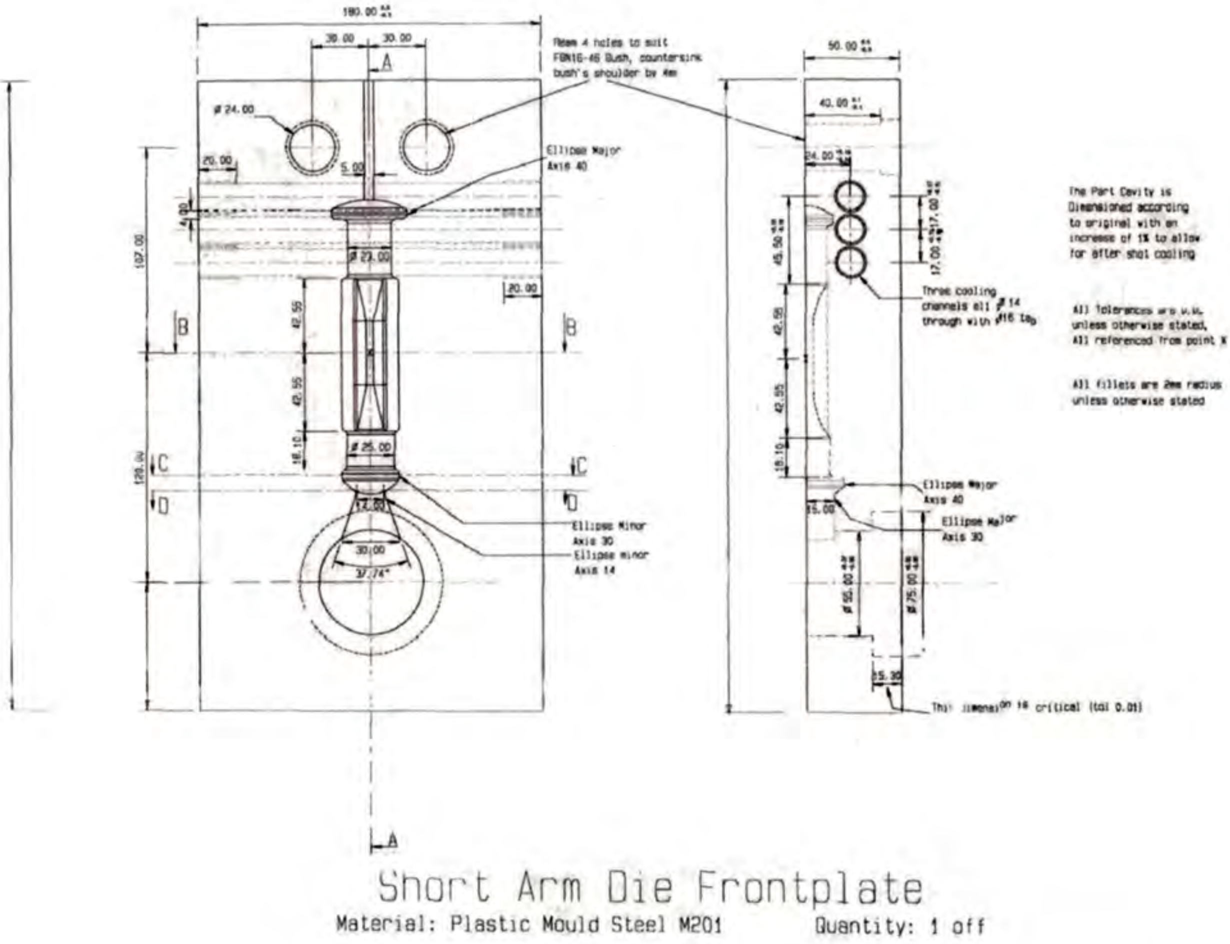
Diagram 4-3: Original Die Back Plate (See Diagram 4-39 for larger modified view)



The conical gate was made so as to shape the metal to a similar cross sectional section as the ellipsoid end cap which the metal will come into contact with first. This gate is an experimental gate and the fact that it is smaller than the thick 25mm diameter cylinder, which according to literature[7] the gate should be of similar thickness, means that it can be milled out to the same size for later experiments.

The front plate of the die mates with the Shot Sleeve through which the metal enters the die. A recess is milled on the external face to envelope the shot sleeve. The recess is 75mm in diameter. The depth of the recess is critical since the end of the shot sleeve must be in contact with the external face of the die and there must be less than 0.1 clearance. If there is more clearance than this the metal will force a passage between the face of the recess and the end of the sleeve and then continue out to atmosphere. This is undesirable for two reasons, the metal pressure will be lost and metal will be lost out of the die and there could be a shortage of metal left to fill the component cavity in the die. The depth of the recess suits the shoulder of the shot sleeve which is 15.3mm.

Drawing 4-4: Original Die Front Plate (See Diagram 4-40 for larger modified view)



The gate is where the metal enters the component. As discussed in the Methods section, two gate geometries were experimented with. The first gate's geometry is ellipsoid in section. This gate is shown in diagram 4-3 and 4-4. The other gate to be experimented with is cylindrical and is 25mm in diameter. Once the experiments have been done with the ellipsoid gate the gate will be milled out to the 25mm diameter size. The 30mm major axis will protrude from the cylindrical gate which will give the cylindrical gate more volume and slightly more surface area. This is not seen as a problem to the casting. This cylindrical gate is not shown in diagram 4-3 or 4-4.

The other machining work on the die, worth mentioning, are the air vents. These are machined on only one half of the die, the back plate half. The depth of these is 0.2mm. From experience in industry this is the maximum depth through which the molten Aluminum, under pressure will not escape. The requirement in the methods section that the air flow through this vent should not choke, means that the maximum airflow must be calculated.

The top three vents will be considered since the bottom two will be blocked by Aluminum in the last moments of the die being filled. The condition when the two side vents are blocked and only the top vent open and all the flow of air is escaping through this vent is neglected. The reason for neglecting this condition is that this only happens during filling of the very top layer of the ellipsoid hemisphere, which is a non critical portion of the casting.

When the air can only escape through the top three air vents, the metal flow rate will still be at its highest value. The maximum flow rate used in the experiments will be obtained when the injection plunger travels at its highest velocity, which from Chapter 3 is given as, 0.85ms^{-1}. The corresponding fluid flow rate for this injection plunger velocity is:

$$\begin{aligned} Q_{dm} &= u_p\ A_{cs} && \text{Eqn. MF} \\ &= 0.85\ [\text{ms}^{-1}]\ \pi\ m_d^2 / 4 \\ &= 0.85\ [\text{ms}^{-1}]\ \pi\,(47.76[\text{mm}])^2 / 4 \\ &= 0.001523\ \text{m}^3\text{s}^{-1} \end{aligned}$$

Where Q_{dm} is the flow rate of the metal

u_p is velocity of the injection plunger

A_{cs} is the cross sectional area of injection plunger

m_d is the diameter of the metal injection plunger

The flow rate of air out of the die through the vents must equal the flow of metal into the die. Since there is no other passage through which the air may escape and for negligible increase in air pressure Eqn. AF must be satisfied.

$$\begin{aligned} Q_{dm} &= Q_{da} && \text{Eqn. AF} \\ &= (\,A_{csa}\,)(\ u_a\ ) \\ 0.001523\ \text{m}^3\text{s}^{-1} &= (0.2\ [\text{mm}] * 4\ [\text{mm}] * 2\ [\text{off}] + 0.2\ [\text{mm}] * 0.010\ [\text{mm}]\ )\ u_a \end{aligned}$$

Solving for u_a,

$u_a \quad = \quad 585.685 \text{ ms}^{-1}$

Where Q_{dm} is the flow rate of the metal

Q_{da} is the air flow rate

V_d is the depth of the air vent channel

V_w is the width of the air vetn channel

V_n is the number of effective air vent channels

u_a is the velocity of the traveling through the vents

From B.S. Massey [46] the air escaping experiences choking at the speed of sound. We are assuming the passage of the flow of air is very close to isentropic (adiabatic and frictionless).

$$a = \sqrt{(\gamma RT)} \qquad \text{Eqn. SS}$$

For the air escaping we can safely assume it is at, at least the same temperature as that of the die, 250°C at the time of metal injection into the die. For air of moderate humidity, $\gamma = 1.4$ and $R = 287$ J/(kg K)

$$a = \sqrt{(1.4)(287)(273 + 250)}$$

$a = 458.4 \text{ ms}^{-1}$

Now the required air velocity is 585.685ms^{-1} however the maximum speed that the air will rise to through the vent [modeled as a simple nozzle] is 458.4 ms^{-1}. This means there will be an increase in air pressure because of the differing speeds. It is not necessary here to calculate what pressure will be reached. It is necessary to take note of this and consider that due to the increased air pressure it more likely that air will be entrapped inside the metal during the filling of the die when an injection speed of 0.85 ms^{-1} is used as opposed to 0.3ms^{-1}. In the analysis of the cast component it will be necessary to check well for any entrapped gas (which will cause spherically shaped porosity).

At the lower injection plunger velocity, 0.3 m s^{-1} the required flow rate, from Eqn. MF is, 0.000537 m^3s^{-1} and the velocity of the air through the vents required to satisfy Eqn. AF, is 206.7 ms^{-1}. For this case it is clear that there is a very low likelihood of any air pressure build up inside the die during filling since this is well below the choking speed of 458.4 ms^{-1}.

4.2.2 First Run of Component and Results

4.2.2.1 Short Shot

A short shot is a casting that is completed without completely filling the mould. The reason for doing a short shot is to investigate the metal flow path(s) and characteristics. To create a short shot two methods can be used, either less metal than that required to fill the mould is used – the result is an incompletely filled mould; the other method is to stop the metal injection plunger before it reaches the required stroke to fill the casting – the result is also an incompletely filled mould. The second method is closer to the actual filling since the same amount of metal is used in both. For this reason the second method was chosen. Since the die casting machine has real time shot control it is possible to stop the plunger at any possible displacement during the injection stroke.

The short shot will show only a snapshot of the flow. It will show the flow fronts at the time when the injection plunger is halted. Since this is thixotropic flow the momentum of the fluid may be neglected since the viscosity is so high and increases drastically and almost spontaneously upon the instant the shear action is ceased as in the case when the plunger is halted. The area of interest is after the hour glass restriction. This restriction is an obstruction and can cause the flow front to split into more than one front. To see if this is the case the plunger is halted when the top cylinder (after the hour glass section) is 50% full.

The following injection settings were used to create the short shot,

From table 3-11 in the Test and Experimental Methods Section,

Stroke required to fill the cavity	295.08mm
Less the stroke corresponding to the volume of the overflows 5901.00 mm^3	
Stroke = Volume / Area of Plunger = $8043.79/[\pi (47.7)^2/4]$ =	-3.30mm
Less the stroke corresponding to the volume of section 7, 8043.79mm^3	
Stroke = Volume / Area of Plunger = $8043.79/[\pi (47.7)^2/4]$ =	-4.50mm
Less the stroke corresponding to the volume of 50% of section 6, 5158.63mm^3	
Stroke = Volume / Area of Plunger = $5158.63/[\pi (47.7)^2/4]$ =	-2.89mm
Stroke required to create the short shot	284.39mm

Table 4-7 below gives the settings used on the shot control computer to create the short shot. Diagram 4-5 is a graphical representation of table 4-7 and also shows the actual injection profile measured during casting of the short shot.

Table 4-7: Short Shot Machine Settings

	Start	Out of Cup	Out of Cup	2nd Stage Point	At Gate	Plunger Halt Position	Injection Stop	Cavity fill time	Intensification
Time [ms]	0.0	1200.0	1200.0	1797.5	1797.5	1958.1	1958.1	160.6	n/a
Speed [m/s]	0.100	0.100	0.200	0.200	0.300	0.300	0.300		
Disp [mm]	0.00	120.00	120.00	239.50	239.50	287.69	287.69		

Diagram 4-5: Injection Profile of Short Shot

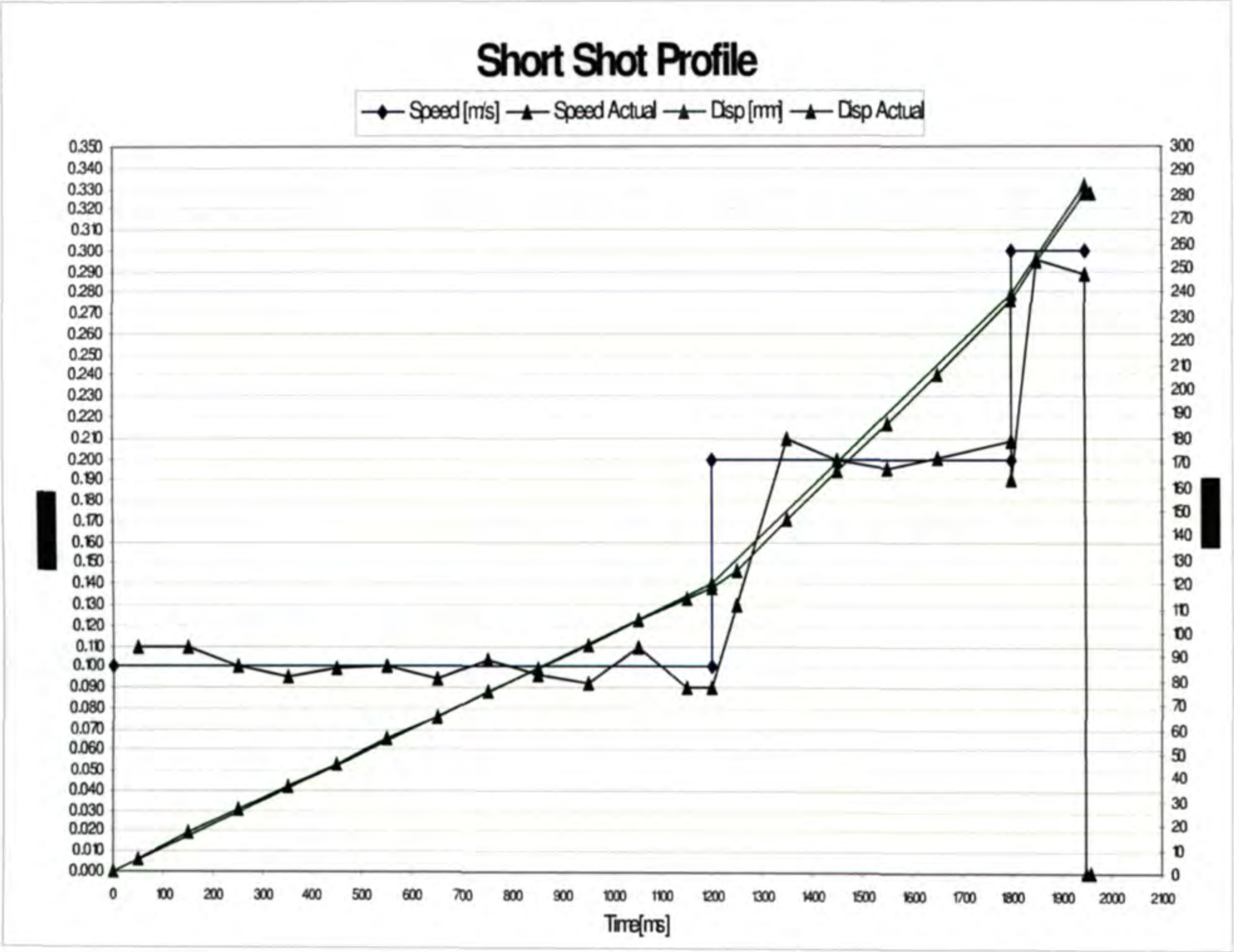


Diagram 4-6 shows the short shot created using the setting in table 4-7.

Diagram 4-6: Short Shot of Short Arm Component

The area of interest is on the far left. It is clear to see that there are two distinct flow fronts caused by the hour glass obstruction. For discussion purposes this area is enlarged and shown in Diagram 4-7.

Diagram 4-7: Close up of Short Shot

When ever a flow front splits into two or more and then meets again a cold shut may occur which can give rise to a crack. The short shot in diagram 4-7 shows secondary flow and different flow fronts meeting. Secondary flow is defined as when a cavity partly fills and then the fluid, from a different flow front, passes over the metal surface of the partially filled cavity.. At the top of diagram 4-7 there is evidence of two separate flow fronts. These flow fronts meet after they have cleared the hourglass shaped obstruction. Upon meeting there is a possibility of a cold shut occurring. Special attention therefore must be paid to the top section of the component when analysis of the part is done. The analysis incorporates X-Ray radiography to examine the inside of the casting. Cracks will show up as lines that are of an inhomogeneous appearance to the rest of the radiograph. There after the casting is sectioned and suitably mounted to view these cracks under a Scanning Electron Microscope (SEM) equipped with an X-Ray Energy Dispersion Spectroscopy Module (EDS).

4.2.2.2 Full Shots

The full castings were cast next. The full castings were done using the following shot profile shown in table 4-8 and graphically in diagram 4-8.

The end of the stroke is calculated using the volume of the casting and the diameter of the shot sleeve. From table 3-11 in the Tests Experimental Methods Section and remembering that this die has not had overflows cut into it yet,

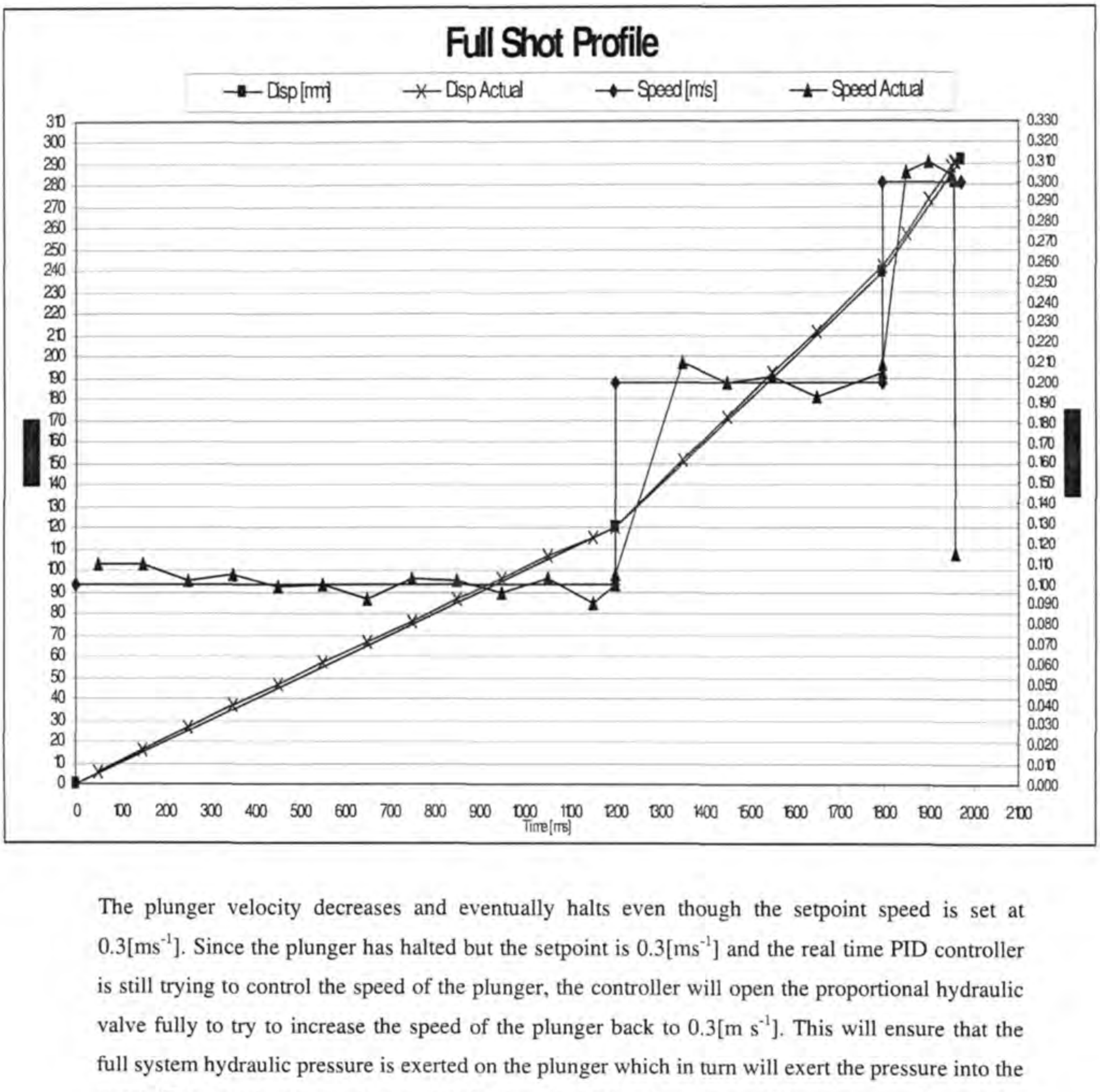
Stroke required to fill the cavity	295.08mm.
Less the stroke corresponding to the volume of the overflows 5901.00 mm^3	
Stroke = Volume / Area of Plunger = $8043.79/[\pi\,(47.7)^2/4]$ =	<u>-3.30mm</u>
Stroke required to create the short shot	<u>291.78mm</u>

Table 4-8: Full Shot Profile

	Start	Out of Cup	Out of Cup	2nd Stage Point	At Gate	Plunger Halt (cavity full) Position	Injection Stop	Cavity fill time	Intensification
Time [ms]	0.0	1200.0	1200.0	1797.5	1797.5	1971.8	1971.8	174.3	10sec
Speed [m/s]	0.100	0.100	0.200	0.200	0.300	0.300	0.300		0.300
Disp [mm]	0.00	120.00	120.00	239.50	239.50	291.78	291.78		

The plunger decelerates as the cavity fills up with metal. This is shown in diagram 4-8, after approximately 1950[ms] the velocity begins to decrease. This is due to the incompressibility of the fluid (metal) filling the die.

Diagram 4-8: Injection Profile of Full Shot Castings

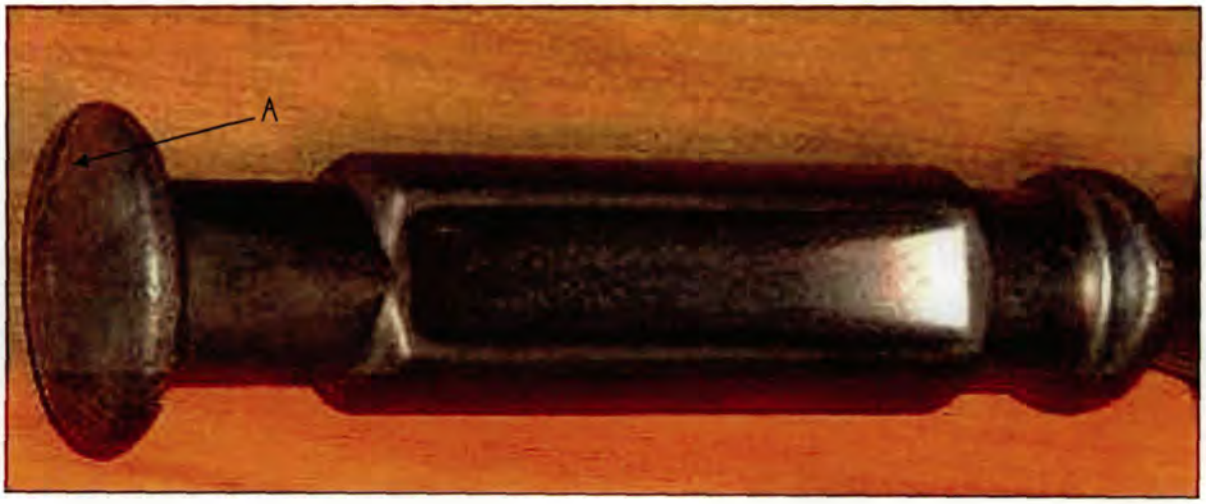


The plunger velocity decreases and eventually halts even though the setpoint speed is set at 0.3[ms^{-1}]. Since the plunger has halted but the setpoint is 0.3[ms^{-1}] and the real time PID controller is still trying to control the speed of the plunger, the controller will open the proportional hydraulic valve fully to try to increase the speed of the plunger back to 0.3[m s^{-1}]. This will ensure that the full system hydraulic pressure is exerted on the plunger which in turn will exert the pressure into the metal. The metal pressure is calculated from the hydraulic pressure. For these experiments the system pressure was set to 16MPa and after the shot was fired the pressure dropped to 14.5MPa. From Eqn 2.1 in the Test and Experiment Methods Chapter the metal pressure is 609.789[MPa].

The metal temperature used was 580°C and the heating/cooling channels were left open to atmosphere.

Diagram 4-9 below shows a typical casting produced from the settings above. The surface finish of all the parts were very consistent. The arrow "A" is pointing to a region of darkly coloured metal. This is Aluminium oxide. It is seen at the end of the end cap. The oxide is from the billet which was used to cast the component. During reheating the surface of the billet oxidises and this oxide is carried with the flow front. Since the layer is on the surface it is from the front of the flow front. Now when the flow fronts meet the oxide layers may mix and be deposited in those areas. The ideal situation is to encourage the oxide layer to remain in the shot sleeve or to encourage the oxide layer to be deposited in an overflow (which does not form part of the finished product). The initial die design does encourage the situation, since there is a small pocket in the back plate of the die which forms the end of the shot sleeve. However the second situation is not possible since there are no overflows machined into the part. It is clear from diagram 4-9 that an overflow is necessary at the top of the component (after the end cap furtherest from the gate).

Diagram 4-9: Photograph of Full Shot Casting



What is not known at this stage is how and where else the oxide layer may have deposited itself through out the casting. Internal non destructive and destructive analysis techniques are used to investigate this further.

4.2.2.3 X-Ray Radiographs and Rurther Analysis of the Complete Parts

X-Ray radiographs of the parts were done establish the internal integrity of the part. One of the castings X-Ray radiograph, Diagram 4-10, has clear evidence of a crack on the side of the cylinder furtherest from the gate. Diagram 4-11 shows an enlarged section of Diagram 4-10.

Diagram 4-10: X-Ray Radiograph of Component

This casting was then sectioned appropriately to reveal the crack as described in section 3.3 of Test and Experiment Methods Chapter. The section was mounted in resin suitable for the analyses with the Scanning Electron Microscope (SEM). This section is shown before mounting in diagram 4-12. A small section of the crack is shown in diagram 4-13. Diagram 4-13 is taken using the SEM at 200 times magnification.

The crack was then further analysed using the Energy Dispersive Spectroscopy (EDS) unit on the SEM. To do this a line is drawn along which the EDS unit scans and then plots the values of the elements of interest. The elements of interest are Aluminium, Silicon and oxygen. Aluminium and Silicon are the two major alloying elements of the metal cast, A356. The oxygen is of interest, as mentioned in the Test and Experiment Methods Chapter, since a high concentration of Oxygen indicates a cold shut.

The line along which the EDS unit scanned is shown in diagram 4-13 and the plot of the intensity of the elements is shown in diagram 4-14. In diagram 4-14 the higher the intensity the higher concentration is of that element. It is of importance to note that the Aluminum concentration is high and the Oxygen concentration is low in the surrounding matrix of the crack (this is grey in colour in diagram 4-13). It is also important to note that at the interface of the crack and the matrix of predominantly Aluminium there is a rapid increase in Silicon and Oxygen. This increase in Oxygen indicates that the crack is a result of a cold shut from two flow fronts meeting. To remove this defect it will be necessary to experiment with modifications to the die geometry (including the addition of overflows), different metal temperatures and heating/cooling channels.

Diagram 4-11: Enlarged Section of diagram 4-10

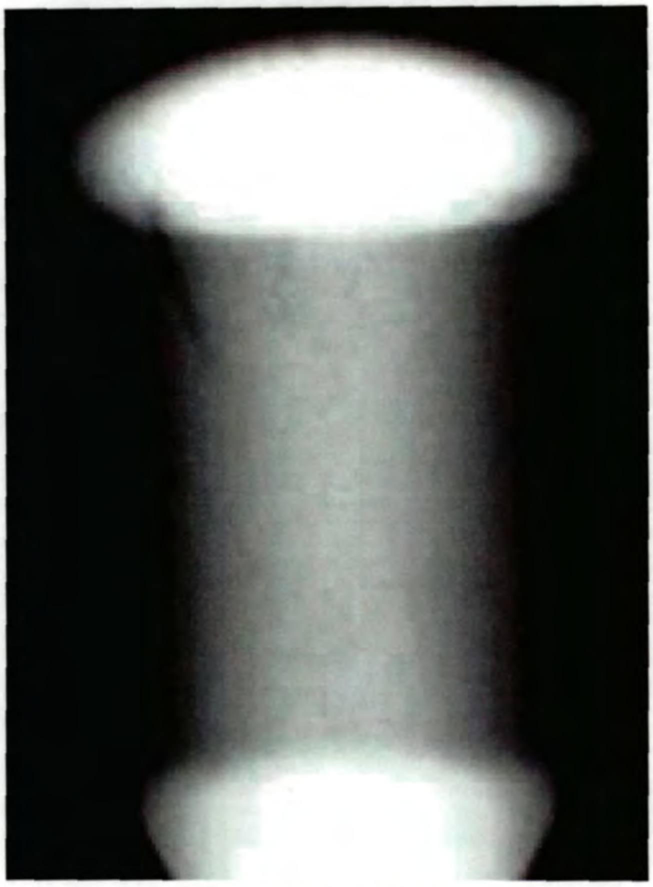


Diagram 4-12: Photograph of Section Through the Crack

Diagram 4-13: SEM Microscopy of the Crack

Diagram 4-14: Results of EDS Scan Along Line Shown in diagram 4-13

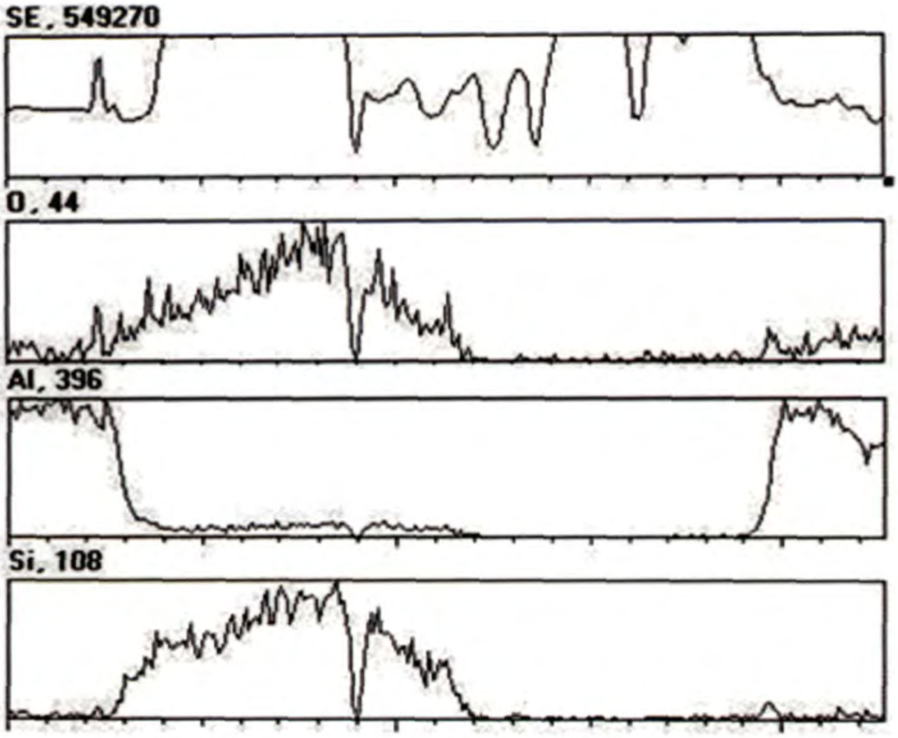
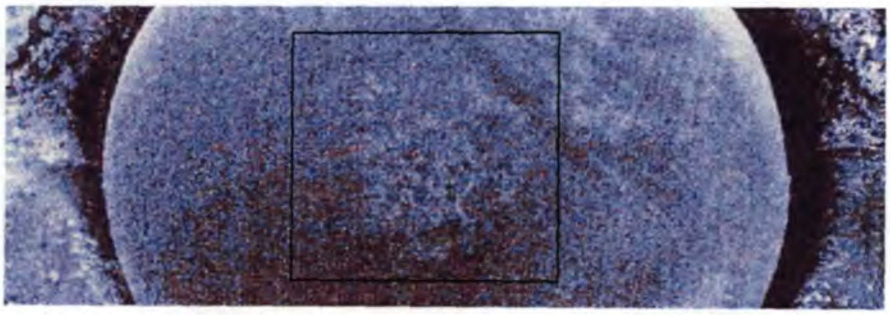


Diagram 4-15: Radiograph Showing Porosity

In another of the castings from this same experiment there was another defect type – porosity. Diagram 4-15 shows the porosity. The section inside the square is inhomogeneous in terms of the darkness of the radiograph. The darker the radiograph is the less the material is absorbing and or deflecting the X-Rays trying to pass through it, let us term this the amount of resistance offered to the X-Rays. The amount of resistance can change for various reasons, thickness of casting changing, density of material changing, material missing (porous section) or a combination of these. The amount of resistance is changing across this small section since the radiograph changes rapidly from light to darker colour and back to a lighter colour again as one moves across the section inside the square.

Because a geometry change (in the thickness) of the part does not correspond to the location of the squared defect section one must believe the patch is caused by a change in density either due to a change in material or porosity. To determine what is the root cause the casting was sectioned. The sectioning procedure is described in the Test and Experiment Methods section. The result is shown in diagram 4-16. The photograph shows porosity (boxed). The porosity is jagged and not globular in nature, thus it is shrinkage porosity.

Diagram 4-16: Photograph of Section Through Defect highlighted in Diagram 4-15



Cold Shuts and Porosity defects are apparent in the initial castings produced. To understand the formation of these defects further, the fluid flow characteristics and the solidification process need to be investigated and then modified so as to avoid the defects forming.

4.3 The Modular Die Results

For the Short Arm component to be successful they must have very high internal integrity. That is the casting should have no internal inhomogeneities. As already discussed the inhomogeneities are of three main classes – Cold shuts (and or hot tears) giving rise to cracks; Porosity (shrinkage or gaseous) and oxide entrapment. To avoid cold shuts a uniform continuous flow is desired where flow fronts do not meet and if they do, they have sufficient latent energy so as to be able to fully weld together. The hot tears are more a function of geometry and alloy type and the design of both these criteria must be such so as to avoid these defects [13]. The porosity must be avoided by assisting the shrinkage of the metal by feeding new metal to the place of solidification and by avoiding gas entrapment or gas formation inside the casting. The oxide entrapment must be minimised through the optimisation of the fluid flow with regards to minimising the number of flow fronts and the containment of the oxide in a non-critical area of the casting or an overflow.

Taking into account the above aim and the results seen in the previous section - the cold shut problems seen in diagrams 4-10 – 4-14 and the porosity problem in diagram 4-15 and 16, it was decided to develop a better understanding of the fluid flow as this ultimately determines the flow fronts. The normal procedure in this field of research as well as in industry is to simulate the fluid flow inside the die as the fluid (metal) fills the die. The simulation procedure is to use a Computerised numerical calculator performing iterations of varying degrees of filling of the die using either finite element or finite difference calculation principles. Initially there was no funding available for this and so it was decided instead to simplify the casting into various planar models. The simplified planar models would also give insight into the porosity problems because the different geometries are isolated in each planar model.

Since the casting is symmetrical about its polar axis in two planes it is necessary only to use two planar models. The concept of planar models is explained further here. In the planar model there are geometrical changes in one plane only, that is the component is of a constant thickness. Having a constant thickness allows the fluid flow in all other planes to be neglected for the purposes of understanding the fluid flow in the plane which has changing geometry. These two models are represented in the two views of the original part in diagram 4-17(a) and (b) below.

Diagram 4-17(a): First Plane Component

Diagram 4-17(b): Second Plane of Component

Due to the expense associated with manufacture of a die it was necessary to reduce the cost of manufacturing dies to produce the above two planar model castings. The solution decided upon was to manufacture one die which would be able to cast both components. This was made possible by using interchangeable inserts in a common bolster.

The die is made up of four major sections. The die shall be refered to as the "Modular Die". The four sections of the Modular Die are, the Back Plate, Insert holder (labeled as SQ in diagram 4-18), the inserts and the front plate.

Diagram 4-18 shows the two die halves. The Back Die half which is mounted on the ejector platen consists of the Back plate onto which the insert holder plate (SQ) is bolted onto. The Insert Holder plate or SQ is also doweled onto the Back plate. This is to ensure accurate positioning for the Inserts. The Inserts are then carefully inserted inside the hollow left by plate SQ and bolted into place by means of cap screws into threaded holes in the back plate. Fit of the inserts is critical to prevent Aluminum leaking from the cavity into the small cavities between the plates. For this reason the inserts were made to fit "size for size" into the hollow of plate SQ. Plate SQ is responsible together with the bolts of each insert for containing the metal pressure inside the cavity. Plate SQ (blue) has four dowel pins in the centre of each side which mate with reamed holes in the back plate. These dowel pins are not sufficient to support the load of the metal pressure inside the cavity. Also as the die opens it is necessary keep plate SQ attached to the back plate so as to maintain the correct die splitting procedure. The procedure should be such that the front plate splits from the plate SQ and inserts, and the casting is left inside the cavity made by the inserts. To achieve this it is necessary to bolt plate SQ onto the back plate.

These bolts also serve to reduce the high bending moment stress set up along each side of plate SQ due to the internal metal pressure. The bolt holes on plate SQ are not shown in diagram 4-18. Diagram 4-19 is a photograph of the plate SQ and inserts to make up the planar model. The diagram 4-19 does not have the insert for the hour glass obstruction in the centre as this insert is attached to the back plate. The diagram 4-19 shows the extra holes for bolting and securing plate SQ.

Diagram 4-18: Isometric of the Assembled Modular Die

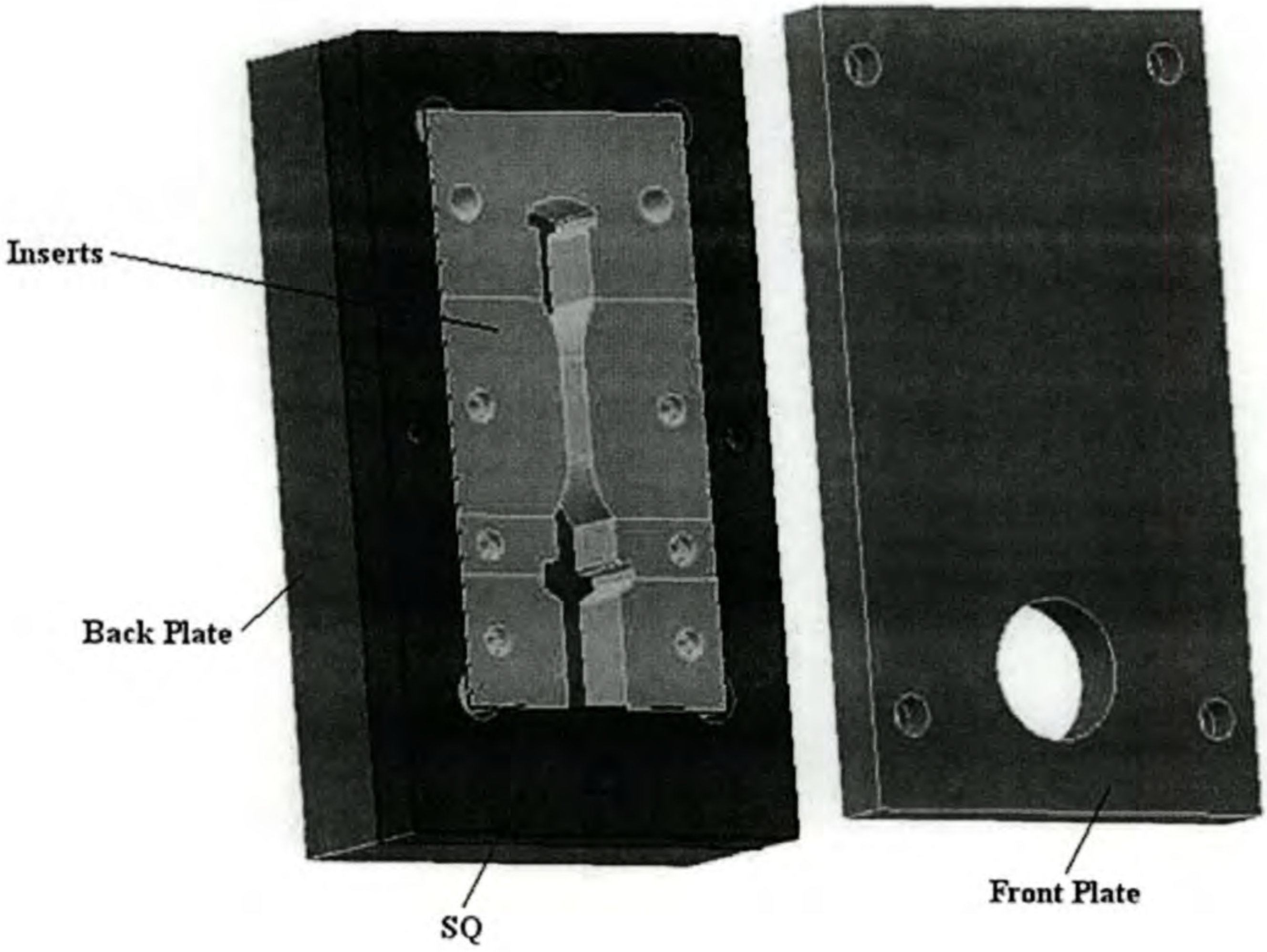
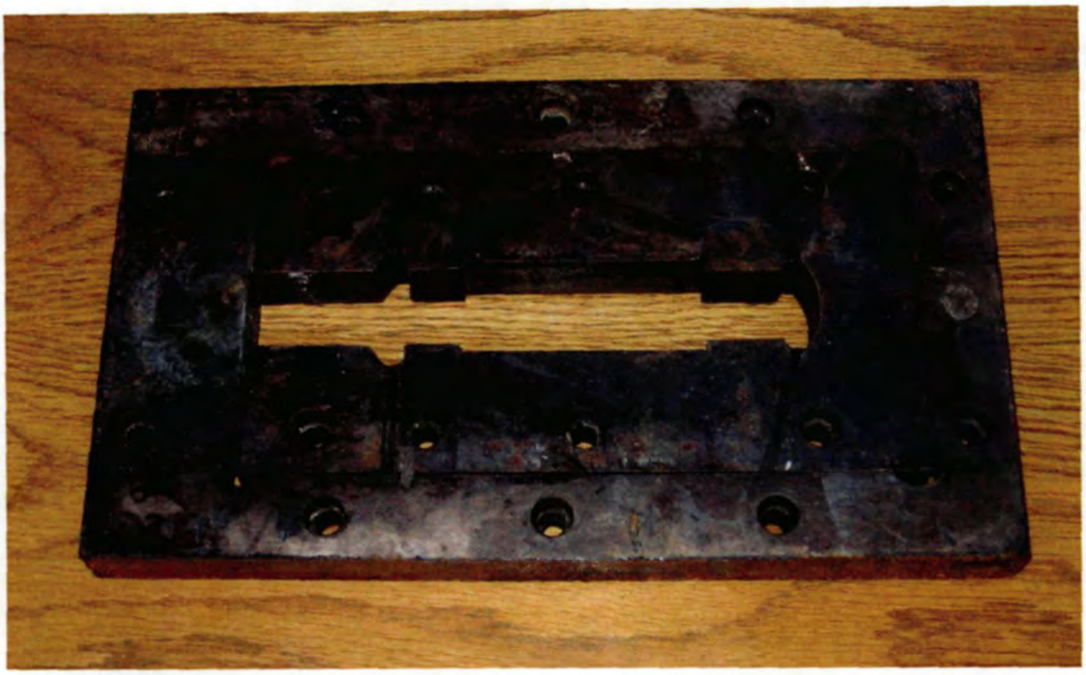


Diagram 4-19: Inserts Assembled in Plate SQ



The inserts make up two distinct planar models. The two are diagrammatically represented in Diagram 4-20 and 4-21 below.

Diagram 4-20: Inserts for 1st Planar Model

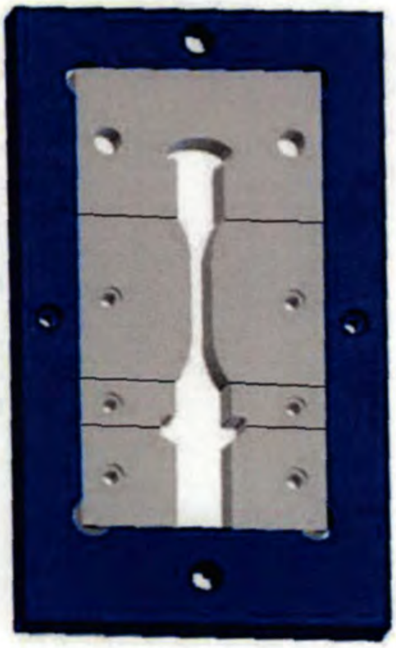
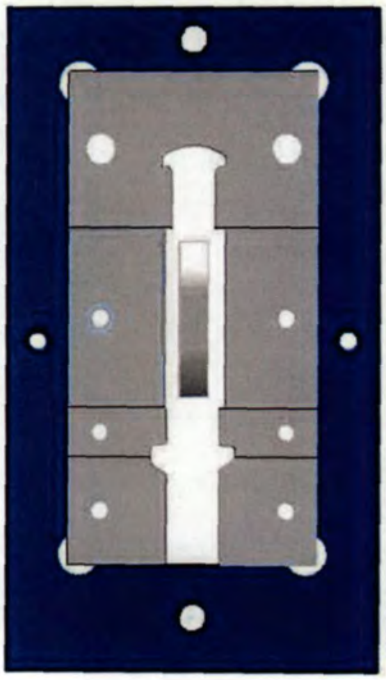


Diagram 4-21: Inserts for 2nd Planar Model



The thickness of each model remains constant, this allows us to neglect flow effects in this plane. The geometry of the model is that of equivalent geometry. This means however that the volume and the surface area will not be consistent with the original part. Each section of the casting will thus have a slightly different volume and surface area to that of the same section of the original part. Since the fluid flow is of interest here slight changes in the volume and surface area may be neglected. However it is noted here that should there be defects associated with solidification the conclusions and results made with the casting of these models may not be carried over directly to results and or conclusions on the original part castings. But they may give rise to concerns and may also suggest that the same defects may occur in the original part castings, however verification of this will be necessary.

The thickness of the models was arrived at from two angles – ease of manufacture of the modular die and relative similarity to the original part. Looking at section 2 from diagram 3-4 in the Test and Experiment Methods Chapter it is seen that this section has a cross sectional area of a circle of diameter 25mm. Equation VolTh below equates the circular section to a square section by volume equivalence. The square section [on the right of the argument] represents the planar model casting. The planar model casting has a width of 25mm at this same point. The width is 25mm because the planar model die is a geometry equivalent model as explained above.

$$\pi d^2 = tw \qquad \text{Eqn VolTh}$$

$$t = \pi d_o^2 / w$$

$$t = 19.6mm$$

Where

d_o	Diameter of the cylinder of section 2 [of diagram 3-4], 25mm
t	Thickness of the planar model to have equivalent volume to the original part
w	Width of the planar model to have equivalent volume to the original part, 25mm

The thickness chosen was 25mm. The reason for this was because the closest standard thickness that gauge plateIS available in is 25mm. The inserts are made of gauge plate.

4.3.1 Results of Planar Model One

Planar model one (with no obstruction in the centre, shown in diagram 4-20) was cast first. Short shots were done at six distinct percent cavity full. Each percent full chosen corresponds to a geometry change.

It is clear from diagram 4-22 that the Fluid is thixotropic and will not change shape until it meets a constriction. The constriction causes two phenomena, a pressure increase in the metal before the constriction [46] and all the surfaces of the fluid to be in contact with the surface of the die which increases the shear surface area. The second phenomena causes the apparent viscosity to decrease[7, 68]. The first phenomena will cause the fluid before the constriction to expand outwards towards the surface of the die. The two phenomena work together to cause successful filling of the cavity and thus cause the fluid to enter all the extremities of the die cavity before the constriction. However it is noted that the cavity of the initial section is only filled after the fluid has already started filling the next section which must be a section of a smaller cross sectional area (constriction).

From the discussion above it is clear that when designing the gating of the component one should "try" to achieve fluid flow through ever decreasing cross sectional areas. That is one should gate into the largest cross sectional area and then subsequently feed into decreasing cross sectional areas through the component. This same procedure is further supported for successful directional solidification, described in Test and Experimental Methods Chapter, section 3.2, Die Design subsection Gating where a decreasing modulus is desirable. A decreasing cross sectional area will in most cases also give rise to a reduction in the modulus (Volume to Surface area in contact with the die). For many practical reasons however it is not always possible to achieve this type of filling of the cavity. The reasons for this are also discussed in the same section.

Diagram 4-22 shows six short shorts. A short shot is an interrupted filling of the cavity. The filling is interrupted by using the shot control capabilities of the die casting machine. The injection speed is set to zero at the point where the filling is to be halted. Table 4-9 shows the injection positions at which the injection plunger was halted.

The shot number of table 4-9 is referenced to diagram 4-22 by the number underneath each casting at the bottom of the diagram. From diagram 4-22 is it very clear no deformation of the thixotropic fluid will take place and hence the cavity will not be filled into its extremities unless the flow front of the fluid is acted upon in shear in more than two planes. This is most easily seen by comparing casting 1 to casting 2a, it is not until the plane of the front of flow front is placed under shear stress that the extremity is filled. For this to take place it is clear that a converging cross sectional area is required with respect to the path of the fluid flow. This implies that the direction of fluid filling the die should be from the largest cross sectional area to the smallest cross sectional area. That is the flow path should move through the sections of the die in such a manner so that each consecutive section's cross sectional area is smaller than the last (that is converging).

Diagram 4-22: Short Shots of 1st Planar Model

Table 4-9: Parameters for Short Shots

Short number	Plunger Halt Position [mm]	Volume Displaced [mm^3]	Volume of Component Displaced [mm^3]
1	241.62	574047.9	48989.6
2a	257.4	611538.5	86480.2
2b	258.6	614389.5	89331.2
3	263	624843.1	99784.8
4	279	662856.4	137798.1
5	280	665232.2	140173.9
Sleeve Diameter	55		
Displacement required for metal to reach gate	221		

From the short fills shown in diagram 4-22 it is evident that the fluid does not curl back on itself, this is clear by comparing casting number 4 to casting number 5. This is of importance since if the flow were to curl back upon itself then there is a very high likelihood of oxide entrapment and cold shuts forming[17].

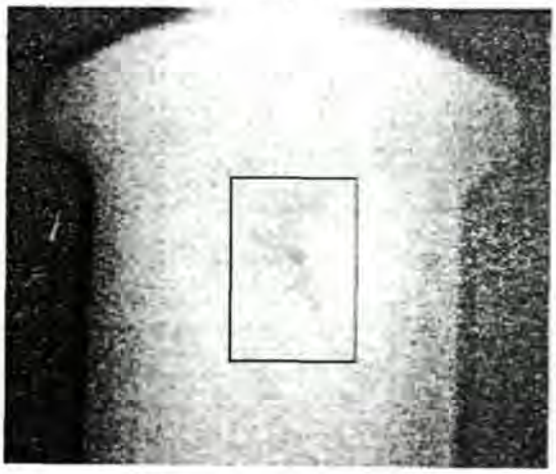
The flow behaviour of the original part may be postulated by examining the short shots in diagram 4-22. In short shot number 1 the fluid did not fill the bottom end cap even after the flow front had passed it. Only when the fluid encounters a constricting section change,, short shot 2a, an increase in internal fluid pressure occurs (start of the hour glass section), this results in the end cap filling, 2a and 2b depict this happening. The end cap fills uniformly from the main centre shaft by expanding outwards. The flow front travels at ninety degrees to the main shaft and takes up the entire cross section of the cavity (2a and b). The top of the hour glass section is the next area of interest. Here the die geometry of the hour glass section diverges to form the top cylindrical representation section. The diverging cavity is not filled fully until it is subjected to an increase in pressure, 4 and 5. This is the same behaviour displayed by the bottom end cap. As the flow front leaves the hour glass restriction and begins to flow through the diverging section, there are only two shear faces acting on it[17]. This reduces the shear rate. The literature survey showed that a reduced shear rate will result in an increased viscosity. This explains why the fluid displays plug like (high viscosity) flow through any diverging cavity. This is undesirable filling and could result in secondary flow. Secondary flow is defined in the literature survey. Secondary flow will only occur if there is formation of another flow front – to form another flow front the internal kinetic energy must be greater than the surface tension energy, this condition must be met for a new flow front to form. Only when the fluid flow front comes into contact with the top surface of the die cavity does the diverged cavity begin to fill. The cavity begins to fill from the bottom upwards. The new fluid flows up the hour glass restriction and then is confronted by the static fluid which is still the width of the hour glass restriction. The empty cavity on either side is the only cavity that the new fluid may occupy.

To establish whether the fluid breaks the surface tension at the bottom of the diverging section and then travels upwards on either side of the static fluid as two new flow fronts or the fluid rather forces the static fluid to expand outwards from the bottom first, it is necessary to look for evidence of more than one flow front. The evidence would be in the form and of the type described in the 3.3 of Test and Experiment Methods Chapter, cold shuts and oxide layer(s). The top section of the casting was scrutinised using X-ray radiography and no evidence of cracks or cold shuts were found The top section was also sectioned at ninety degrees to the polar axis at the centre of the cylindrical representing section and this was suitably mounted and polished for analysis in the SEM. The EDS scanned across the section but no found, sharp increases (or high) oxide levels or cracks, symptomatic of secondary fluid flow. Given the decreased neck size of the hour glass section and hence the increased tendency for hot tearing (due to lack of directional feeding) it is more likely that, should there have been any cold shuts or oxides these would have been enlarged and shown up as cracks[13]. From the discussion presented it is unlikely that the fluid broke the surface tension and formed new flow fronts, rather it would appear that the fluid expanded outwards at ninety degrees to the original fluid flow direction and so filled the cavity on either side of the static fluid without creating any defects typical of secondary flow.

The porosity of the planar model was inspected with the use of X-Ray radiography. The X-Ray machine was set with following settings, beam strength 105[kV] and 2[mAs] using a FFD (focal distance) of 100. There is clear indication of an inhomogeneity at the top of the X-Ray, diagram 4-23. This section is in the centre of the top thick cylindrical representation section and due to the hour glass restriction it is not fed any new metal during solidification. This is because the thin hour glass restriction section has already solidified before the thick top section (from Chvorinov's rule[16]). This means that the internal semi-solid metal (in the thick top section) will leave voids (shrinkage porosity) when it shrinks during solidification that is no directional solidification took place (directional solidification is discussed in the Literature Survey Chapter).

The porosity is shown in diagram 4-23 in the boxed square. The darker sections on the edges are due to geometry changes of the draft angle which give rise to reduced volume and hence reduced resistance to the X-Rays passing through the part to produce the radiograph. The central section of the radiograph has no geometry changes however it is clear, from inspecting the boxed section that the X-Rays passed more easily through this section with the result that the section is inhomogenous with respect to the lighter and darker sections. This change from light to dark with no corresponding geometrical change can be explained by porosity (pores) in the metal in this section. The pores will allow the X-Rays to pass through with less resistance and cause the radiograph to be darker.

Diagram 4-23: Porosity in Top section of 1st planar model



The casting was sectioned through the area indicated by the X-Ray radiograph to have porosity. Porosity was found and was of the type typical of shrinkage porosity, jagged pores. To eliminate this defect it is necessary to "feed" the shrinkage with new molten metal. This is directional solidification and was discussed in the Literature Survey Chapter and the Test and Experiment Methods Chapter.

Directional solidification is required to eliminate the porosity. The situation here is emphasized by the very narrow hour glass neck section in the centre of the planar model casting (see diagram 4-22). The modulus of this section is,

Volume - 8mm x 38.48mm x 25mm = 7696 mm^3
Surface Area - 2 x [8mm x 38.48mm] + 2 x [25mm x 38.48mm] = 2539.68mm^2
Modulus - Volume / Surface Area = 7696 / 2563.68 = 3.03 [Eqn M1]

In the original component the Modulus of this section is, 4.7753 [Table 3-6].

The sections which are "fed" by the constricted hour glass are the end cap and cylindrical section [sections 6 and 7 in the original component]. The porosity was located in the section representing section 6 of the original component (top cylindrical section) and boxed in diagram 4-23. The modulus of this section is,

Volume - 23mm x 28.08mm x 25mm = 16146mm^3
Surface Area - 2 x [23mm x 28.08mm] + 2 x [25mm x 28.08] = 2695.68mm^2
Modulus - Volume / Surface Area = 16146 / 2695.68 = 5.99 [Eqn M2]

In the original component the Modulus of this section is, 5.81 [Table 3-6].

It is clear that the thin neck of the hour glass will solidify long before the section that it feeds – the top cylindrical section equivalent. This is shown by the modulus calculations above [Eqn M1 and M2] [16]. The neck's modulus is 3.03 where as the next section is 5.99. This experiment shows the importance of directional solidification and obeying Chvorinov's Rule.

To overcome this problem there are number of possible solutions. The first is obvious and that is to change the modulus of a or both sections so that the modulus is descending. This is not possible in this example however since the geometry is not allowed to be altered from that of the original design. Another method to have the modulus in descending order is to have another gate feeding this section of the casting. This is also not desirable however since this will cause more fettling costs to remove two gates as opposed to one. Another solution is to use a squeeze pin to remove porosity. The squeeze pin is hydraulically operated and operates onto the section with the high modulus and assists reduces porosity by squeezing metal from a pseudo overflow into this section. Squeeze pins are costly and can alter the geometry of the part, for these reasons this method was not followed. The other method to assist directional solidification is to change the temperature of the mould in the areas required.

Since the top cylindrical section has a higher modulus than the hour glass section, it will cool slower. Chvorinov's rule assumes the mould temperature to be uniform through out. However if the mould is sufficiently heated in a particular section where the modulus is low then this section will actually cool slower and if the mould is sufficiently cooled in a section where the modulus is high then this section will cool faster than the corresponding higher and lower modulus sections respectively. In this challenging component it is clear that to eliminate the porosity this method should be used. The method is also not as costly as the squeeze pin technique and also will not alter the geometry of the finished part.

To cool or heat the die in localised areas channels are machined into the die in those areas and cooling fluid (fluid that is colder than the general mould temperature) or heating fluid (fluid that is hotter than the general mould temperature) is passed through the channels. From this experiment it is clearly postulated that the top section (large cylindrical section) above the hour glass restriction of the die (mould) should be cooled. Three cooling channels will be machined into the die which will pass behind the top cylindrical section and water at room temperature and at a good flow rate will be passed through them. This will be done in the original component die and the results evaluated.

4.3.2 Results of Planar Model 2

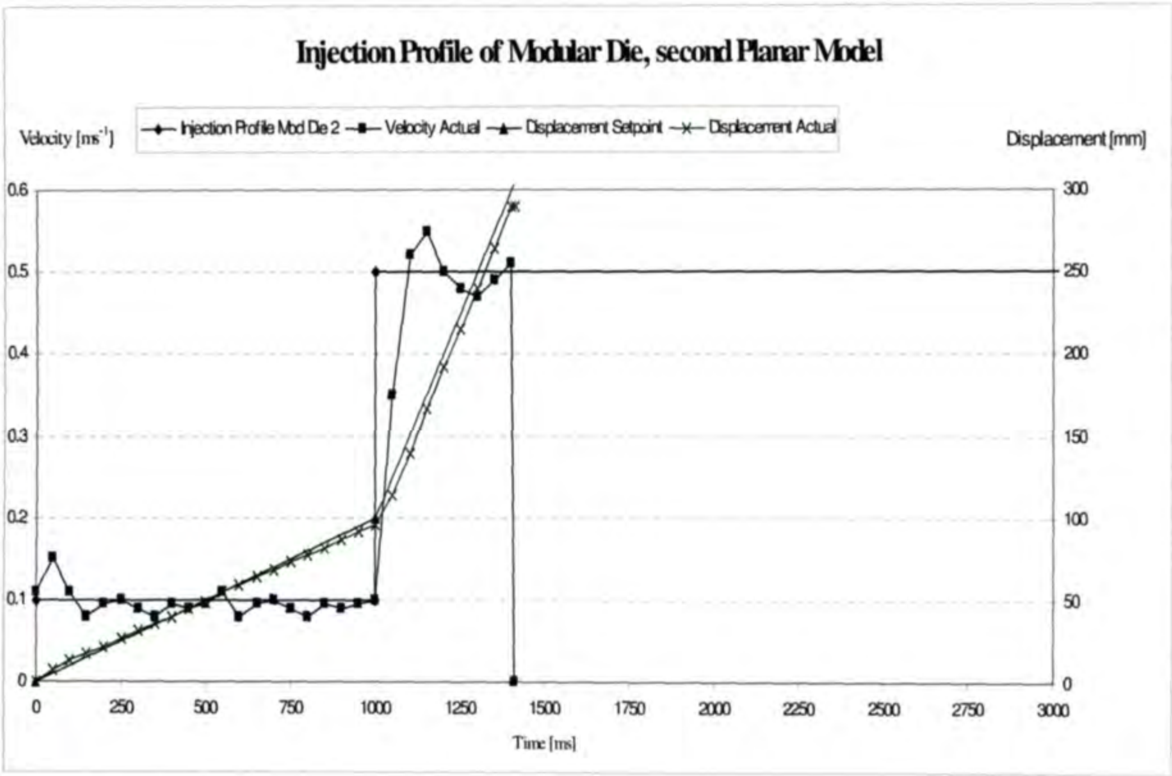
The second planar model simulates the geometry of the of the plane shown in diagram 4-17(b) using the inserts shown in diagram 4-21. The obstruction in the centre of the flow path is anticipated to split part of the flow front into two separate flow fronts.

Four full castings were done of this model. One of the castings (the second run) was not successful due incorrect machine settings, this casting was discarded. The castings were then analysed using X-ray radiography. The castings whose X-Ray radiography results showed defects were sectioned appropriately to investigate the defects. The injection piston velocity profile is tabulated in table 4-10 and shown diagrammatically in diagram 4-24.

Table 4-10 - Injection Profile Modular Die 2

Velocity	0.1	0.1	0.5	0.5
Time	0	1000	1000	5000
Displacement	0	100	100	2100

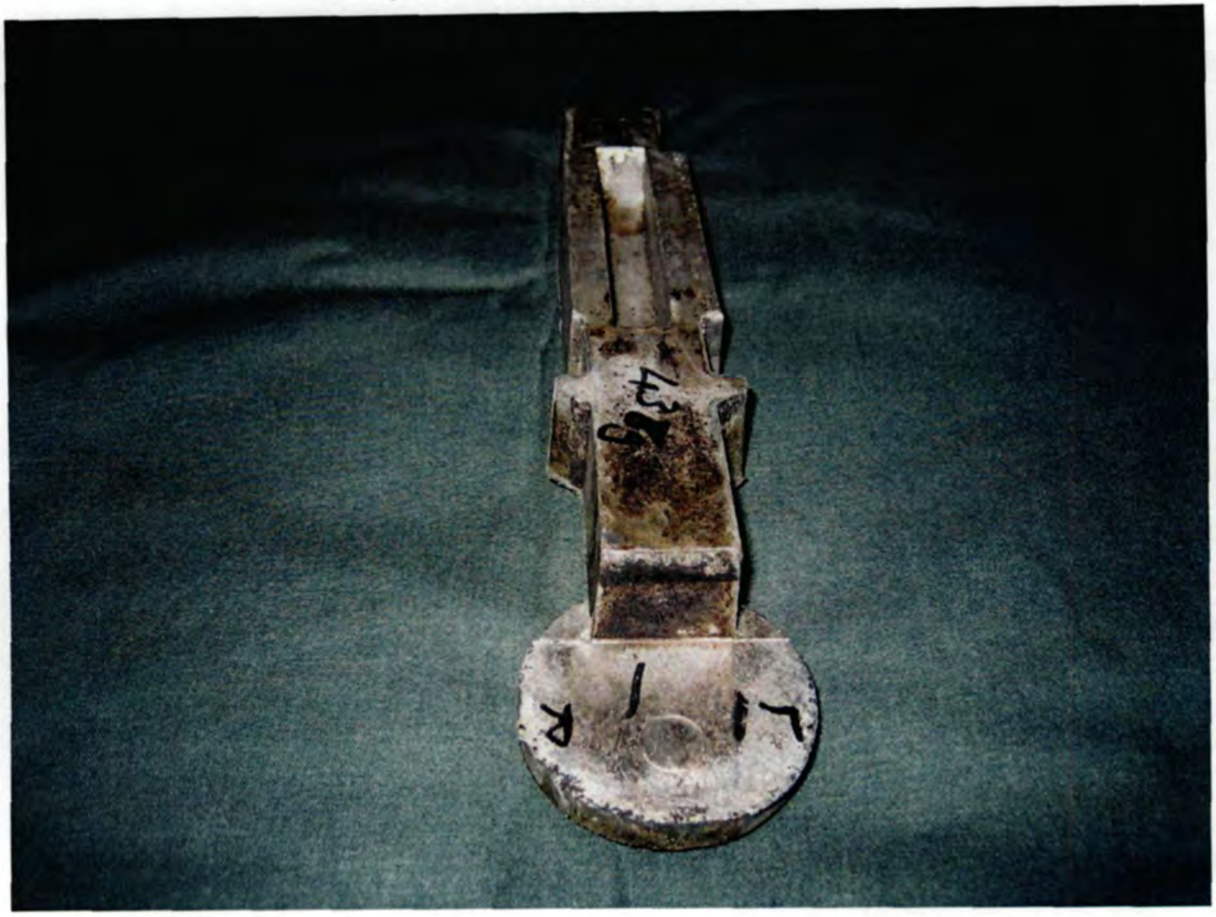
Diagram 4-24: Injection Profile of Modular Die 2



4.3.2.1 Visual inspection Results

The resulting castings are in Diagrams 4-25, 4-26, 4-27. There is evidence on all the castings of a crack on the surface. This is at the top after the hour glass obstruction. This is expected since when the flow front comes into contact with the obstruction it must split and move along each side. At the end of the obstruction it must rejoin. Diagram 4-28 is a close up of the end of the hour glass obstruction of casting run #3. It is apparent that there is a joining of the flow fronts. In some castings the crack is more visible than in others and in casting run #1 the crack is accompanied by shortfill, diagram 4-29.

Diagram 4-25: Photograph of Run 1



Shortfill was defined in the Literature Survey Chapter. The three primary reasons why it comes about are repeated here for discussion purposes. The first is a build up of air pressure. This increase in air pressure may form a pocket of air at a pressure higher than the metal pressure which will then not allow the metal to displace it and as a result there will be a vacant pore in the place of the pocket of air. The second is a shortage of metal – that is there is insufficient metal in the mould to take up the entire cavity. The third is that the metal has solidified before it has fully filled the mould cavity. In this case it appears that there may not be sufficient metal in the mould to start with. This is substantiated by analyzing the amount of metal used to make the casting together with the stroke of the injection piston. The obvious shortfill was apparent in casting run# 1, diagram 4-29.

Diagram 4-26: Run 3

Diagram 4-27: Run 4

Diagram 4-28: Close up of Casting Run #3, Showing Crack

Diagram 4-29: Close up of Casting Run#1 Showing Shortfill

Diagram 4-30: Photograph showing Biscuit Thickness of Run #1

The biscuit size (indicated by the white arrows in diagram 4-30) is 14.5mm. The minimum biscuit size possible from the stroke of the machine and the thickness of the fixed half of the die is given in Eqn PM2.

$$l_{b_{min}} = l_{sleeve} + l_{sprue} - l_{stroke} - l_{shoulder} - t_{washer} \qquad \text{Eqn. PM2}$$

$$14.7 = 300 + 25 - 300 - 15.3 + 5$$

Where,

l_{sleev}	is the length of the shot sleeve
l_{sprue}	is the length of the sprue bush (fixed plate thickness)
l_{stroke}	is the stroke of the injection cylinder
$l_{shoulder}$	is the length of the shoulder of the sleeve that protrudes into the sprue bush (fixed die)

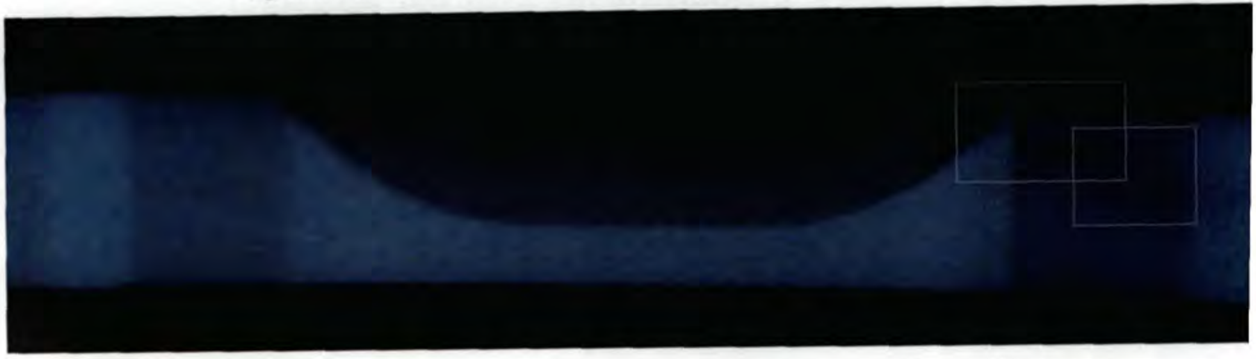
From Eqn PM2 the minimum is 14.7mm. Now by measurement of casting run #1, the biscuit length is 14.5mm. There was insufficient metal to fill the cavity completely. Also there was no metal pressure to force metal into the extremities of the die. This was because the hydraulic pressure inside the injection cylinder was forcing the injection piston to the end of its stroke and causing it to ram up against the end cap of the cylinder, it reached the end cap of the cylinder since there was not enough metal inside the shot sleeve. All the injection force was taken up by the end cap of the cylinder and none by the metal. This resulted in no force acting from the injection piston (plunger) onto the metal and so there was zero metal pressure. The result is that the metal was not under pressure and so was not forced into the extremities of the mould as mentioned above. This resulted is the shortfill shown in Diagram 4-29. It is of paramount importance to have sufficient metal to produce the casting otherwise a shortfill defect will be formed.

4.3.2.2 X-Ray Radiography results

All the castings were X-ray radiographed. The radiographs of run#1 only need to be presented and discussed here since run#2 and run#3 produced similar defects. The X-ray radiographs for run #1 are shown in diagrams, 4-31 and 4-32. Each casting was X-ray radiographed in both planes (top view and side view), this is necessary for two reasons, to inspect for defects thoroughly and to be able to locate the defects on/in the castings. The flow of metal is from the left to the right in diagrams 4-31 and 4-32, the gate is on the left.

Diagram 4-31: Top View of X-ray radiograph of Run #1

Diagram 4-32: Side View of X-Ray radiograph of Run #1



The boxed area on the right in diagram 4-31 and 4-32 clearly shows some form of reduced resistance to X-rays along a continuous line. This is characteristic of a crack. The casting was sectioned here so as to ascertain what the defect is. This area is enlarged in diagram 4-34. Diagram 4-35 is a photograph of the sample mounted. The crack is clearly visible. The crack is caused by the flow fronts meeting.

Diagram 4-34: Enlarged Section of diagram 4-31

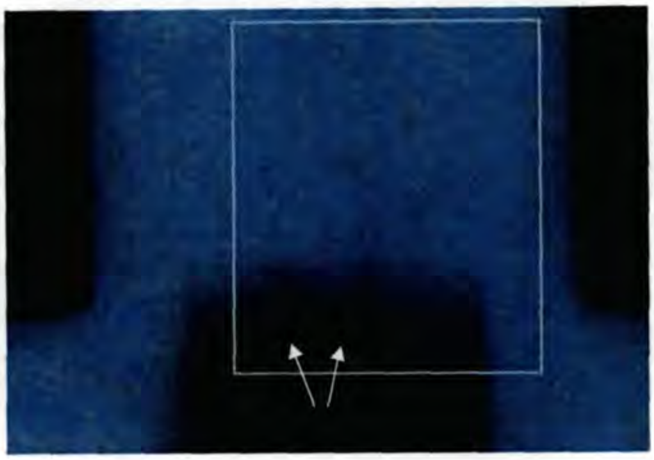
Diagram 4-35: Photograph of Sectioned Mounted Sample of Crack

The boxed area on the left in diagram 4-31 and 4-32 is also a defect. The defect is very faintly seen in diagram 4-31 however it is much clearer in 4-32, the defect area of 4-31 is enlarged in diagram 4-36.

There are two defects shown in diagram 4-36. The first defect is at the bottom right corner of the highlighted square in the shape of a V and is in the same place as the surface defect of shortfill seen on the surface of the same casting in diagram 4-29. This V-shape is clearly the shortfill defect.

The second defect is seen faintly as a darkened patch to the right and above, of the V-shaped defect, in diagram 4-36. This defect is however very clear in diagram 4-32 in the left boxed area. This is also of the form of reduced resistance to X-rays along a continuous line – hence a crack. Again here it is due to flow fronts meeting.

Diagram 4-36: Close up of Defect in diagram 4-31



The presence of two cracks in two different planes gives evidence to more than one set of flow fronts meeting. This implies then that there are at least three flow fronts converging after the central obstruction. These cold shuts are undesirable in the finished products.

There are three possible methods to remove these defects. The first is to have a large overflow which, by causing more metal to flow through the section and then to fill the overflow, should then entrain the cold shuts (defect sections) into the overflow itself. The next method is to heat the metal to a higher temperature, a higher fraction liquid [lower fraction] solid. The third method is to inject at a higher speed so that the metal has less time to cool before the mould is filled. Another method could be to heat this section of the mould to a hotter temperature. This however would adversely effect directional solidification as already discussed in the section of the first planar model.

From the above discussion it is clear that there is a conflict between removing the cold shuts and removing the porosity. To remove the cold shuts the top cylindrical section of the mould should be heated and to remove the porosity this same section should be cooled. It is clear then that a combination of the solutions will have to be incorporated to achieve a component with no cold shuts and no porosity, a component with high internal integrity.

4.4 Discussion of Results from First Original Component and Planar Model Castings

Through all experiments of the first original component castings and the Planar model castings there are two defects types common to all the castings. The two defects types are porosity and cold shuts.

4.4.1 Cold Shuts

The encouraging data came from the Planar Model castings where it became apparent that the cold shuts were created where ever more than one flow front met. This only happens where there is an obstruction which will cause the flow front to split into two or more flow fronts. In the case of the component the obstruction is the hour glass section in the centre of it. The only part of the casting which is affected by the obstruction is the top cylinder and endcap – those are the only sections after the obstruction. Of these affected sections only a small volume is affected. In the case of the planar model castings it is in the centre of the upper most section of the top cylinder. In the original component it is to the left of the upper most part of the end cap and partly into the end cap of the component. Thus it is likely that this defect may be pushed out of the top section of the casting and into an overflow. Also from the information collected in the X-ray radiographs it is possible to predict the size of the overflow needed to fully remove the cold shut from the casting.

4.4.2 Porosity

The porosity seen in all the castings is due to insufficient directional solidification taking place. This has been discussed at length at the end of 4.3.1 of this section. The solution here appears to be cooling and or heating channels. In all of the castings produced, both the planar models and the first original component cast there is evidence of porosity. In all cases it is in an area that is not fed successfully by new metal. This did not allow directional solidification to take place. The result is shrinkage porosity.

4.4.3 Improvements to Overcome the Defects

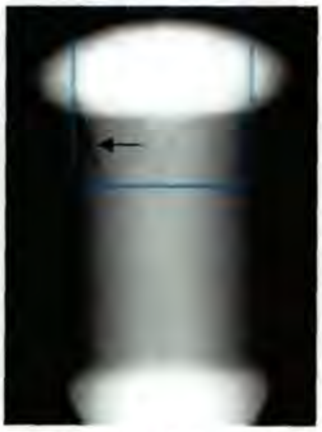
To overcome these two problems a number parameters are experimented with and modifications are done to the die. The parameters are process parameters. Three process parameters are experimented with. These are the cast metal temperature, the injection speed and the water cooling of the die. Two levels of each parameter are experimented with. The experiment procedure is explained in detail in section 9 of the Test and Experiment Methods chapter. Table 3-9 gives the settings of these process parameters.

Another improvement necessary to overcome the cold shut defects are overflows. It was discussed in the Test and Experiment Methods Chapter that there are specific criteria for the introduction of overflows onto a casting. To summarise, the overflows must be placed in the area which is last to fill and the size of the overflow must be of the correct size so as to flush out the defect.

From the results it has been seen that the cold shut defects are found in the centre of the casting. In one of the original component castings the cold shut was seen on the interface between the top cylinder and the end cap. The end cap is not a critical area, however the cylinder is. The volume of metal needed to be removed is that metal that contains the cold shut and the metal en route between the cold shut and the overflow.

From diagram 4-11 the volume is part of the end cap. The cold shut is in part of the cylinder and remains within the perimeter of the cylinder as it extends into the endcap. To remove this cold shut the overflow size must be big enough to remove the metal between the cold shut and the overflow and the metal surrounding the cold shut itself (arrow points to cold shut). The volume described is boxed in turquoise in diagram 4-37.

Diagram 4-37: Defect Area of diagram 4-11



The reason why the box is across both sides of the cylindrical section is because due to the unpredictable flow behaviour the cold shut could form on either side. So to be safe the entire volume is included as volume to be removed. However by measurement of the Radiograph it is seen that the boxed section only extends to 80% of the diameter of the actual part. From diagram A-1, the volume of this section to be removed can be approximated by a cylinder fitting into the boxed section. The dimensions of this cylinder is,

Diameter = 0.8 x 23mm

Length $= \frac{1}{4} \times 28.05 + 9.9 = 16.9125$ mm

The ¼ of 28.05 is taken by inspection from diagram 4-37 since the boxed area takes up ¼ of the top cylinder. The 9.9 mm takes into account the end cap. This is the extra distance the cold shut would need to move into the overflow. The volume required for the overflow is,

$$Volume = \frac{\pi \times (0.8 \times 23)^2 \times 16.9125}{4} = 4497.108mm^3$$

According to the defects seen in diagram 4-31 and 4-32 the cold shuts are seen to be in the centre of the top cylinder. This implies then that only the central section of this section needs to be replaced with new metal to remove the cold shuts. For this reason and by inspection of diagrams 4-31 and 4-32, one third of the diameter the top cylinder encompasses the defects (cold shuts).

Diagram 4-38: Radiograph Showing Defects in Planar Model 2 Castings

For this case the volume of metal required to move into the overflow to remove the cold shut defect, according to diagram 4-38 is,

$$Volume = \frac{\pi \times \left(\frac{23}{3}\right)^2 \times (28.05 + 9.9)}{4} = 1751.922mm^3$$

The first volume is bigger and to be sure that if a cold shut forms it will be removed from the critical section of the casting, this bigger volume (4497.108mm^2) must be the minimum volume of the overflow.

To reduce the shrinkage porosity cooling channels are drilled in both die halves behind the top cylinder. The channels have water flowing through them at room temperature at a flow rate of three litres per minute. The cooling channels will cool the top section of the die which is in contact with the top cylindrical section of the casting. This will cause the same section of the casting to cool faster than the rest of the casting. If this section of the casting cools at a quick enough rate it will solidify before the hour glass section which must feed new metal to it. The hour glass restriction section has a lower modulus than the top cylindrical section and if the surface of the die is the same temperature for both sections Chvorinov's rule says the hour glass section will solidify before the top cylindrical section. This is what this investigation is trying to avoid and so the cooling channels are strategically placed behind the top cylindrical section of the casting to cool this section drastically. Water cooling is used very successfully in industry. In Asia it is the norm to cool dies using water. Where as in Europe and United States it more common to use oil together with a heat exchanger unit to heat or cool the oil and subsequently the die. More drastic cooling is achieved using water than with oil. Using oil however allows for more accurate temperature control of the die temperature, within a restricted range. For the case at hand it is desirable to cool the localised section of the die as much as possible and so water cooling was chosen. Water cooling is a also a lot cheaper and less involved than oil cooling.

The rate of heat exchange is proportional to the difference in temperature between the two heat exchanging bodies. It follows then from Chvorinov's Rule, time to solidify is proportional to the modulus of the body, that to get two sections of different moduli to have the same time to solidify the temperature difference (between the body and the surface of die) of the higher modulus body should be higher than the lower modulus body.

We know from Chvorinov's Rule that

$$m^n = \left(\frac{V}{A}\right)^n = k \cdot t \qquad \text{From Eqn Chv}$$

Also from basic Thermodynamics theory,

$$\int \dot{H} dt = s \int \Delta T dt$$

Now we assume that ΔT remains constant with respect to t (time) while the casting solidifies – that is the mould is in steady state conditions. There is no super heat in the casting since it is in the semi solid range, it contains only latent heat and this is why the temperature of the casting and ΔT then may be assumed to be virtually constant.

$$H = s \cdot \Delta T \cdot t$$

$$t = \frac{H}{s \cdot \Delta T}$$

Where s is a constant dependant on the materials undergoing the heat exchange.
Now for two sections, 4 and 6 from diagram 3-4.

$$\frac{m_4''}{m_6''}=\frac{k_4\cdot\frac{H_4}{s_4\cdot\Delta T_4}}{k_6\cdot\frac{H_6}{s_6\cdot\Delta T_6}}$$

Now since the materials are same for 4 and 6, $s_4 = s_6$

Also H_4=latent heat of the volume of the section

$H_4 = l\cdot V_4$ and $H_6 = l\cdot V_6$

$$\frac{m_4''}{m_6''}=\frac{k_4\cdot\frac{V_4}{\Delta T_4}}{k_6\cdot\frac{V_6}{\Delta T_6}}=\frac{k_4\cdot V_4\cdot\Delta T_4}{k_6\cdot V_6\cdot\Delta T_6} \qquad \text{Eqn M}$$

Now k_4 and k_6 depend on the properties and initial temperatures of the mould and metal. The properties of the mould do not change between section 4 and 6 however the initial temperatures are clearly different since 6 has cooling and 4 does not have cooling. However equation M shows that the ratio of the modulus of two different sections cooled at two different rates are inversely proportional to the ratio of temperature differences of the mould and the metal of the two sections.

The temperature difference for section 4 is $\Delta T_4 = 580-250 = 330^\circ C$ and section 6 is $\Delta T_6 = 580-41 = 539^\circ C$.

The experiment will tell by the lack or presence of porosity in the top cylinderical section whether this temperature difference is sufficient to allow directional solidification to take place in the top cylindrical section. To overcome this, this section will be cooled rapidly by using water passing through the cooling channels in this area.

4.4.4 Implementation of Improvements onto Die

The overflow dimensions were chosen as a rectangular block machined out of the die plate on both side using a 10mm diameter ball nose cutter. The cutter is to cut only 4mm deep into each plate. This is so as maintain a draft angle where the cavity of the overflow meets the die face to aid in release of the overflow section of the casting from the die. On either side of each endcap on the split line of the die small overflows are machined into only one die half.

The dimension of the rectangular section was calculated to hold 3947 mm^3. For this volume the dimension is 35.8mm by 20mm. The overflow has a gate which is machines on both halves of the die, 11 x 5 x 3mm deep. The four small overflows on each side of the end caps are near spherical and have a gate of 10 x 5 x 3mm deep on one half of the die only.

Diagram 4-39 shows the modified back plate die half and diagram 4-40 shows the modified front plate die half. The volume of the two small overflows on either side of the top end cap and the big rectangular overflow together with their gates is 4744.6 mm^3. This is satisfies section 4.4.3 above where the biggest section is that needed to be removed was 4497.108 mm^3. The two small half spheres on either side of the top and bottom end caps will help remove defects as well as assist in the filling of the end caps.

The next improvements were already machined into the die originally and they are the cooling/heating channels and the gate. The gate is a cylindrical gate of the same diameter of the first cylinder it feeds via the end cap (diameter 25mm). There are three cooling channels and they are machined as through holes at the top of the die. They are located directly behind the top cylindrical section. For the experiments in this investigation – these channels will be used as cooling channels. This is because as discussed in the section 4.4.2 Porosity and 4.4.3 Improvements to Overcome the Defects, it is necessary to try to achieve a much lower die surface temperature in the thick cylindrical section so as to try to solidify before the thinner hour glass section feeding it.

Diagram 4-39: Drawing of Modified Short Arm Die, Backplate

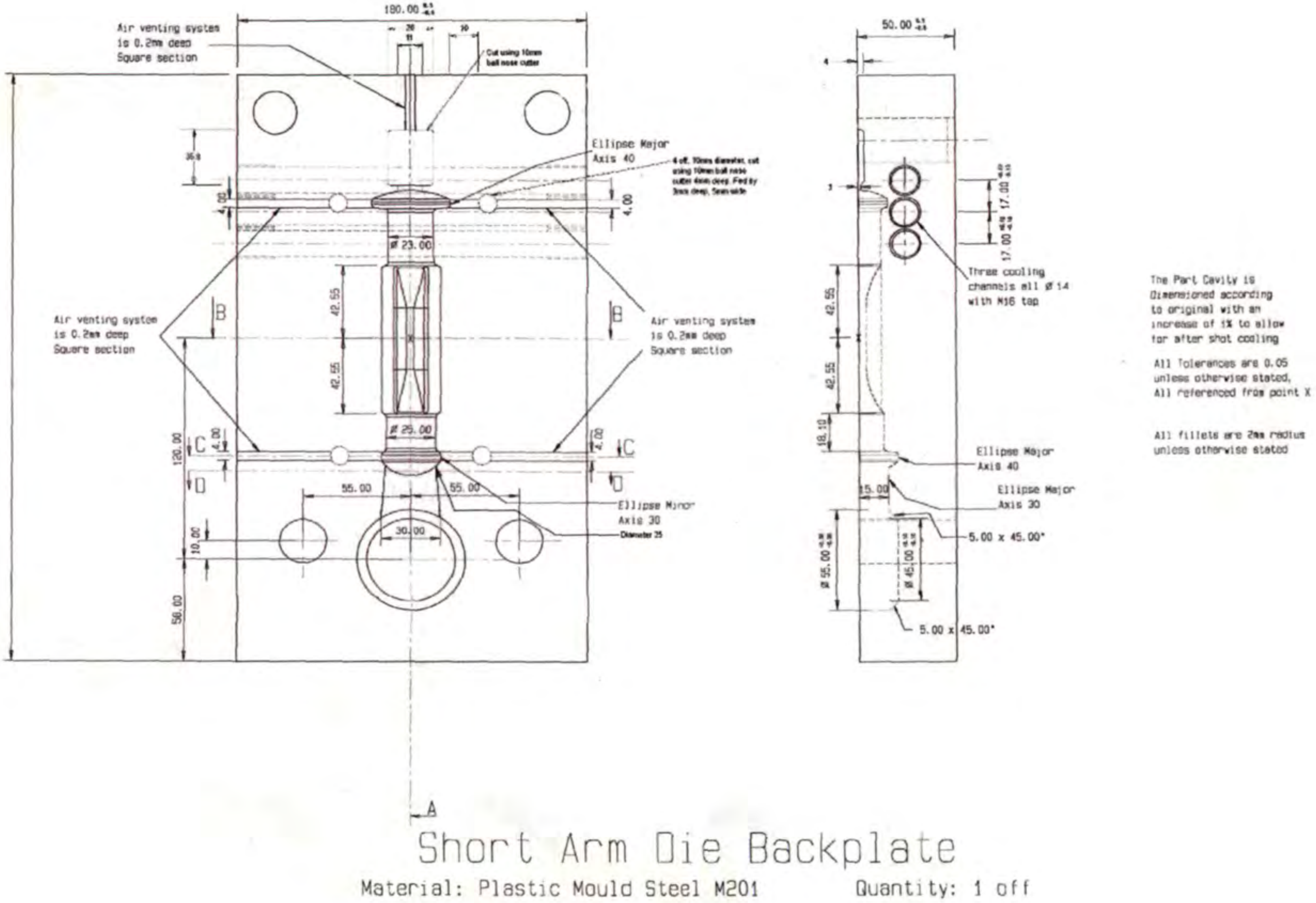
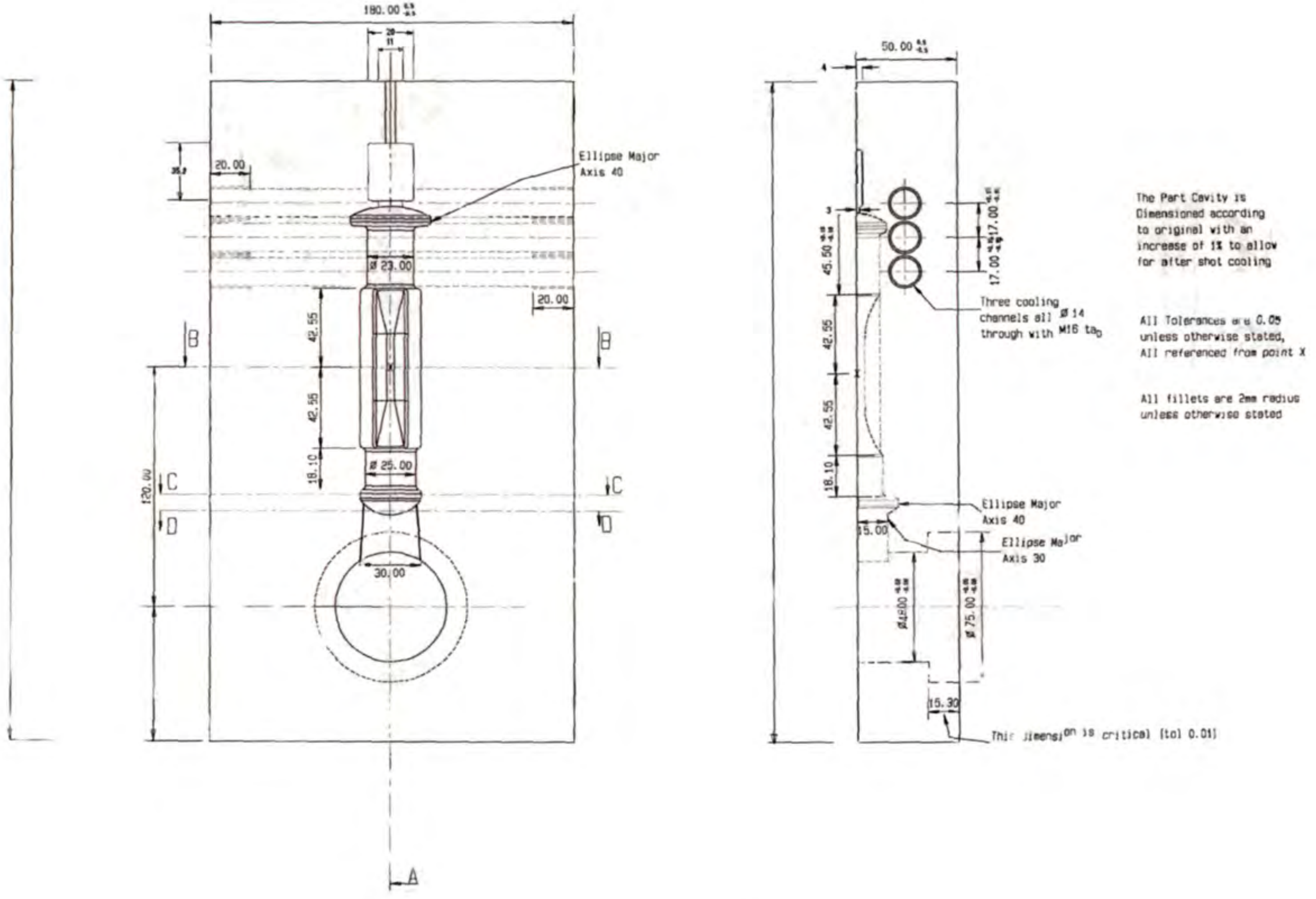


Diagram 4-40: Drawing of Modified Short Arm Die, Frontplate



Short Arm Die Frontplate

Material: Plastic Mould Steel M201 Quantity: 1 off

4.5 Results of Original Components After Die and Process Variable Setting Selection from Taguchi

This section deals with the Results from the casting of the Original Component Die after modifications were done to it. The first subsection discusses the Process Variables Recorded during the experiments. Once the experiment was completed X-ray Analysis was done on all the castings and these results are discussed here. The castings Density was also measured and discussed.

4.5.1 Process Variables Recorded

The eight components that were cast at the settings described in the Test and Experiment Methods Section had various variables measured and recorded during the experiment. These included the Die temperature measured just after casting on the surface of the die in various areas, the velocity profile of the metal injection plunger, the injection intensification pressure and the metal temperature just before casting.

Table 3-13 from the Test and Experiment Methods is repeated here to assist the reader with the setting level of each variable for each experiment, remembering that two runs of each experiment were done.

Table 3-13: Variable level settings of the Experiment (Reprinted here)

Experiment # / Factor	Water Cooling (A)	Injection Speed (B)	Metal Temperature (C)	Result
1	3 l/min A_1	0.85 m/s B_1	582°C C_1	Y_1
2	3 l/min A_1	0.30 m/s B_2	578°C C_2	Y_2
3	0 l/min A_2	0.85 m/s B_1	578°C C_2	Y_3
4	0 l/min A_2	0.30 m/s B_2	582°C C_1	Y_4

4.5.1.1 Die Temperature

The die temperature is of interest as discussed above in section 4.4.2, 3 and 4 as well as in the Literature Survey. The dies cooling channels had water flowing through them at room temperature which on the day in question was 15°C at a flow rate of 3l/minute. The experiment as described in the Experiment and Test Methods Chapter used the water cooling as a process variable and it was varied at two levels by the flow rate being 3 l/minute or 0 l/minute. This resulted in different sections of the die being at markedly different temperatures if the cooling water was flowing. The temperatures are shown graphically in diagrams 4-41 to 4-44. From the diagram it is very clear that the cooling channels have a dramatic effect on the die surface temperature before and after the casting is cast. The top of the die (where the channels are) is around 200°C cooler if the channels have water flowing through them. This cooler die temperature will aid directional solidification but may also contribute towards cold shuts. The reasons for the previous statements are given at the end of this section and in the Literature Survey Chapter.

Diagram 4-41: Die Temperature of Experiment 1

Diagrams 4-41 to 4-44 give a history of the thermal cycle the die is undergoing. Let us discuss the first two experiments which incorporate water cooling. Before casting the top of the die (where the water cooling is) is 40°C and the middle and bottom half is hotter at 150°C and 180°C respectively. The metal then enters the die and heats up the surface as heat flows out of the casting and into the die. After thirty seconds the die is opened and the casting is removed from the die. The die temperature is then measured in the same positions. The heat has caused the top of the die to increase in temperature to 120°C and the middle and bottom half to increase to 280°C and 350°C respectively. The reason for the top section being much cooler than the bottom and middle section is due to the water cooling taking place through the cooling channels at the top. Before the next shot the die is left in the open position while the next shot is prepared. The die is then sprayed with die lubricant just before it is closed again and the next casting produced. Thus it is air cooled and also water cooled on the surface by the lubricant which is water based.

Diagram 4-42: Die temperature of experiment 2

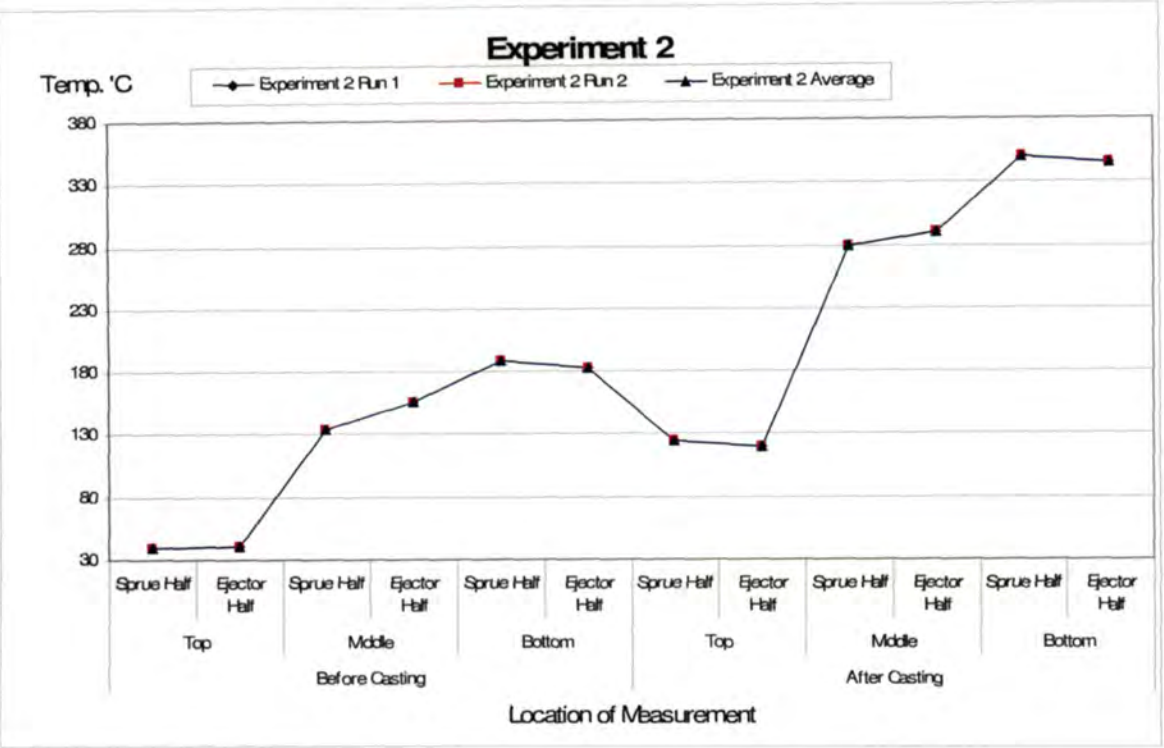


Diagram 4-43: Die Temperature of Experiment 3

Diagram 4-44: Die Temperature of Experiment 4

When the water cooling is not used, that is no water flowing through the cooling channels the result is very different. The top of the die is initially at 235°C and the middle and bottom are at 230°C and 200°C respectively. After casting heat from the metal has been transferred into the die. The top of the die is now at 250°C and the middle and bottom are at 240°C and 222°C respectively. The bottom of the die is cooler than the top. The reason for this is that the bottom of the die is open to the atmosphere through the shot sleeve even when the die is closed. The air of the atmosphere cools the die by convection through the hole of the sleeve.

4.5.1.2 Velocity Profile of the Metal Injection Plunger

The velocity of the metal injection plunger determines the flow rate of the metal filling the cavity in the die. The flow rate determines the cavity filling time (amount of time to fill the cavity). The metal flow rate will influence the behaviour of the fluid as it fills the die with respect to turbulent or laminar flow, the formation of any flow fronts and the shear rate. The metal flow rate will also determine the temperature at which the metal of the flow front is at when it meets another flow front. This is because the flow rate will determine the amount of time taken before the flow fronts meet given that the hot cast metal is losing heat continuously to the cooler die and the flow through convection to the atmosphere of the die. For these reasons the velocity of the plunger is a very important process variable.

The diagrams 4-45 to 4-48 show the velocity profile of experiments 1-4. Two castings were made for each experiment using the set point profile which is displayed in red. The profiles of each casting for each experiment are very similar to each other and so only one profile for each experiment is shown. They are very similar since the die casting machine uses real time closed loop control of the velocity of the plunger with respect to the displacement of the plunger. The first slow stage is to push the metal out the cup. The second slow stage moves the metal to the edge of the gate of the casting. The final fast stage forces the metal to fill the die cavity.

The cavity fill time of each experiment setting was given in table 3-11 in the Test and Experiment methods section, Experiment 1 and 3 are at level 2 and experiment 2 and are at level 1. The cavity fill time, if the velocity remains at the setpoint for the entire profile, for level 2, experiment 1&3, is 64ms and for level 1, experiments 2&4, is 185ms. Diagrams 4-45 to 4-48 however show clear deviation from the setpoint. To determine the actual cavity fill time numerical integration of the actual profile (blue line) must be performed using the trapezoid rule and remembering that $t = \frac{s}{u}$, where t is time, s is displacement travelled from the last point up to this point and u is the velocity at this point.

Table 4-11: Actual cavity fill times for each experiment.

Experiment	1	2	3	4
Cavity Fill Time [ms]	101	189	77	231

Even though experiment 1 and 3 have the same set point for the velocity profile, the cavity fill time is 23% different. Also experiment 2 and 4 have the same set point and their cavity fill times are 22% different. The impact of a consistent velocity profile is clearly shown in the variance of the cavity fill time. By industry standard this variation is in fact quite typical.

Diagram 4-45: Experiment 1 Velocity Profile

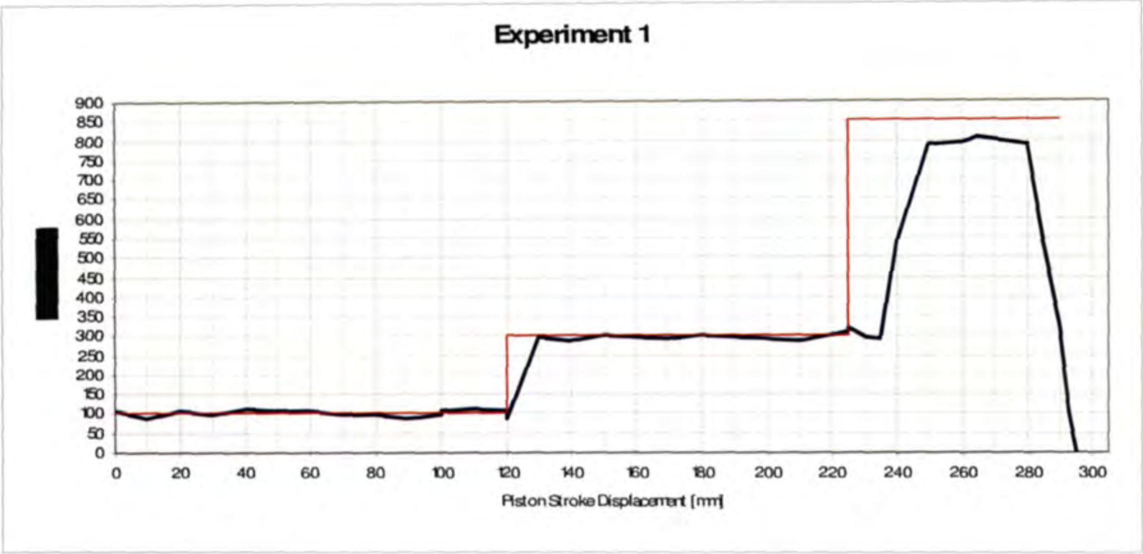
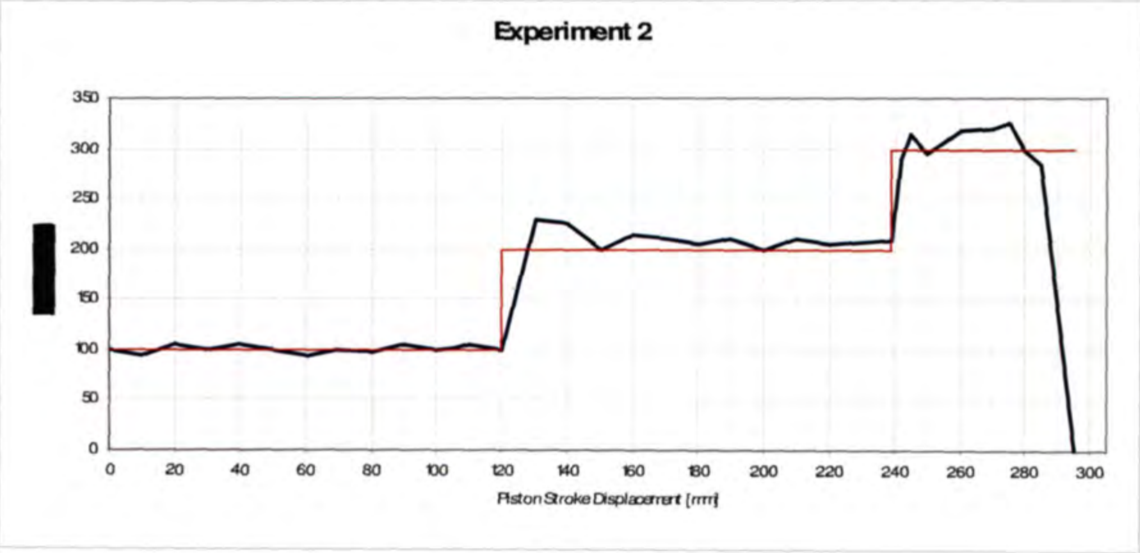


Diagram 4-46: Experiment 2 Velocity Profile



It is undesirable to have a variation of more than 30%. The industry standard for aluminium conventional high pressure castings is to fill the die cavity in 20 to 30ms, however the thicker the casting the longer the time may be. A good example of this is shown in Appendix 2, the product FH44 Body which is very thick in comparison to the Sheerline Handle [67], the cavity fill time is 48ms and 28 ms respectively. A brief summary of this work instruction is contained in Appendix 2. Midson S.P.[32] suggests a cavity fill time of between 0.1 to 0.3 seconds from table 4-11 experiment 2 and 4 fall in this range comfortably.

Diagram 4-47: Experiment 3 Velocity Profile

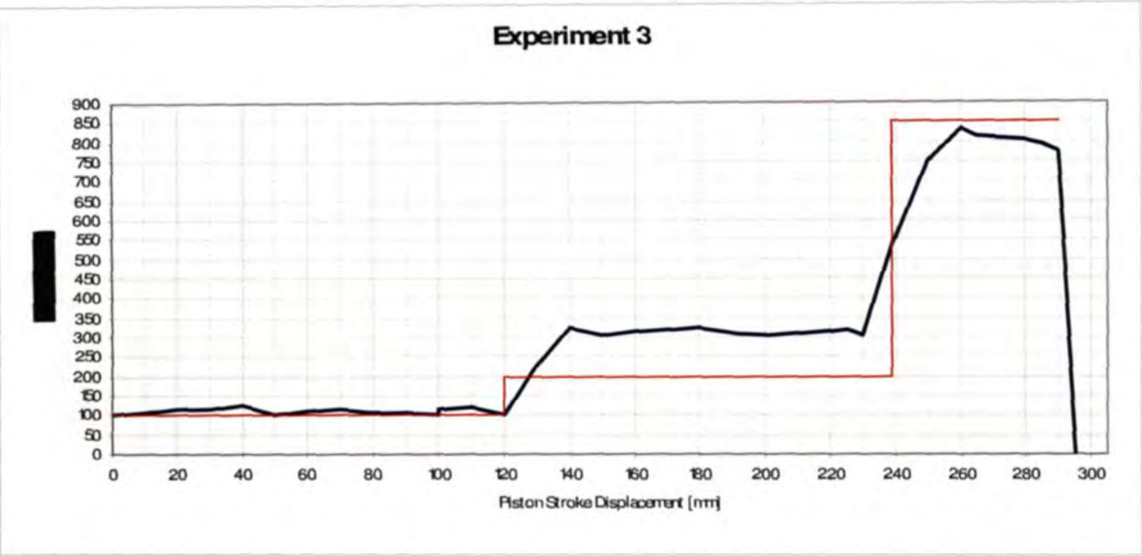
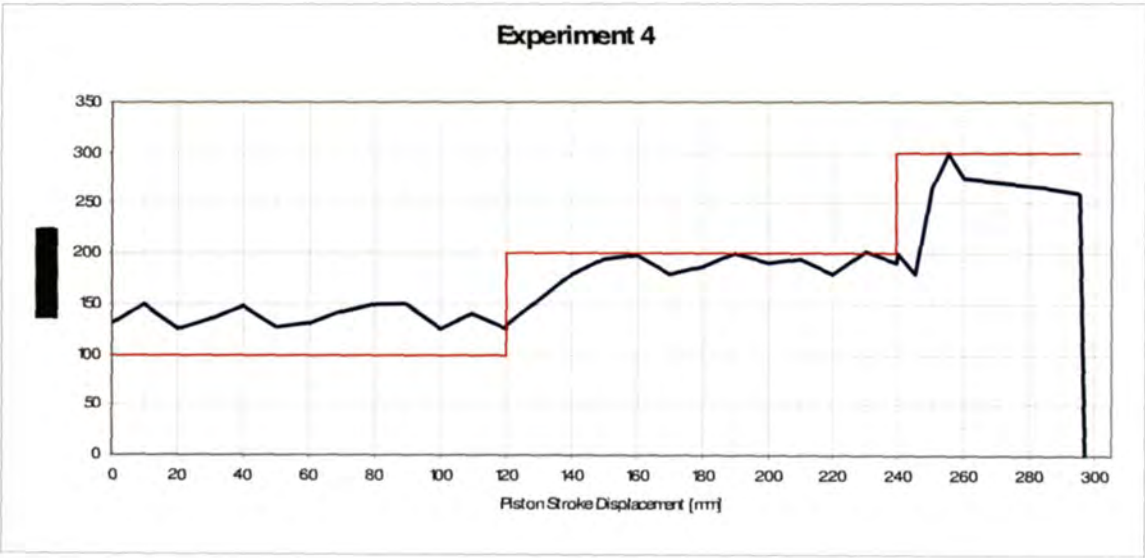


Diagram 4-48: Experiment 4 Velocity Profile



4.5.1.3 The intensification pressure

The intensification pressure is read off a gauge showing the pressure in the hydraulic accumulator. The metal pressure at the end of the injection is proportional to the hydraulic pressure acting on the hydraulic piston from the acculmulator. This hydraulic pressure creates a corresponding metal pressure by the force acting through the plunger rod and the plunger onto the metal surface in the shot sleeve. Table 4-12 gives the hydraulic and corresponding metal pressure for each experiment.

Table 4-12: Metal Pressure for Each Experiment

Experiment	Intensification	
	Hydraulic Pressure [Mpa]	Metal Pressure [kg/cm^2]
1	17.9	752.77
2	18	756.98
3	17.9	752.77
4	18	756.98

4.5.1.4 Metal temperature

The temperature of the metal is measured by a thermocouple wire which is inserted into the billet. The temperature of the billet was used as one of the process variables for the experiment. The table 4-13 gives the target temperature values and the actual values achieved during the experiment.

Table 4-13: Actual vs Target Temperature

Experiment	Temperature 'C	
	Target	Actual
1	582	582
2	578	578
3	578	578
4	582	582

The actual and experiment target values are identical. This was made possible due to the slow change in temperature that occurs in this range and careful and quick reactions of the technician assisting with the experiment. The variation is slow since this temperature range is in the eutectic range of the alloy.

4.5.2 X-Ray Radiography and Density Analysis of Parts

All eight castings produced from the four different level settings of the experiment factors (variables) were X-ray radiographed in two planes.

Experiment 1: Diagram 4-49 is an X-ray radiograph of experiment 1's first run. The part is laid flat and x-rayed using 50kV and 4.5mAs strength beam. At the interface of the top cylindrical section and the end cap there is evidence of a fine crack. This section is enlarged and highlighted in diagram 4-50. The X-ray of this part from the side, diagram

Diagram 4-49: Radiograph of Run 1 of Exp. 1 from the Top

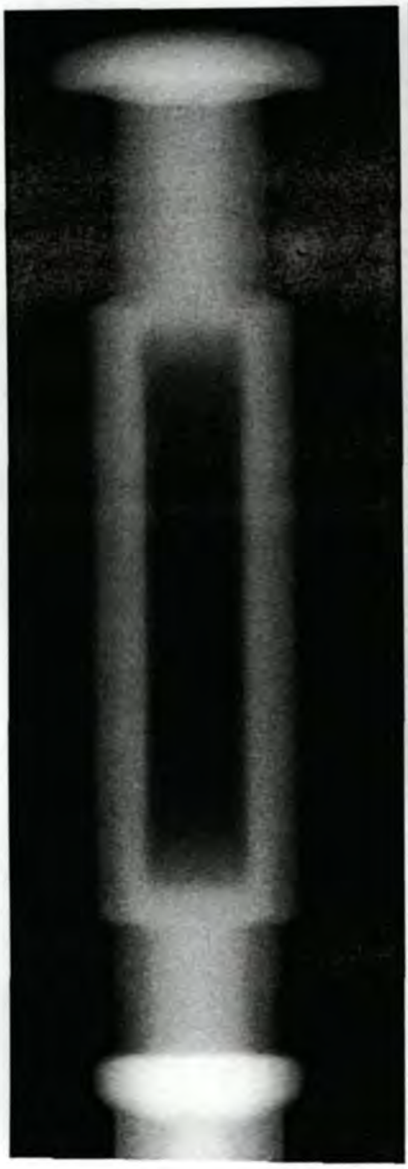
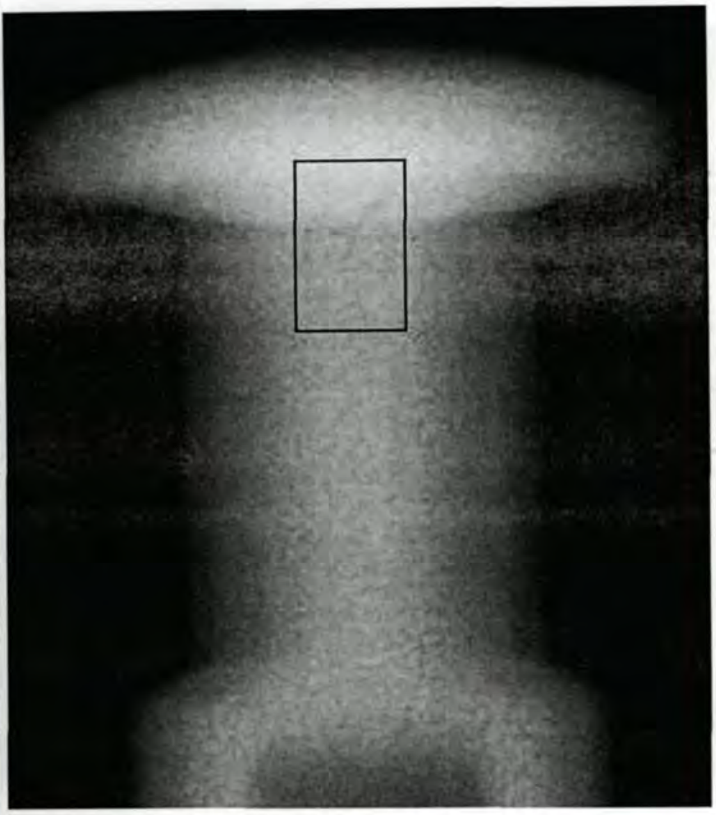


Diagram 4-50: Enlarged section of diagram 4-49



The X-ray of this part from the side, diagram 4-51 shows only very faint evidence of the same inhomogeneities. This means that the crack propagates vertically into the part, when viewed as in diagram 4-49, and is very narrow.

The castings were then weighed suspended in water and then in air, to establish their densities. The density of the part to have zero porosity should be 2.69g/cm^3, however due to the points raised with regards to this method in the Test and Experiment Methods Chapter different results could be obtained. The lower the value however the less dense the part is and hence the more porosity is contained within. The result is tabulated in Table 4-14. The defect size was measured and is tabulated in table 4-16

The second casting run at the same experiment factor level settings produced a casting with no inhomogeneities showing up in the X-Ray radiograph of the part, diagram 4-52 and 4-53.

Diagram 4-51: Radiograph of Run1 Exp1 from side from side

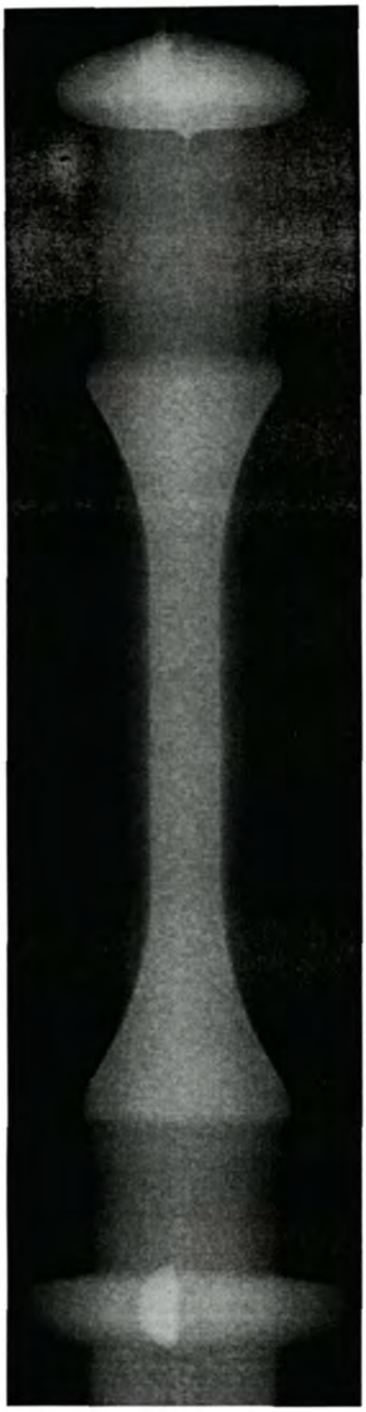


Diagram 4-52:Radiograph Run 2 Exp1 from Top

Diagram 4-53: Radiograph of Exp1Run 2 from Side

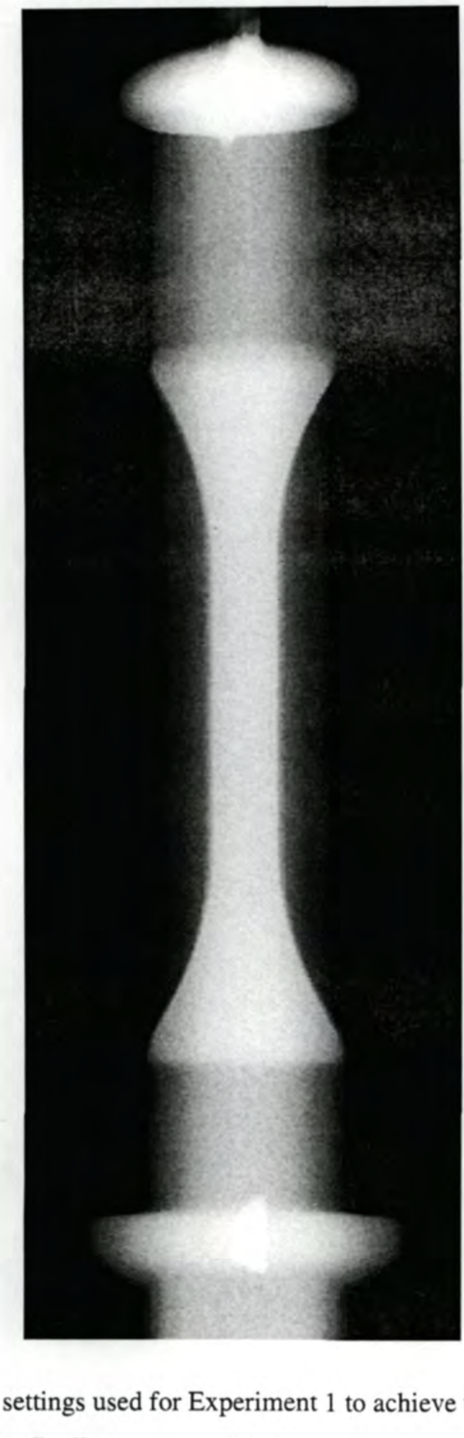
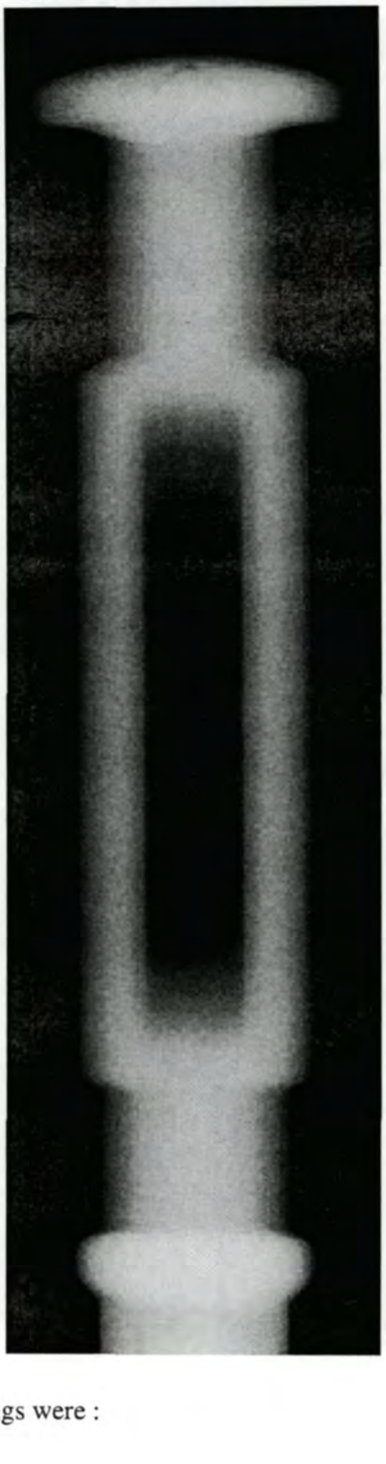


Diagram 4-54: Exp2, Run 2 from top



The settings used for Experiment 1 to achieve these two castings were :

Water Cooling: 3l/minute

Speed: 0.85ms^{-1}

Metal Temperature: 582°C

Experiment 2 was done next and the X-Ray radiographs of the two castings were carried out. Here as before only one of the castings had inhomogeneities show up in the radiographs, this was run 2. The inhomogeneity is seen in Diagram 4-54 at the top of the top end cap.

This inhomogeneity is only visible in the radiograph taken with the casting lying flat. In the radiograph taken from the side, diagram 4-55, there is no evidence of a crack or any inhomogeneity. This means that the crack is very narrow and runs vertically into the casting when viewed in the plane shown in diagram 4-55. Diagram 4-56 shows an enlarged and highlighted view of the inhomogeneity. However upon inspection of the part it was noticed that this casting had very deep score marks which resulted in the fracturing of the part at the top, the damaged section is shown in diagram 4-57 and 4-58.

It is seen from diagram 4-58 that the crack is in fact caused during ejection of the part from the die. Thus it is not a casting inhomogeneity. To avoid this more draft angle on the die should be applied to this face where the score marks are apparent. This section should also be inspected regularly for damage the edge of die face and die cavity "peening" over.

Experiment 2 was done with the following process variable (factor) settings:
Water cooling: 3l/minute
Speed: $0.3ms^{-1}$
Metal Temperature: 578°C

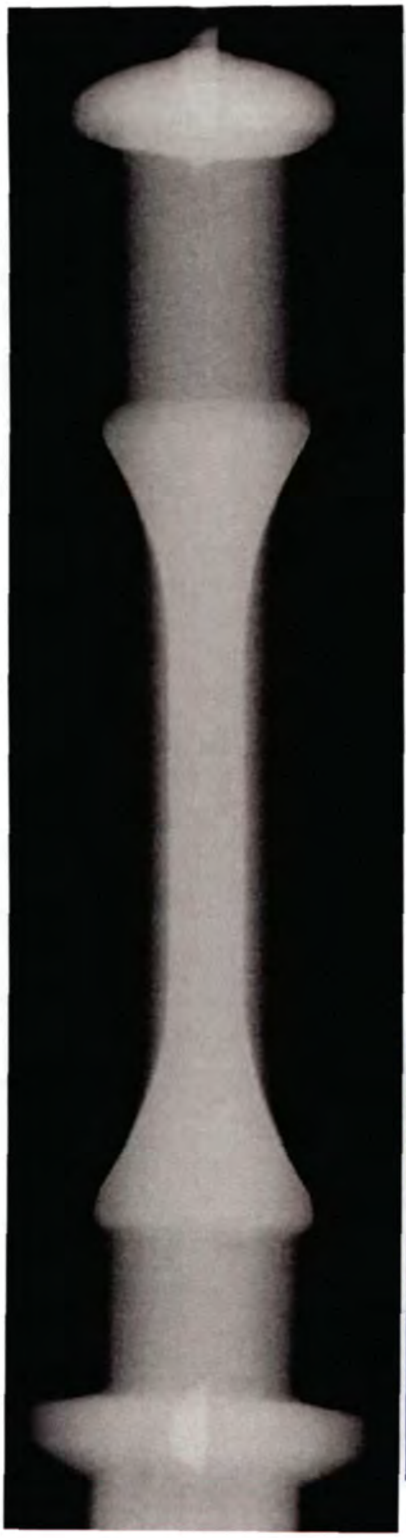
The density is tabulated in table 4-14 and defect size according to the Test and Experiment Methods Chapter is tabulated in table 4-16. The X-ray radiographs of Run 1 of this experiment 2 do not have any inhomogeneities. The radiographs are shown in diagram 4-59 and 4-60.

Experiment 3 was done and the resulting two castings X-ray radiographed. The setting of the experiment factors were:
Water cooling: 0l/minute
Speed: $0.85ms^{-1}$
Temperature: 578°C

The X-ray radiographs showed a cold shut and porosity. The cold shut (crack) is seen in diagram 4-61(a). The porosity is seen in diagrams 4-61(a),(b),(c),(d).

Diagram 4-55: Radiograph Exp. 2 Run 2 from side

Diagram 4-56: Enlarged of top end cap section of diagram 5-54



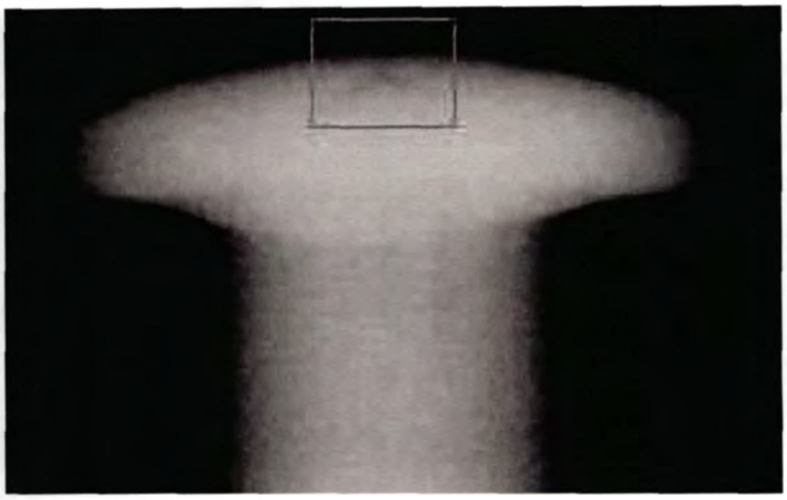


Diagram 4-57: Photograph of close up of section Component from Exp. 2 run 2 showing the defect shown in diagram 4-56

Diagram 4-58: Photograph of close up section of Component from Exp. 2 run 2 from underneath showing score marks

Diagram 4-59: Radiograph of Exp. 2 top view

Diagram 4-60: Radiograph of Exp2 Run 1 from the side

Diagram 4-61: Radiographs of Exp. 3 run 1 (a) & (b) and run2 (c) & (d)

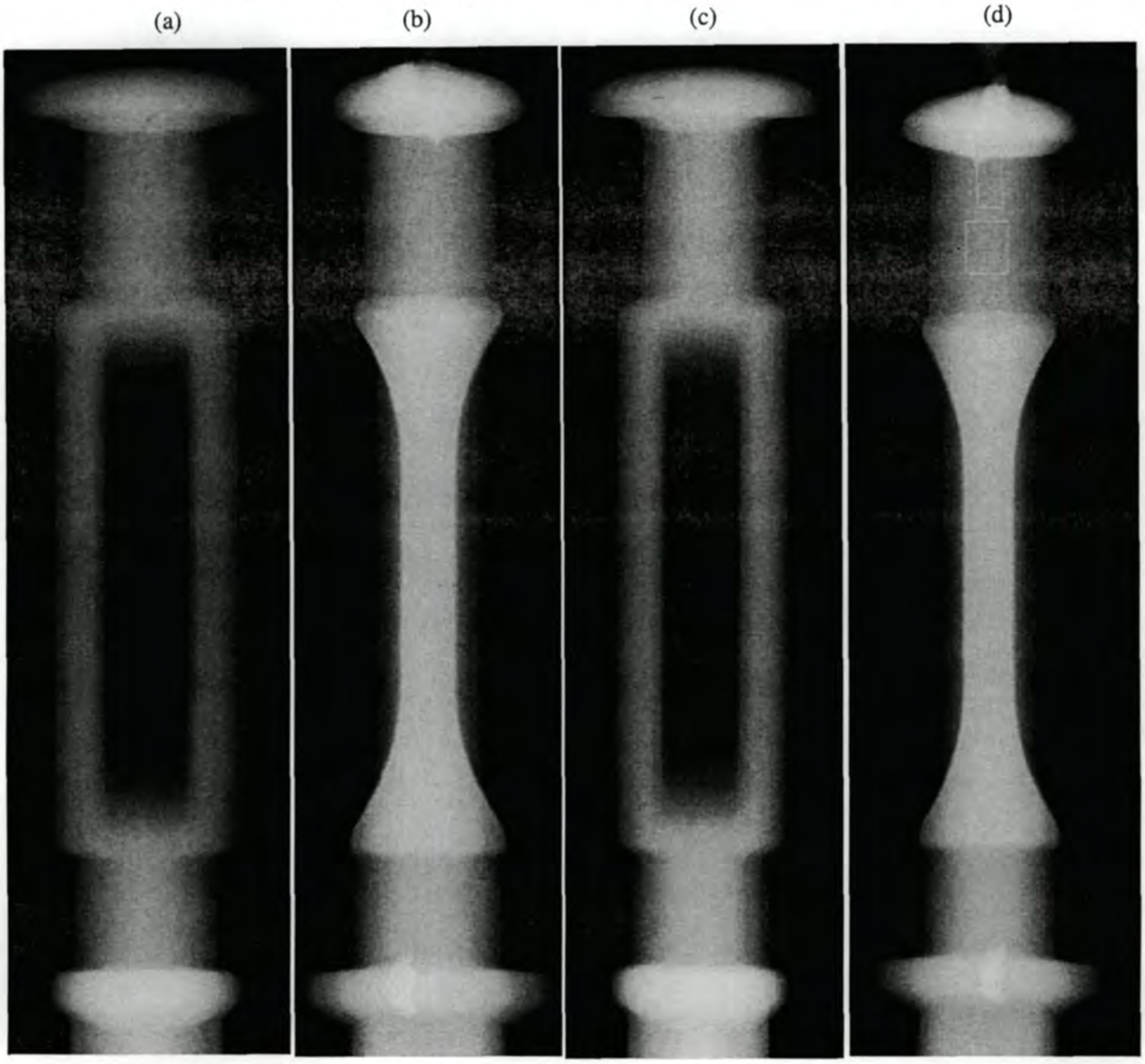


Diagram 4-62 shows an enlarged view of the X-ray radiograph of Run 1 of Experiment 3 (diagram 4-61(a)). The cold shut (crack) is clearly visible and the porosity is also visible. The cold shut is boxed on the left and the porosity is boxed in the smaller box on the right.

Diagram 4-63 shows two porosity spots. Diagram 4-64 shows two small porosity spots. One at the interface of the top end cap and the top cylindrical section and another just below that (boxed in the same box) near the top of top cylindrical section.

Diagram 4-62: Enlarged section of Diagram 4-61(a)

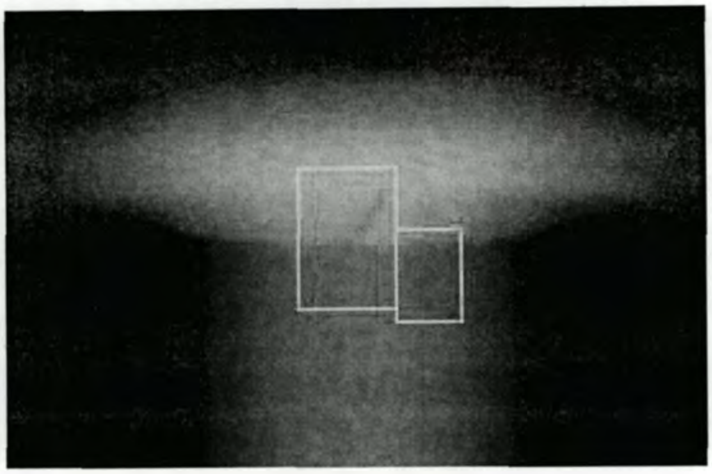


Diagram 4-63: Enlarged section of diagram 4-61(b)

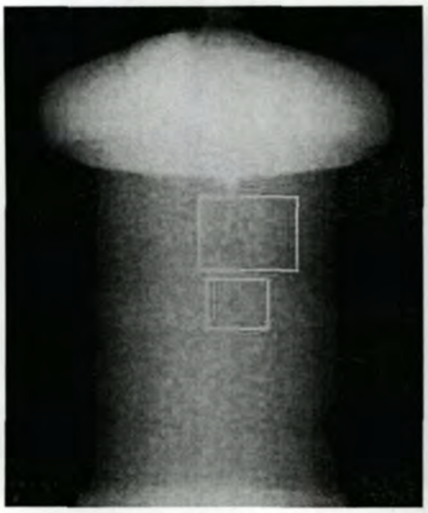


Diagram 4-64: Enlarged section of diagram 4-61(c)

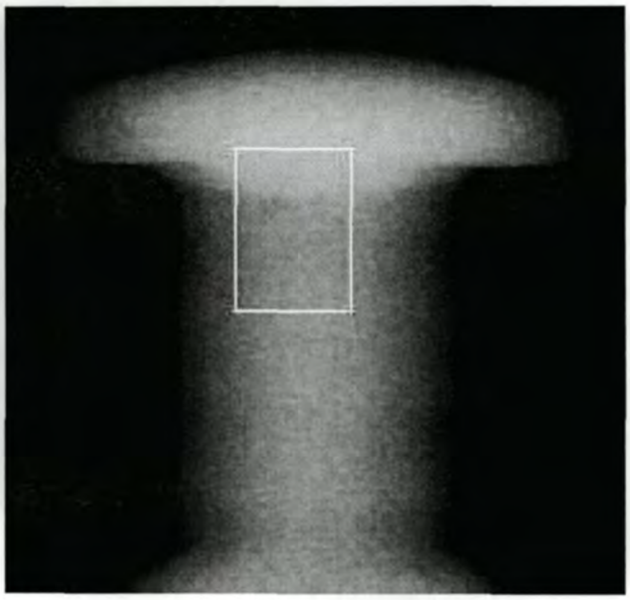


Diagram 4-65: Enlarged section of Diagram 4-61(d)

Diagram 4-65 shows another two patches of porosity, here they are in the centre of the top cylindrical section and at the interface of this section with the top end cap. The defect densities and defect sizes are tabulated in table 4-14 and 4-16 respectively.

Experiment 4 was run twice creating two castings. The two castings were X-Ray radiographed in both planes, diagram 4-66(a) - (d). The setting of the experiment factors were:

Water cooling:	0l/minute
Speed:	0.3ms^{-1}
Temperature:	582°C

The X-ray radiographs show patches of inhomogeneities. In the radiograph of run 1 lying flat (diagram 4-66(a)) there are two such patches. The patches are not distinct enough or follow any particular pattern to make them appear to be a crack. The patches are highlighted in diagram 4-67. When Run 1 is viewed from the side (diagram 4-66(b)), only the bottom patch is visible in the radiograph the area is boxed in diagram 4-68. Experiment 4 Run 2 viewed from the side, diagram 4-66(d), has a very slight dark patch near the interface of the top cylinder and the end cap. This area is enlarged in diagram 4-69.

Diagram 4-66: Radiographs of Exp. 4 Run1 (a) & (b) and Run 2 (a) & (b)

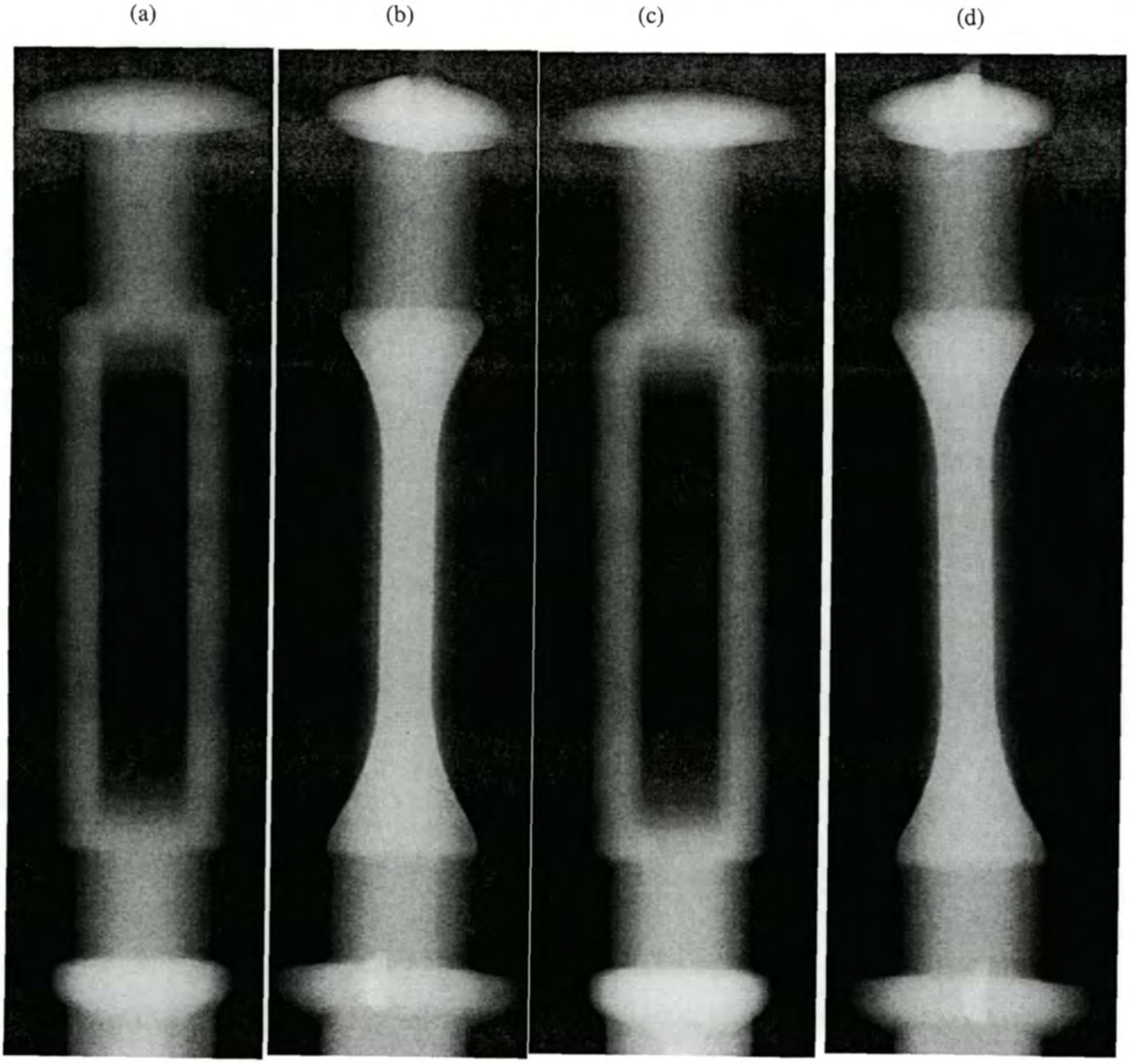


Diagram 4-67: Enlarged section of diagram 4-66(a)

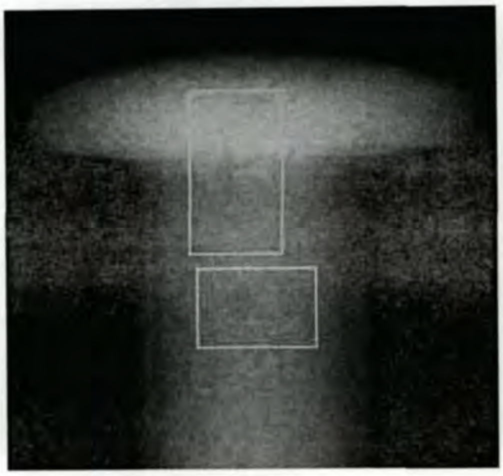


Diagram 4-68: Enlarged section of diagram 4-66(b)

Diagram 4-69: Enlarged section of diagram 4-66(d)

The results for all four experiments are now quantitatively assembled. First the density measurements are presented. Then the defects are presented in tabled quantitative form. Table 4-14 shows the density measured for each casting from all the experiments. This is the analysis of the castings using method two described in the Test and Experimental Methods Chapter. Table 4-16 shows the results of the castings using the first method described in the Test and Experimental Methods Chapter.

Table 4-14: Density of Each Casting from Experiment #1 - 4

Experiment	Run	Mass in Air [g]	Apparent Mass in Water [g]	Density g/cm3	Average Density	Length of Biscuit [mm]
1					Y1	
	1	204	72	2.83	2.78	50.6
	2	205	75	2.73		54.6
2					Y2	
	1	203	75	2.71	2.70	52.2
	2	202	75	2.69		50.5
3					Y3	
	1	205	76	2.70	2.70	51.6
	2	203	75	2.71		51.3
4					Y4	
	1	203	75	2.71	2.69	50.8
	2	205	76.5	2.68		54.6

The length of the biscuit is included in table 4-14 since it is imperative that the biscuit is long enough so that intensification can take place in the casting due to the pressure transfer from the plunger. Since the length of the shot sleeve and the sprue bush is 329.5mm but the stroke of the machine is only 300mm. This means that a biscuit size of less than 29.5 will not allow any intensification. As seen in the table all the biscuits are above this value.

The highest density was recorded in run one of experiment 1. Run two of the same experiment yielded a lower result but still higher than any other. The significance of this is however shaded by the closeness of the values and the accuracy of the density calculating method. Although from this data it is apparent that Experiment one yields the highest density casting. It is noted that the closeness of the values of results Y2, Y3 and Y4 place significant doubt over any conclusions drawn from these measurements of the experiment. None the less the data is analysed for discussion purposes below.

Putting table 4-14's data into the Taguchi analysis response table, table 3-14 from the Test and Experiment Methods Chapter yields table 4-15 below, the % influence is calculated using Analysis of Variance technique (ANOVA),

Table 4-15: Density Response table for Experiments #1 - 4

Factor (Parameter)	Water Cooling A – response	Injection Speed B - response	Metal temperature C - response
Level 1	2.741666667	2.742675439	2.738267974
Level 2	2.697610079	2.696601307	2.701008772
Difference between levels, main effect	0.044056588	0.046074131	0.037259202
% Influence	35.60%	38.94%	25.46%

Remembering that the higher the value the better, it is seen, from Table 4-15, that the best setting for this experiment is Factor A at level 1 (cooling 3l/s), Factor B at level 1 (injection speed 0.85m/s) and Factor C at level 1 (578°C). It is also seen that Factor B, injection speed has the most influence on the result. Diagram 4-70, 71 and 72 are each a plot of the responses. There is seen to be strong interaction between all three factors. It is clear from the literature Survey Chapter that metal temperature and the flow rate of the metal interact together to effect the apparent viscosity of the fluid. The water cooling is also seen to interact with both the speed and the metal temperature, it is suggested that the water cooling in fact interacts with the metal temperature by reducing it. The reduced metal temperature will cause an increase in the viscosity of the metal. This will appear to have the same effect as a slower speed and so the speed response will interact with the cooling, through an indirect interaction. A reduced viscosity would effect the flow behaviour and this could lead to turbulence resulting in gas, and oxide entrapment leading to porosity. An increased viscosity would lead to less or no turbulence and steady flow conditions as discussed in the Literature Survey. An increased viscosity would lead to the Bigot and Reynolds number for the fluid to be with in the process window for successful castings as required by diagram 2-16 and 2-20.

For the purposes of this study however the interactions seen in diagram 4-70 to 4-72, do not warrant further investigation, because the differences between the density values are in fact too small and below the accuracy of the experiment. However it certainly is an area for further study although outside of the scope of this work. From previous study by K.C. Sharma[8] it was shown that a gate velocity of above 3.5ms^{-1} gave rise to porosity. In this experiment the maximum injection speed of 0.85ms^{-1} gave a gate velocity 2.87 ms^{-1}.

Diagram 4-70: Interaction of Water cooling and Injection speed on Density

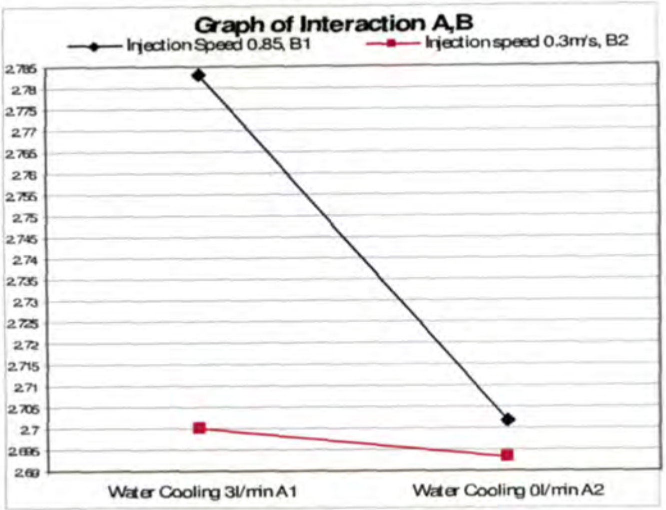


Diagram 4-71: Interaction of Water cooling and Metal temperature on Density

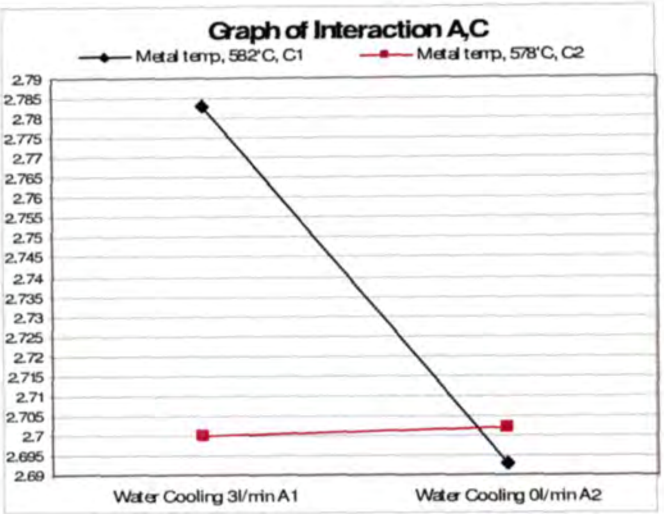
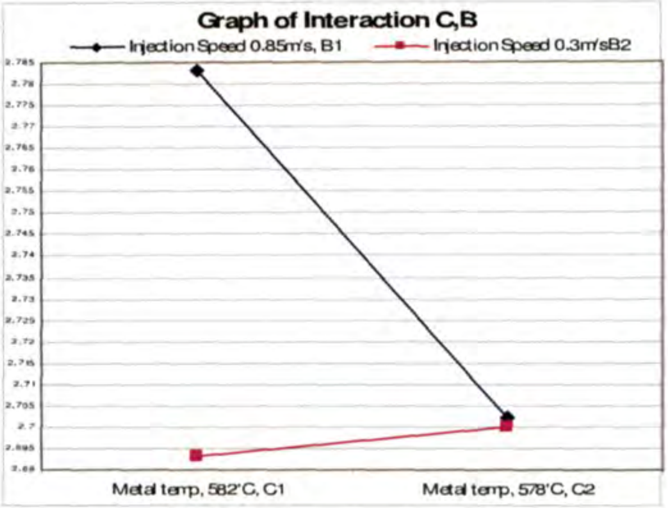


Diagram 4-72: Interaction of Metal temperature and Injection Speed on Density



The data for the X-Ray radiographs are discussed now. The X-Ray radiographs' results do not support all the recommendations put forward by the density study. That is according to the obtaining a casting with the highest density the factor levels should be chosen as follows, Factor A at level 1, Factor B at level 1 and Factor C at level 1. These level settings correspond to Experiment 1. However if one views diagram 4-50 there is a clear defect. Although notably less than those seen in the X-Ray radiographs of Experiment 3 and 4. If one neglects the only defect seen in Experiment

2 run 2, diagram 4-56, as is suggested in this section; due to the defects formation being the cause of to mechanical damage resulting during ejection from the die rather than a casting inhomogeneity, then Experiment 2 has the least defects, not experiment 1. Experiment 2's factor settings are, Factor A at level 1, Factor B at level 2 and Factor C at level 2; that is water cooling on, low speed and low metal temperature. The results from the X-ray radiographs of the eight components using the defect analysis method as the result are tabulated in table 4-16. The defect analysis method is described in

Table 4-16: Results of Experiment #1-4 using the Defect analysis Method

Experiment	Run, View	Number of Defects	Size (severity)	Contrast	Result	Total
1	1 Flat	1	5	5	25	
	1 Side	1	2	3	6	
	Total Run 1					31
	2 Flat	0	0	0	0	
	2 Side	0	0	0	0	
	Total Run 2					0
Total Exp 1					Y1	31
2	1 Flat	0	0	0	0	
	1 Side	0	0	0	0	
	Total Run 1					0
	2 Flat	0	0	0	0	
	2 Side	0	0	0	0	
	Total Run 2					0
Total Exp 2					Y2	0
3	1 Flat	1	6	7	42	
		2	2	4	8	
	1 Side	1	4	2	8	
		2	2	3	6	
	Total Run 1					64
	2 Flat	1	3	4	12	
	2 Side	1	3	4	12	
		2	1	2	2	
	Total Run 2					26
Total Exp 3					Y3	90
4	1 Flat	1	5	7	35	
		2	3	6	18	
		3	1	4	4	
	1 Side	1	3	3	9	
	Total Run 1					66
	2 Flat	1	1	1	1	
	2 Side	1	2	2	4	
	Total Run 2					5
Total Exp 4					Y4	71

the Test and Experimental Methods Chapter and quantitatively describes the inhomogeneities of each casting.

The data presented in table 4-16 is of a much greater range and are more representative than that of table 4-14. For this reason and for the purposes of this investigation the results in table 4-16 will be used to draw conclusions and table 4-14 is for discussion purposes only.

The data in table 4-16 is placed into the Taguchi analysis response table, table 3-14 from the Test and Experimental Methods section. ANOVA techniques are used to calculate the % influence of each variable on the result. The result is shown in table 4-17.

Table 4-17: Response table for Defect Analysis Results

Factor (Parameter)	Water Cooling A - response	Injection Speed B - response	Metal temperature C - response
Level 1	15.5	60.5	51
Level 2	80.5	35.5	45
Difference between levels, main effects	65	25	6
% Influence	86.47%	12.79%	0.74%

From table 4-17 the % influence shows the influence of each factor (A,B and C) on the result relative to each other. Factor A has the greatest influence on the result, 86.5% of the result is caused by factor A. Thus the water cooling is critical for a low defect level casting, i.e. a high internal integrity casting. The next important factor is the injection speed. The experiments conducted show that the lower injection speed of $0.3ms^{-1}$ is the better setting. The influence of this factor is less than a sixth of influence caused by the water cooling factor. The metal temperature has the smallest effect on the result. This may be since the temperature range chosen for the experiments may have been too small and as a result the analysis shows that this has little influence on the integrity of the part, this is an area for further investigation.

There are strong interactions once again between the factors. Diagram 4-75 and 4-76 both have response lines showing a high degree of non-parallelism. Diagram 4-74 has a relatively low degree of non-parallelism.

From diagram 4-74, for both level settings of the injection speed (Factor B, B1 and B2) when there is cooling there is a better result than when there is no cooling. However when Factor B is set to $0.3ms^{-1}$ the effect of the water cooling is more pronounced than when Factor B is set to the higher speed, $0.85ms^{-1}$. This is shown by the response line of B2 having a steeper gradient than B1's response line. The better result (lowest defect score) is clearly obtained using B2, slow speed.

Diagram 4-74: Interaction of Water cooling and Injection Speed on Defects Analysis

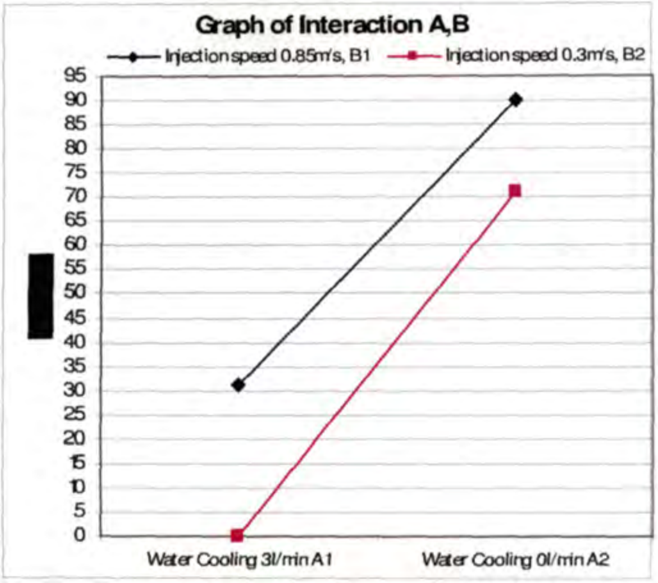


Diagram 4-75: Interaction of Water cooling and Metal Temperature on Defect Analysis

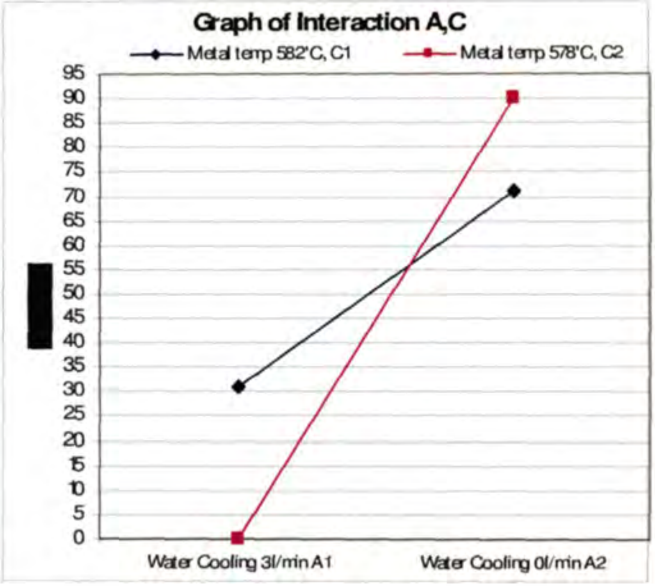


Diagram 4-75 has similar interaction behaviour but here it is even stronger (by comparing the difference of the gradients of each factor response line to those of diagram 4-74). By comparing the two gradients of C1 and C2, it is clear that if the metal temperature is low (C2) then the response to the cooling is more pronounced than if the metal temperature is hot (C2 gradient is steeper than C1). The better result is obtained by using C2, lower temperature. The reason for the interaction could be explained by the top section of the die being cooler when the water cooling is on and so causing a more rapid solidification at the interface of the casting and the die which would result in a higher shear stress being produced inside the metal for the same flow rate. The higher shear stress leads to a lower viscosity and hence better fluidity of the metal and results in a better casting. The cooler the initial metal temperature (C2 as opposed to C1) the more pronounced this effect is and that could be why C2 has a steeper gradient. This is true for the top section of the die only, but this was the only section where defects were observed. This is supported by the Literature Survey however it is conjecture but is discussed to suggest an area for further research however outside of the scope of this investigation.

Another reason why the metal at a lower temperature (C2) gives a better response than a higher temperature would be due to the fluid having a higher fraction solid at the factor level C2. The higher fraction solid fluid will create less solidification porosity when it solidifies (compared to fluid at a lower fraction solid) because a high percentage of it has already solidified.

Diagram 4-76: Interaction of Water Cooling and Injection Speed on Defects Analysis

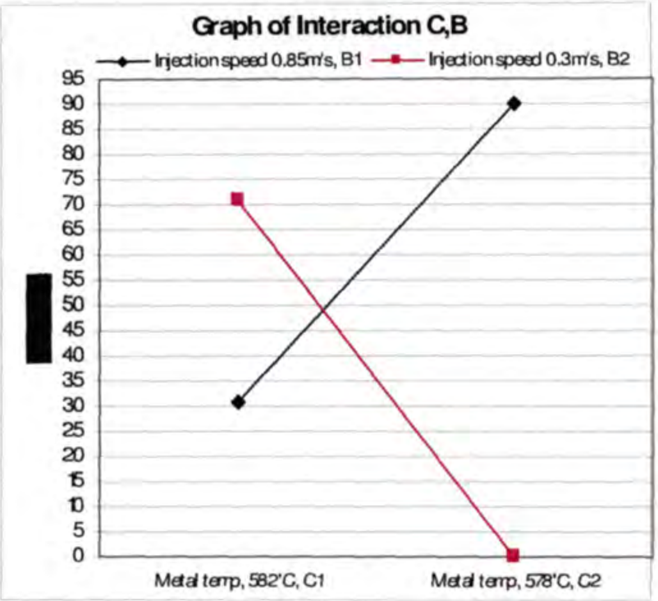


Diagram 4-76 shows an even stronger interaction between the metal temperature (Factor C) and the injection speed (factor B). At the high injection speed (line B1, blue), the colder the metal temperature (C2) is, the worse (higher) the defect score is. At slow speeds, line B2, the hotter the metal temperature (C1) is, the worse the defect score is. This shows an opposing interaction working between the metal temperature and the injection speed. That is for slow speeds a decrease in metal temperature produces a better casting, however for high speeds a decrease in metal temperature produces worse castings. This could be explained by two phenomena. A colder metal temperature in contact with die surface would solidify quickly and as a result cause a higher shear rate so decreasing the apparent viscosity. A higher injection speed (flow rate) will also cause a lower viscosity. It could be that in the case of the high injection speed and the low metal temperature the viscosity has decreased to such an extent that the fluid is now flowing a turbulent manner. That is the lower metal temperature and the higher speed have together caused very high shear stresses which have resulted in the viscosity decreasing to such an extent that the flow rate is now sufficient to cause turbulence. In the case of the slower speed (B1) here the colder metal temperature has increased the shear rate as described already however the flow rate is not high enough to decrease the viscosity to such an extent as to cause turbulence. Also the slower speed is assisting the fluid to remain as laminar flow. The part of the theory put forward here about the flow rate is supported by Jae-Chul Lee, Hyun-Kwang Seok, and Ho-In Lee [18]. The part of the theory put forward about the effect of the metal's temperature in contact with the die surface and the corresponding shear stress increasing is again the opinion of the author and is conjecture. This is another area for further research.

To verify the result it is necessary to run verification experiments. These experiments must be run using the factors set at the levels which optimise the result. In the case of the results in the response table 4-17, factor A should be set to level 1, factor B should be set to level 2 and factor C should be set to level 2. One of the actual runs already done in the experiment is at these optimum factor level settings. The experiment is Experiment 2. Experiment 2's factor settings are, die cooling water on at 3litres per minute, injection speed of plunger, $0.3ms^{-1}$ and the metal temperature at 578°C. There were two casting performed at these settings. Both the castings had a zero defect score. This shows good reproducibility.

The research on this component has shown that in order to produce a sound (defect free) casting, the gate must feed the entire casting and be as wide as the casting as suggested by S.P. Madison, R.B. Minkler and H.B. Brucher [7]. The gate should be positioned in such an orientation to the casting so that it "feeds" the highest modulus section of the casting[13]. The solidification of the part must then be orchestrated so that directional solidification will take place from the gate to the highest modulus section through to the lowest modulus section, in that order. Care must be taken to calculate the modulus of each section so as to gain an understanding of the solidification process that the part will undergo. Once this has been done the gate position may be decided upon and then the placement of heating or cooling channels. The heating/cooling channels will be necessary only if decreasing modulus sections do not feed each other. If this is the case then the section feeding that section should either be heated or the section being fed should be cooled or both, to overcome shrinkage porosity that could form as a result of the lack of directional solidification. In the research it was shown that for this component it was necessary to aggressively cool the high modulus top cylindrical section which was fed by the lower modulus hour glass section. The research shows that a sound (defect free) casting can be consistently produced by cooling this section and as a result no heating channels are necessary. The research has also brought to light some very interesting interactions between all three factors experimented with, metal temperature, metal flow rate and the presence or absence of cooling channels. The required setting for the metal temperature is 578°C, the required injection speed using a 47.7mm diameter plunger is $0.3m^{-1}$ and the water flow rate through cooling channels is 3litres per minute to produce a defect free Short Arm component using the current system. For the purposes of this investigation the research has predicted the correct process settings required to repeatably produce a sound casting. An experiment using these process settings was carried out to verify the prediction and two out of two sound (defect free) castings were produced.

Chapter 5: Conclusion and Recommendations

By evaluating all the common manufacturing processes applicable to cast or forged components and by utilising the NADCA Product Specification Standards for SSM & Squeeze Casting Processes [40] a quantitative assessment of various components suitability to the Semi-solid Metal High Pressure Die Casting (SSM HPDC) manufacturing process was achieved by modifying the Product Specification Standards with weighting factors. The quantitative assessment enabled a suitable component to be selected with confidence, on which to carry out this investigation.

To manufacture the Short Arm (the selected component) a die was successfully designed and a compatible HPDC machine utilised [62.5 ton modified shot control Edgewick]. The investigation used Chvorinov's rule to design the die to reduce porosity and results from the simplified modular die to achieve correct filling behaviour. The investigation showed that the gating of the component should achieve fluid flow through ever decreasing cross sectional areas (converging flow) starting with the gate. This will ensure that there are always more than two shear planes acting on the fluid. SSM fluid will not deform and fill into the extremities of a die cavity unless the flow front of the fluid is acted upon in shear in more than two planes.

This requirement of flow through converging cross sectional areas also contributes towards the correct geometrical requirements for directional solidification. Directional solidification must be maintained through the casting to avoid shrinkage porosity. A decreasing modulus of each section with respect to the geometrical position of each section is required to eliminate shrinkage porosity. The decreasing cross sectional area will in most cases also give rise to a reduction in the modulus (ratio of Volume to Surface area in contact with the die). For practical reasons it is not possible to achieve this type of filling at certain sections in the Short Arm Component. Other techniques were used to ensure that correct die cavity filling behaviour and successful directional solidification occurred in these sections.

The transition of the Short Arm's geometry from the hour glass section to the top cylindrical section is a diverging section with respect to the decided direction of the fluid flow during cavity filling. The diverging section results in a reduced shear rate which increases the viscosity of the fluid and the fluid no longer has three shear planes acting on it. The result is that cavity will not fill with one continuous flow front taking up the whole cross sectional area which may cause undesirable secondary flow. The possibility of secondary flow was investigated and avoided through the correct selection of the flow rate and metal temperature. These conclusion were arrived at by using X-ray radiography, short shots, SEM and EDS techniques and the Taguchi analysis method of the X-ray radiographs. It was not necessary to use a second gate to change the filling behaviour and thereby reduce the yield of the casting. This resulted in the economics of the manufacturing process not being adversely affected.

The reduced modulus of the hour glass section solidification feeding the larger modulus top cylindrical section did not result in shrinkage porosity. This was because the die surface of the top cylindrical section was aggressively cooled locally using cooling channels cut through the die just (5mm to 8.5mm) below the die cavity surface. The flow rate and temperature of the water through the cooling channels to eliminate shrinkage porosity was 3 litres per minute and 15°C. The Die Design of SSM HPDC components must obey Chvorinov's rule. If the design does not follow the rule then external localised thermal control of the die is necessary. Solidification porosity was eliminated through directional solidification and low metal temperature. A lower metal temperature gives a better response to high internal integrity of the component since the higher fraction solid forms less solidification porosity due to a higher percent of the fluid already being solidified. These results were obtained from analysing the X-ray radiography of the planar model castings and the component castings themselves.

The die was modified by, machining the gate larger and machining overflows of a critical size and location into the die. These physical modifications improved the internal integrity of the component as evaluated using X-ray radiography techniques. The process parameter of the die temperature in localised areas was found to be critical to the internal integrity of the part. By cooling the correct area of the die at the correct rate the directional solidification was improved and specific fluid flow characteristics were achieved which together resulted in high internal integrity components. These results were obtained from analysing X-ray radiographs of the component castings.

The shear rate experienced by the SSM fluid during die cavity filling is a function of the injection velocity. The shear rate and fraction solid determines the viscosity of the SSM fluid. There is an interaction between the injection velocity and the metal temperature due to their common relationship to the viscosity of the SSM fluid. The Reynolds and Bingham [47,49] numbers of the SSM fluid determine whether the fluid is within the process window for successful cavity filling which avoids undesirable turbulence and unsteady jet flow patterns. The desired fluid flow behaviour will avoid cold shut and oxide entrapment defects. Evidence from X-ray radiographs, short shots, SEM and EDS of the planar model castings and the component castings themselves determined the injection plunger velocity. By using Taguchi experiment analysis of the X-ray radiographs the correct plunger injection velocity for the Short Arm Die was found to be $0.3ms^{-1}$.

There is an interaction between the localised cooling of the die and the SSM fluid temperature with respect to the internal integrity of the casting. When the metal temperature is 578°C the response to localised cooling of the die is stronger than when the metal temperature is 582°C. The desired result of high internal integrity castings was obtained using a metal temperature of 578°C and localised cooling of the die cavity. It appears that a lower metal temperature together with localised die cavity surface cooling will create a higher shear stress than that created by a higher metal temperature together with the same localised die cavity cooling and result in a lower viscosity giving rise to the desired cavity filling behaviour. A full investigation of this interaction is outside the scope of this work and is an area for further research.

There is another strong interaction between the metal temperature and the injection velocity with respect to the internal integrity of the casting. When a high metal injection velocity is used the internal integrity increases with respect to higher SSM fluid temperature. Where as when a slow metal injection speed is used the internal integrity decreases with respect to higher SSM fluid temperature. In this investigation it appears that the reason for the phenomenon is due to the increased shear rate experienced by a lower temperature fluid and the lower injection velocity causes the Reynolds and Bingham numbers to be in the desired range for desirable cavity filling, where as a lower metal temperature and higher injection velocity cause the Reynolds and Bingham numbers to go outside of the range for desirable cavity filling. A full investigation of this phenomenon is outside the scope of this work and is an area for further research.

The experiment method used allowed the effect of various variables (factors), which act simultaneously on the system and interact with each other, to be successfully analysed together. The optimum levels of the process parameter settings for high internal integrity Short Arm components, was predicted by the Taguchi method of analysis and design of the experiments. These predicted values were tested by two verification experiments. Both experiments yielded zero defects. Good repeatability was obtained with the process and die design determined by this investigation. The investigation designed and produced a high internal integrity SSM HPDC component through the use of a methodical process which determined the correct process and die design parameters. The investigation culminated in the manufacture of a high internal integrity component.

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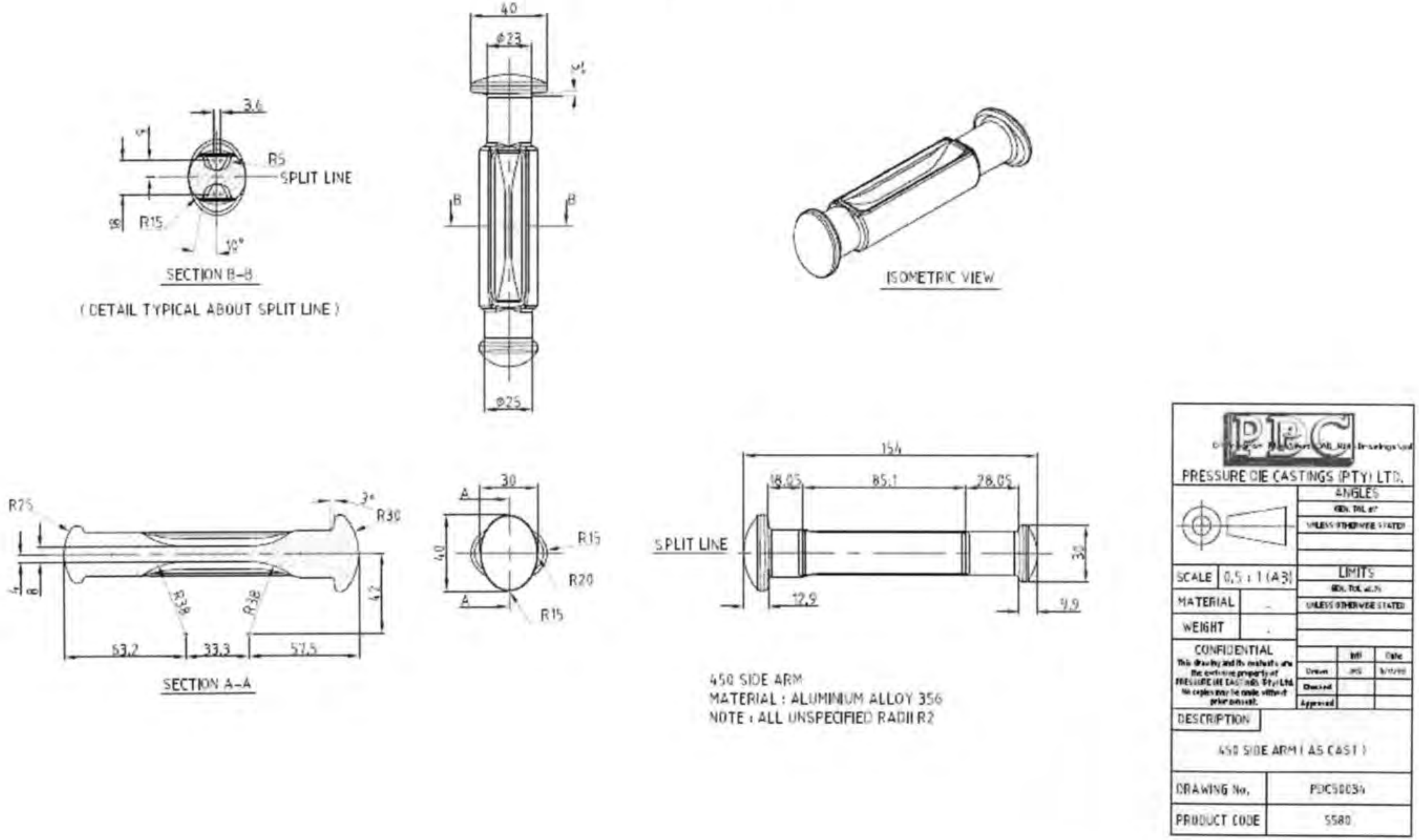
Appendix 1

Diagram A-1



Appendix 2

SUBJECT: DIE SETUP SHEET
DOC. TYPE: WORK INSTRUCTION
ISSUED BY: C. REINHARDT
APPROVED BY: M. STEPHENSON

REF NO.: PQW-C33
REV. NO.: 12
DATE: 2006/10/26
DEPT: CASTING

NB: 1) Speed point must be set to the second stage position plus 70mm so an example F1 1/2" Second stage is 220mm therefore set the speed point to 220+70 = 290mm
2) If second stage is below 100mm then the safety must be set to 10mm less than the second stage position, example 2nd stage 60 then safety circuit = 60-10 = 50mm

Die Setup Sheet compensating for slow Solenoid action

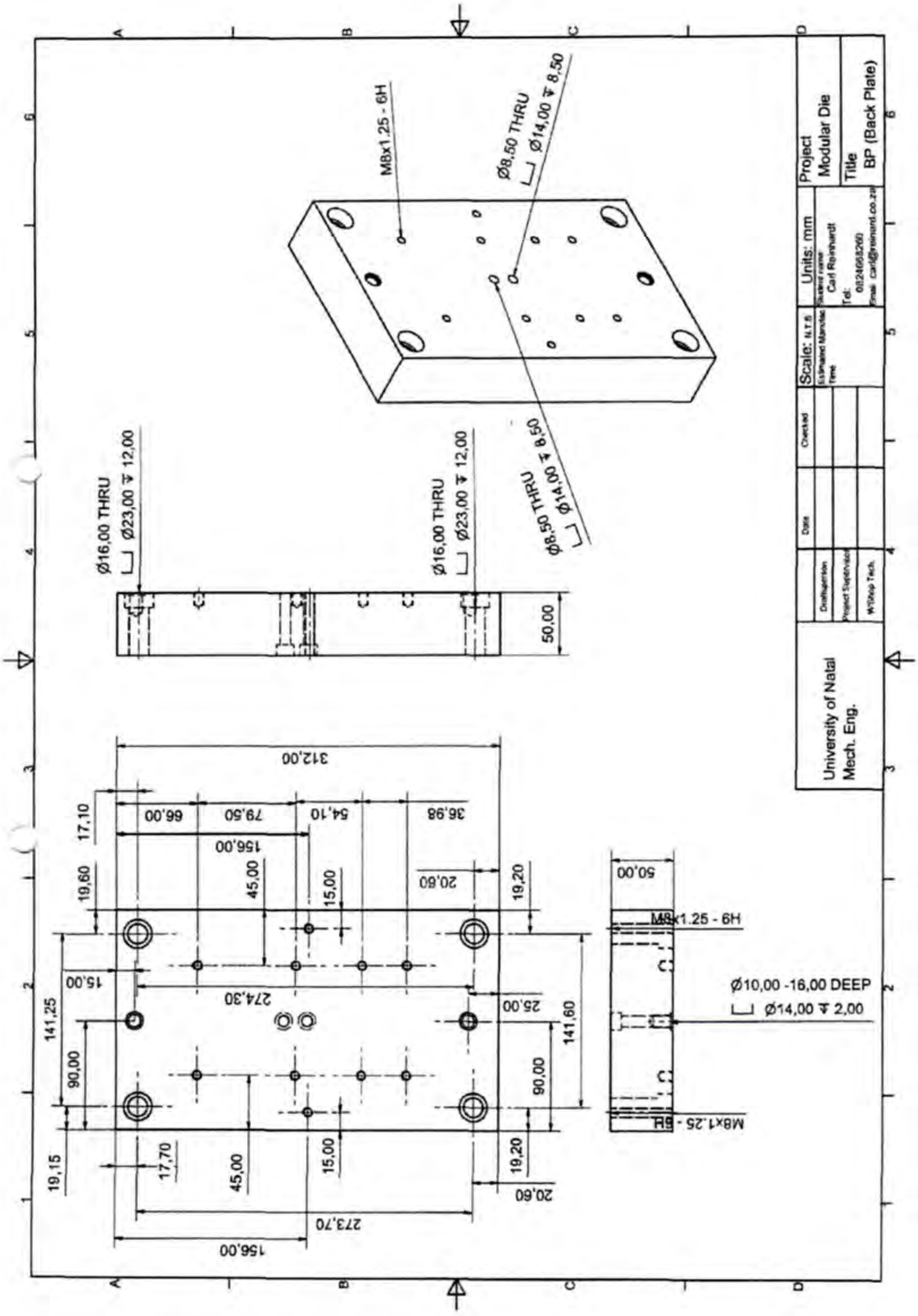
DIE SETUP DATA

		5:37			theoretical			actual		Cooling Time	Cooling Time
Die	**cavities**	**machine**	**Plunger**	**biscuit**	**Settings**	**nominal**	**upper**	**computer**	**velovisor**	**Min**	**Max**
1/2"	12	1,3, 5,7,9	**50** mm	**30** mm	2nd stage trigger 2nd stage velocity MAX intens. Pressure	**225** mm **1.5** m/s **15.9** Mpa	mm 2.6 m/s Mpa	220 mm 1.5 m/s 16 Mpa	220 mm 1.6 m/s Mpa	seconds 3	seconds 5
Die	**cavities**	**machine**	**Plunger**	**Biscuit**	**Settings**	**nominal**	**upper**	**computer**	**velovisor**	**Min**	**Max**
Reliable 4.9 modified	**12**	1,3, 5,7,9	**50** mm	**30** mm	2nd stage trigger 2nd stage velocity MAX intens. Pressure	**204** mm **1.6** m/s **15.9** Mpa	mm 2.8 m/s Mpa	215 mm 1.5 m/s 16 Mpa	200 mm 1.5 m/s Mpa	seconds 3	seconds 5
Die	**cavities**	**machine**	**plunger**	**Biscuit**	**Settings**	**nominal**	**upper**	**computer**	**velovisor**	**Min**	**Max**
Reliable 4.9 modified	**8**	1,3, 5,7,9	**50** mm	**35** mm	2nd stage trigger 2nd stage velocity MAX intens. Pressure	**245** mm **1.1** m/s **23.0** Mpa	mm 1.9 m/s Mpa	250 mm 1.5 m/s 20 Mpa	N/A mm N/A m/s N/A Mpa	seconds 3	seconds 5
Die	**cavities**	**machine**	**plunger**	**Biscuit**	**Settings**	**nominal**	**upper**	**computer**	**velovisor**	**Min**	**Max**
Long Cooling Time, *Fascor rivet body* **NO 2nd Stage Speed, Fast 1st stage only, Long Cool time**	1	10	**50** mm	**40** mm	2nd stage trigger 2nd stage velocity MAX intens. Pressure	**218** mm **0.9** m/s **56.0** Mpa	mm 1.4 m/s Mpa	mm m/s Mpa	300 mm 0.8 m/s Mpa	seconds 10	seconds 12
Die	**cavities**	**machine**	**Plunger**	**biscuit**	**settings**	**nominal**	**upper**	**computer**	**velovisor**	**Min**	**Max**
RH or LH SheerlineHandles	10	2,10	**50** Mm	**40** mm	2nd stage trigger 2nd stage velocity MAX intens. pressure	**181** mm **2.9** m/s **15** Mpa	mm 3.1 m/s Mpa	mm m/s Mpa	121 mm 2.2 m/s Mpa	seconds 4.5	seconds 6

Calculation Data for Fascor Body

		Fascor Body	**Sheerline Handles**
density of metal	g/cm3	2.7	2.7
shrinkage factor	%	5	5
no. of cavities		1	10
weight of hand	g	512	727
weight of casting (incl. O/F)	g	217	41
biscuit size	mm	40	40
cavity fill time	**ms**	**48**	**28**
plunger diameter	mm	50	50
sleeve length	mm	320	325
die split line area	cm2	97	
gate area	mm2	110	59
DCM tonnage	ton	160	160
plunger stroke	mm	315	315
plunger area	mm2	1963	1963
volume of hand (liquid)	mm3	199610	283431
volume of hand (solid)	mm3	189630	269259
volume of castings	mm3	84600	159844
Hyd. piston diameter	mm	85	85
Hyd. piston area	mm2	5675	5675
2nd stage trigger	**mm**	**218**	**181**
2nd stage velocity	**m/s**	**0.9**	**2.9**
MAX intens. pressure	**Mpa**	**56.0**	**15**
gate velocity	m/s	16.0	9.8
filling sroke	mm	43	81
intensifiation stroke	mm	5	7
end of cavity fill (liquid)	mm	270	268
Metal Pressure		1648.634724	

Appendix 3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University of Natal
Mech. Eng.
Draftsperson
Project Supervisor
W/Shop Tech.
Date
Checked
Scale: N.T.S
Estimated Manufac Time
Units: mm
Student name Carl Reinhardt
Tel: 0824665260
Email: carl@reinardt.co.za
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Modular Die
Title
BP (Back Plate)
A
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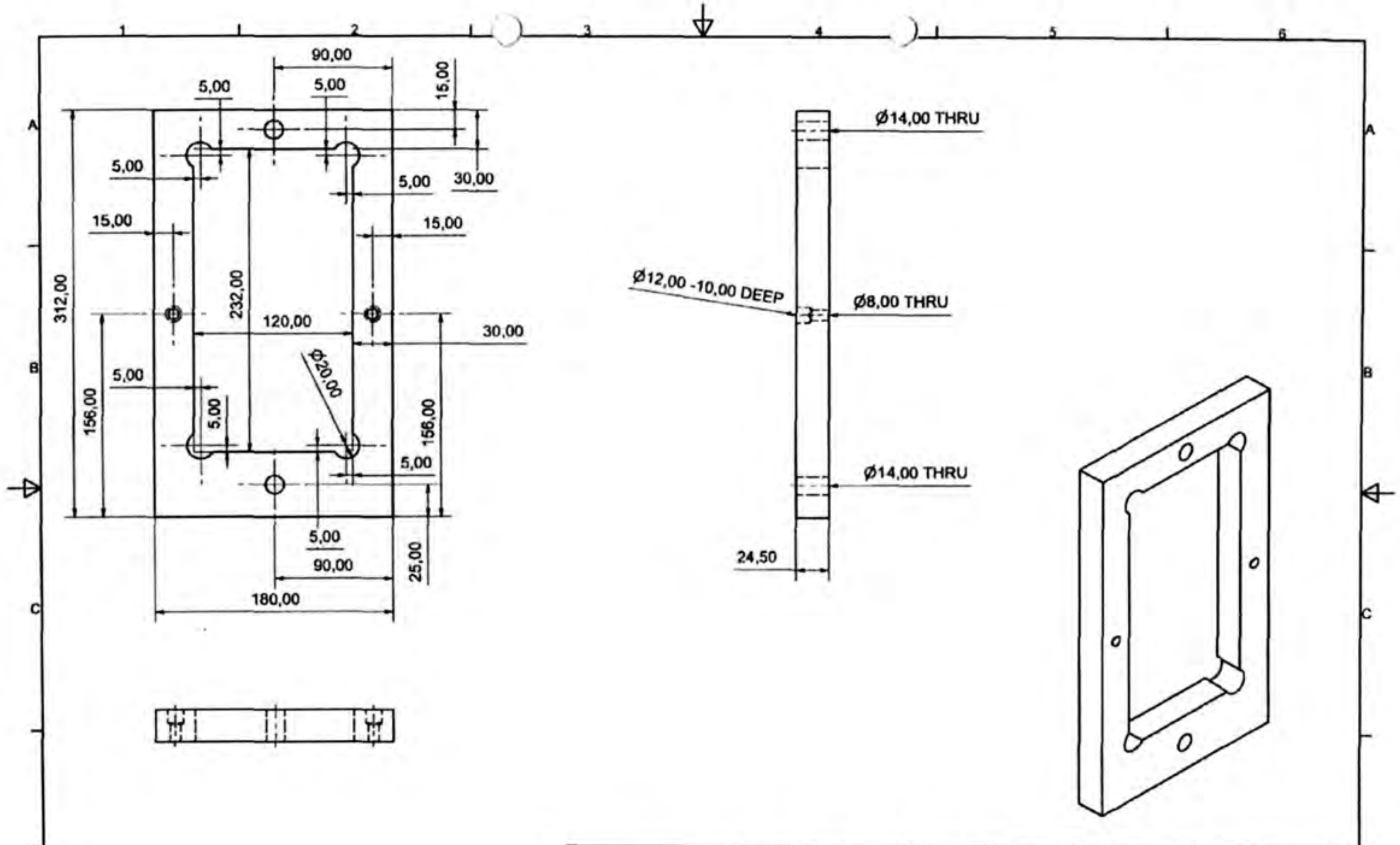

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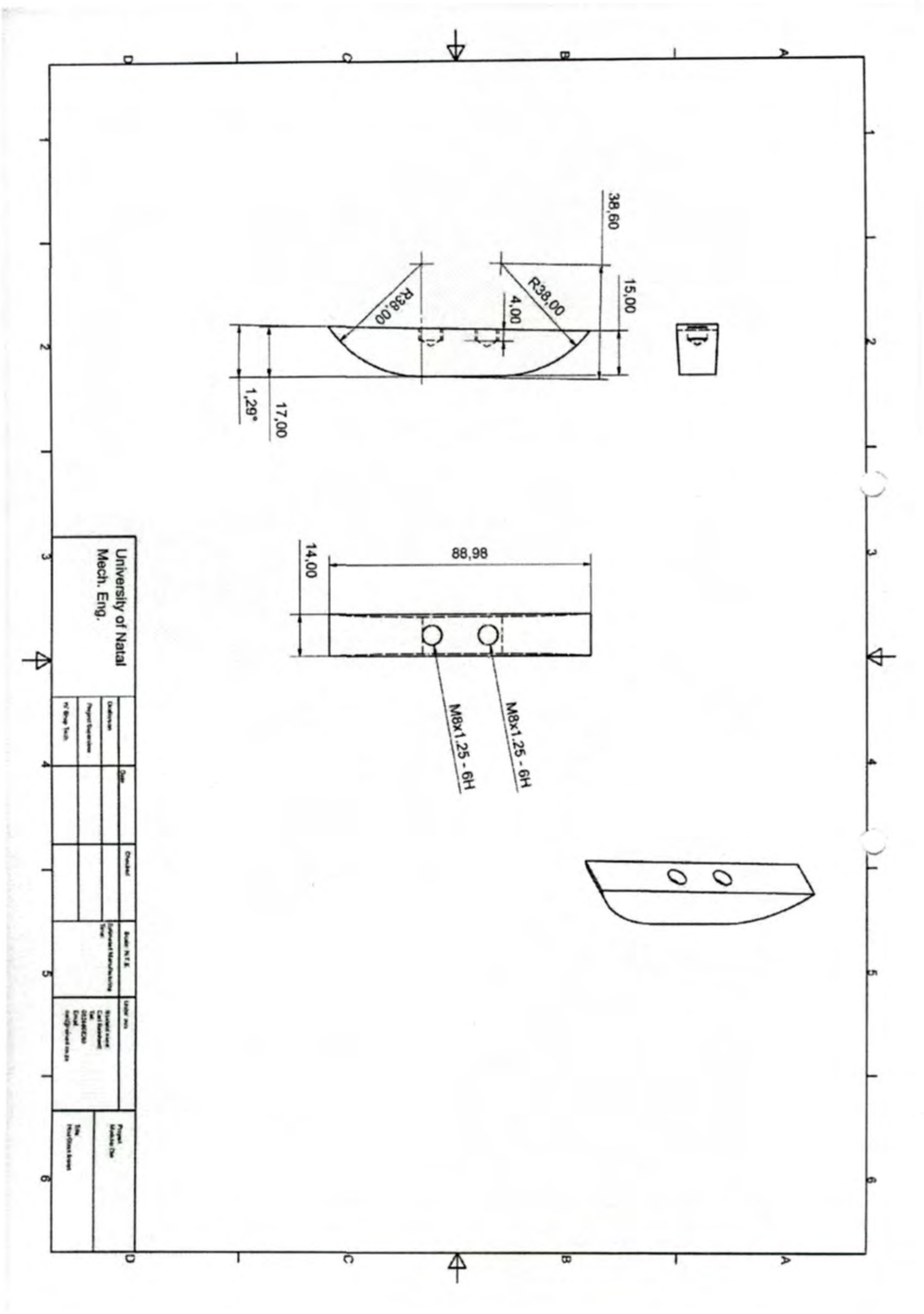
	WShop Tech.					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University of Natal
Mech. Eng.
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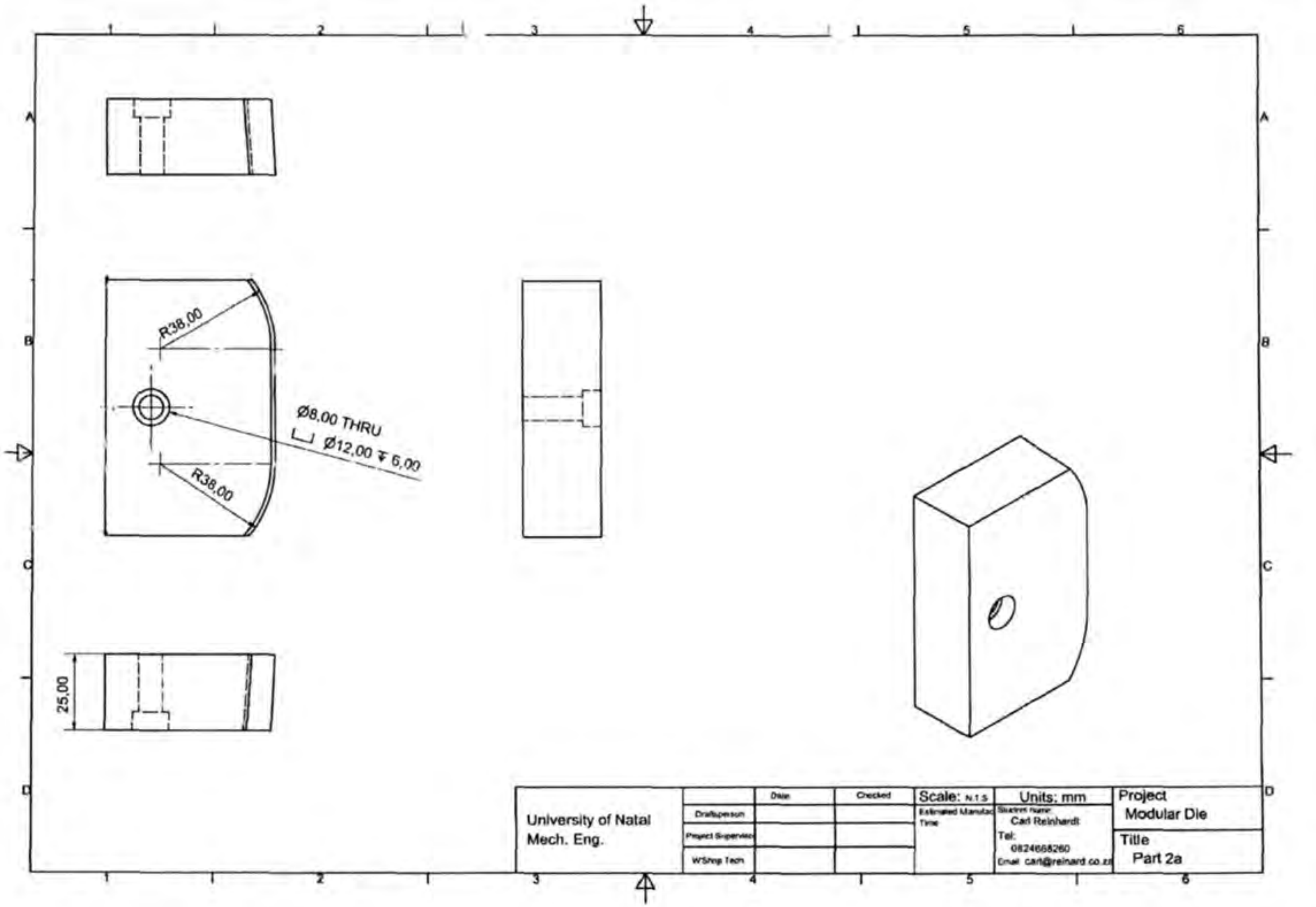

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Mech. Eng.

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Project Supervisor		
WShop Tech		

Scale: N.T.S
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Units: mm
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Carl Reinhardt
Tel:
0824668260
Email: carl@reinard.co.za

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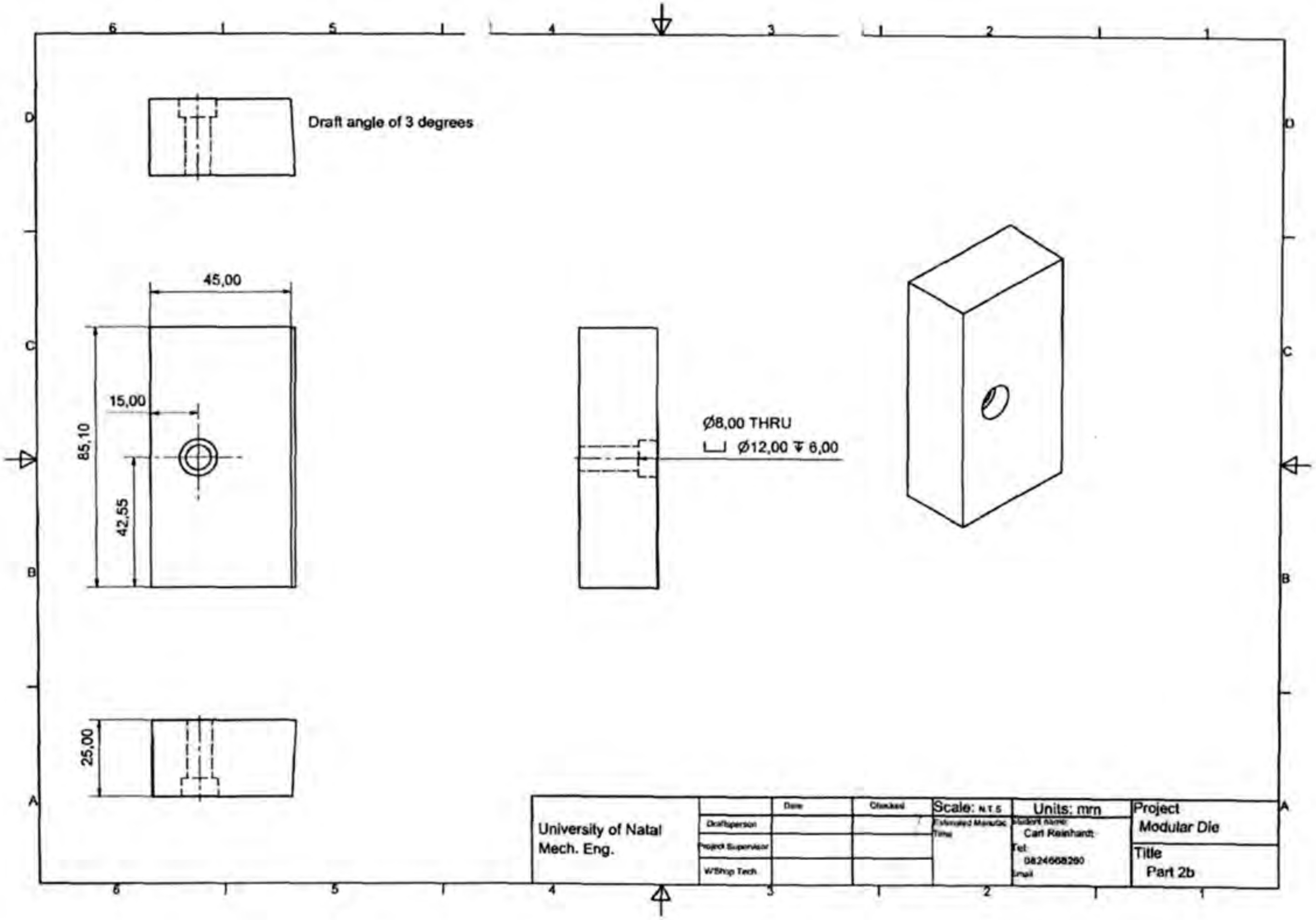
Title
Part 2a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Student Name:
Carl Reinhardt
Tel:
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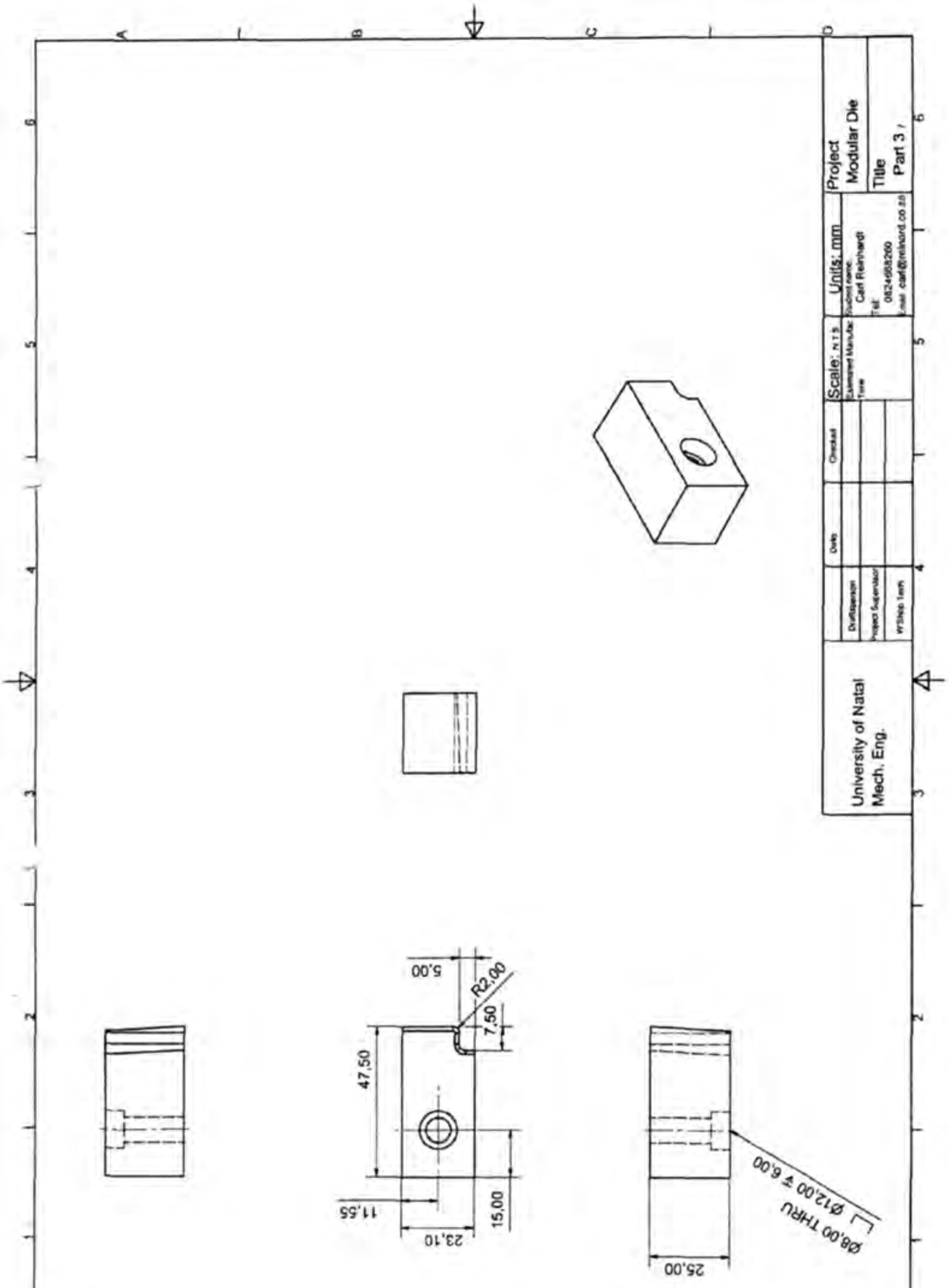
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Email: carl@reinord.co.za
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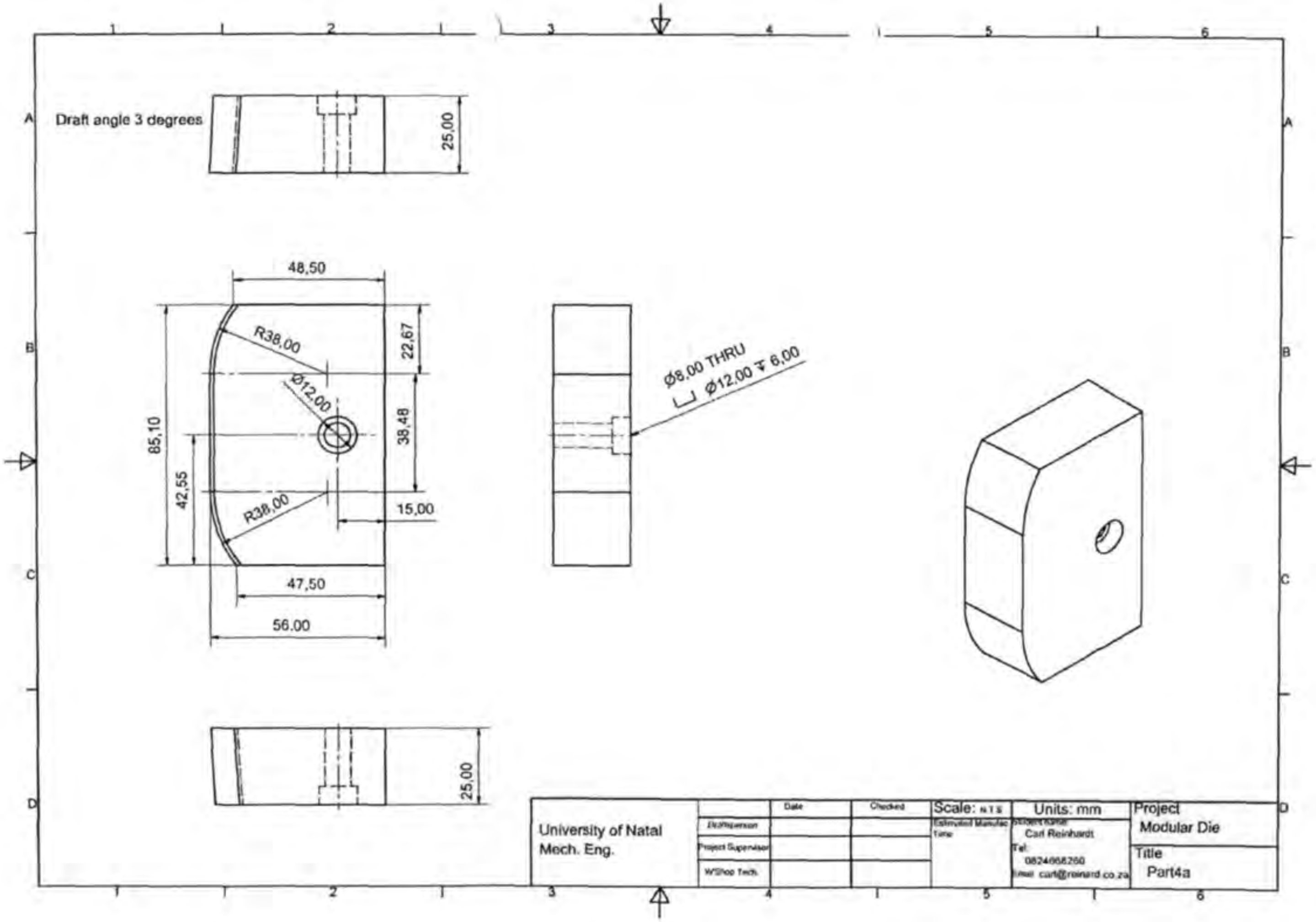
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Dr/Person
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W'Shop Tech.
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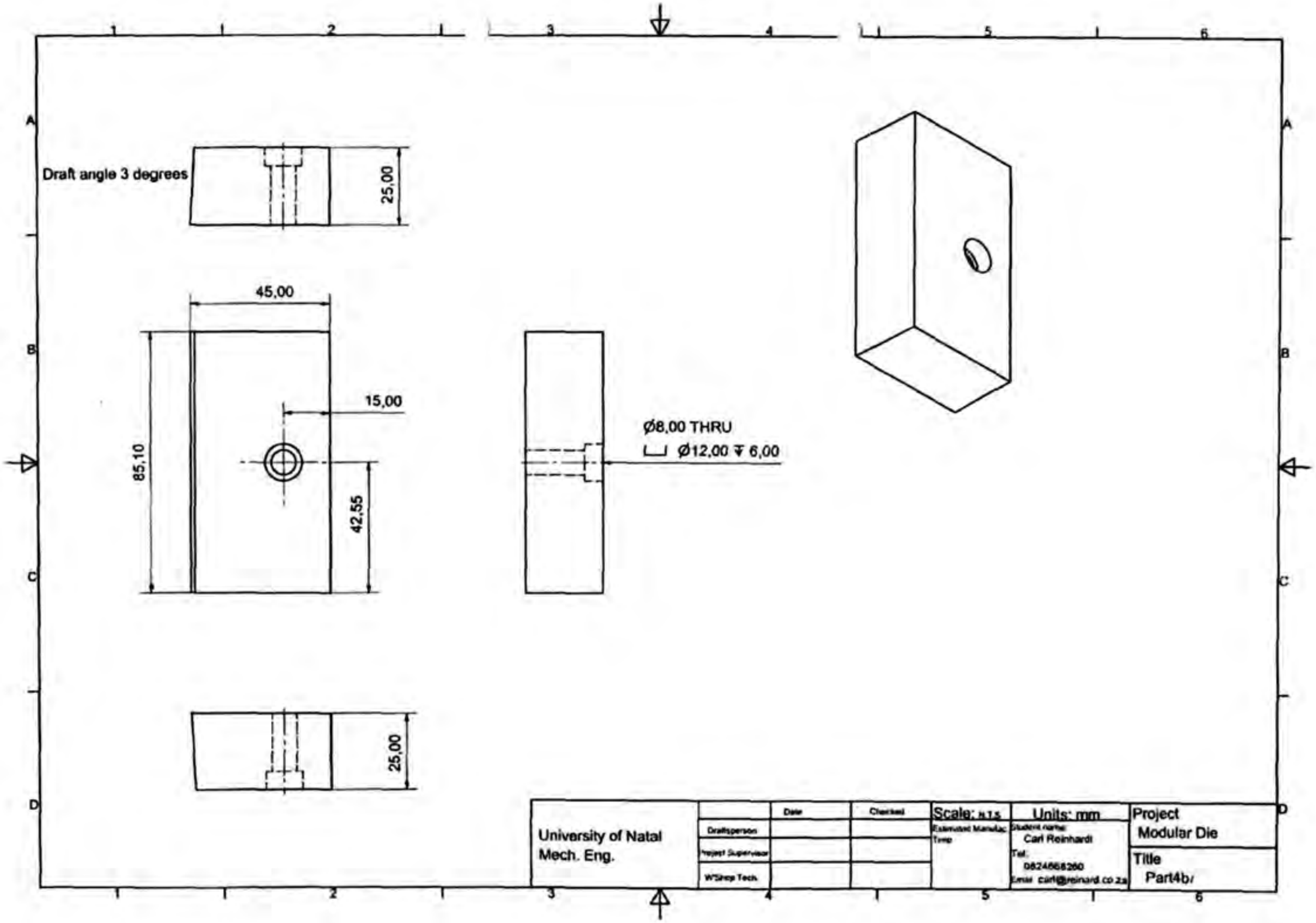
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Mech. Eng.
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Tel:
0824668260
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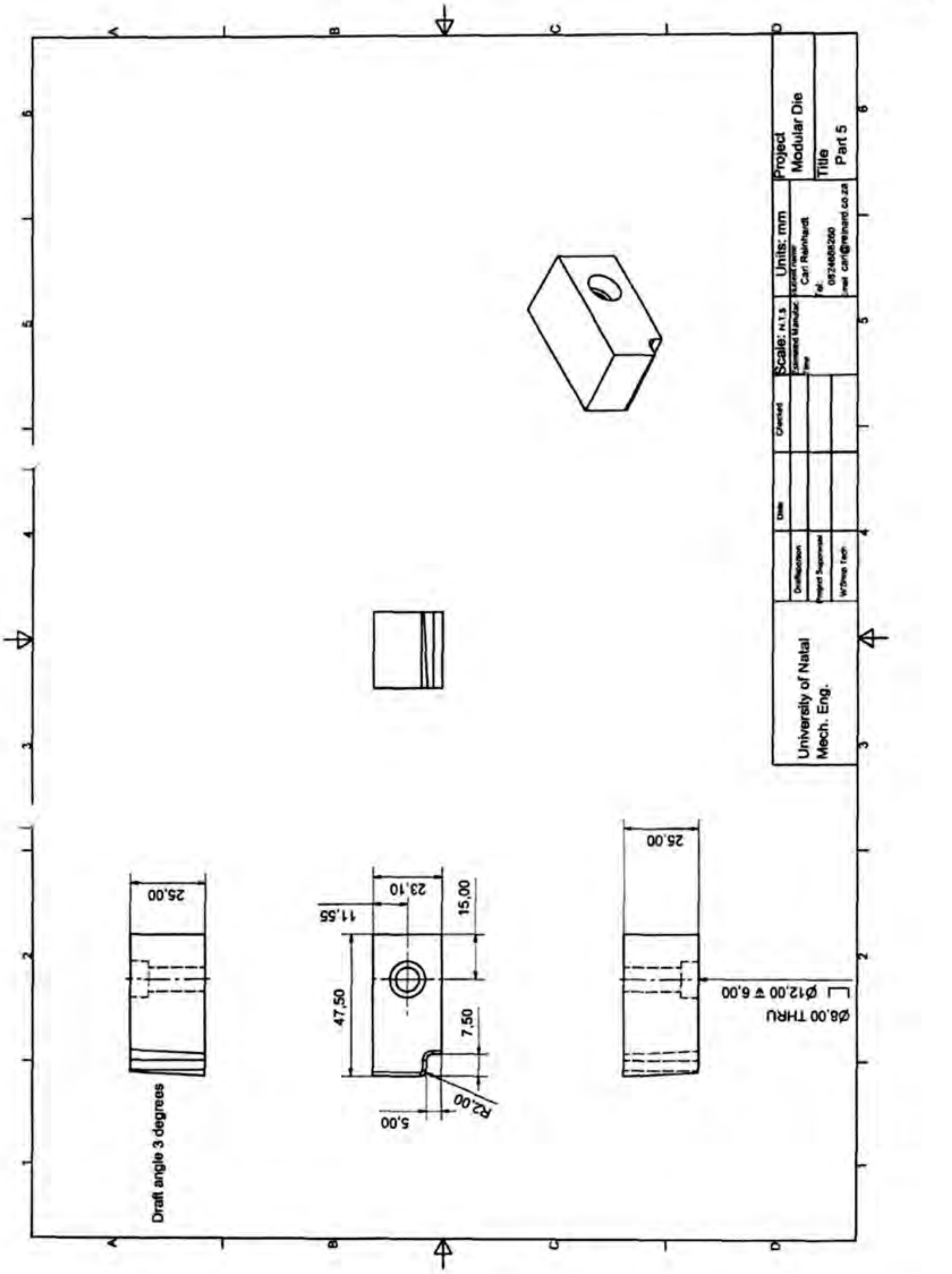
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Project Supervisor
W/Shop Tech
Date
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Carl Reinhardt
0824668260
carl@reinard.co.za
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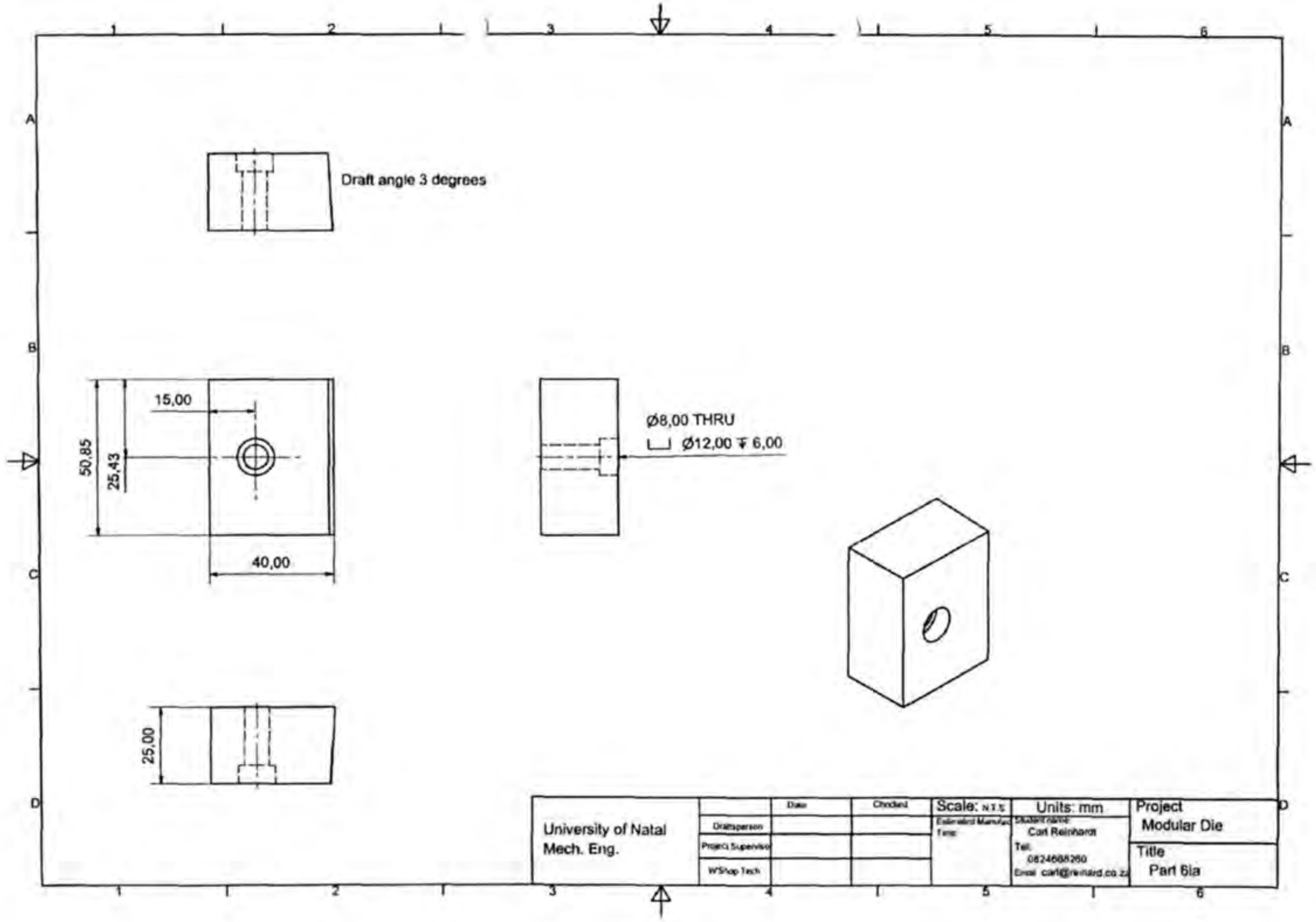
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Tel:
0824688260
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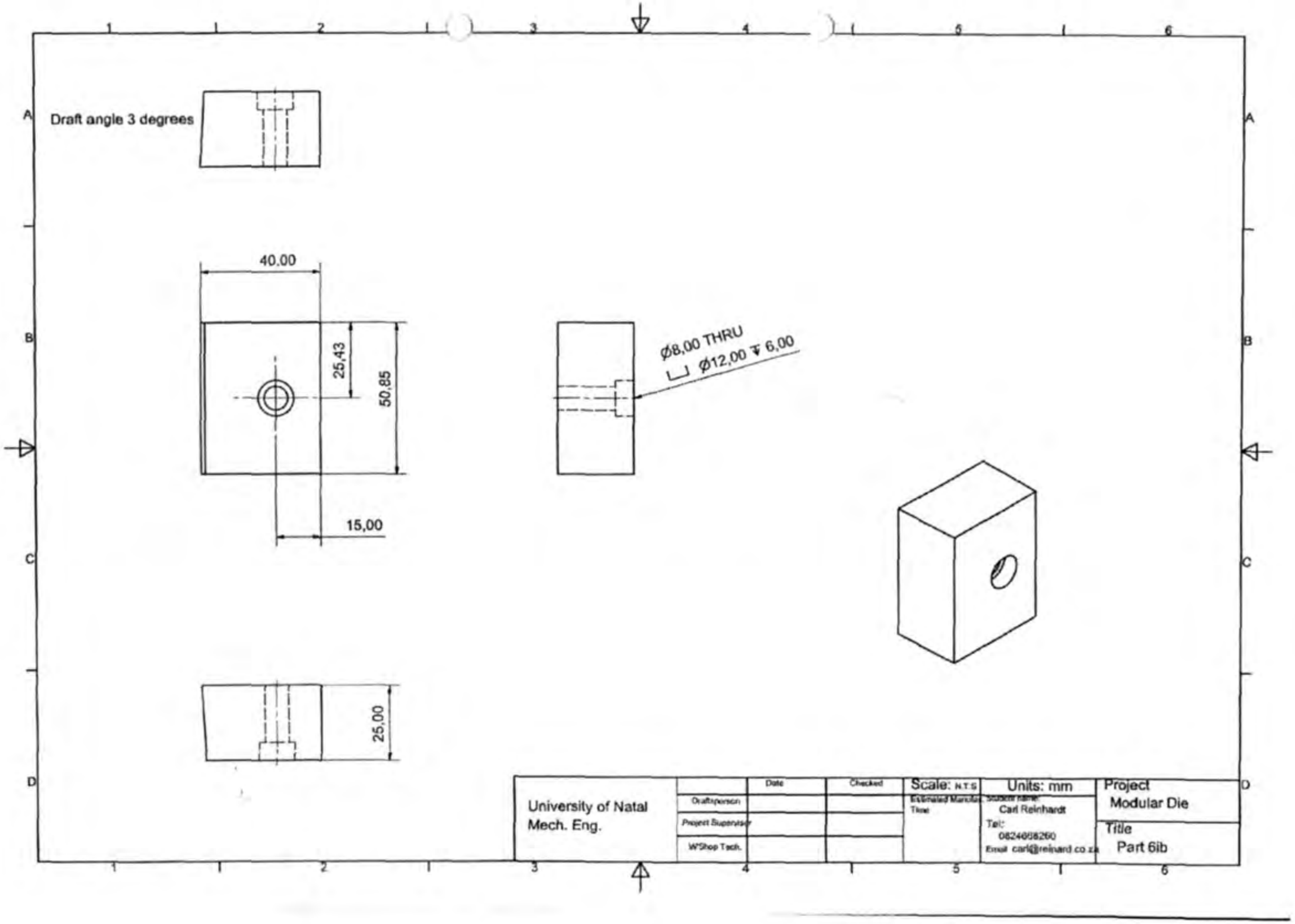
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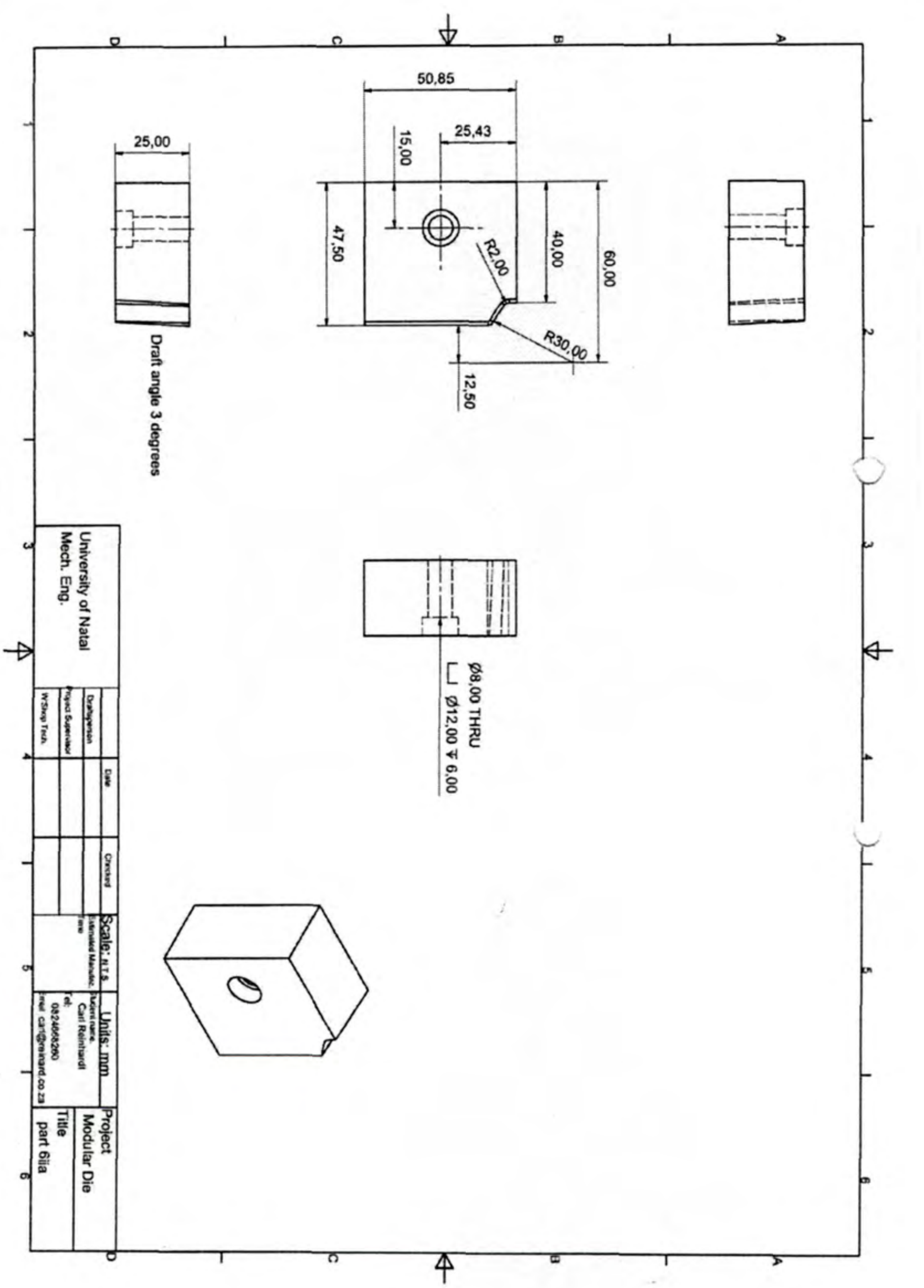
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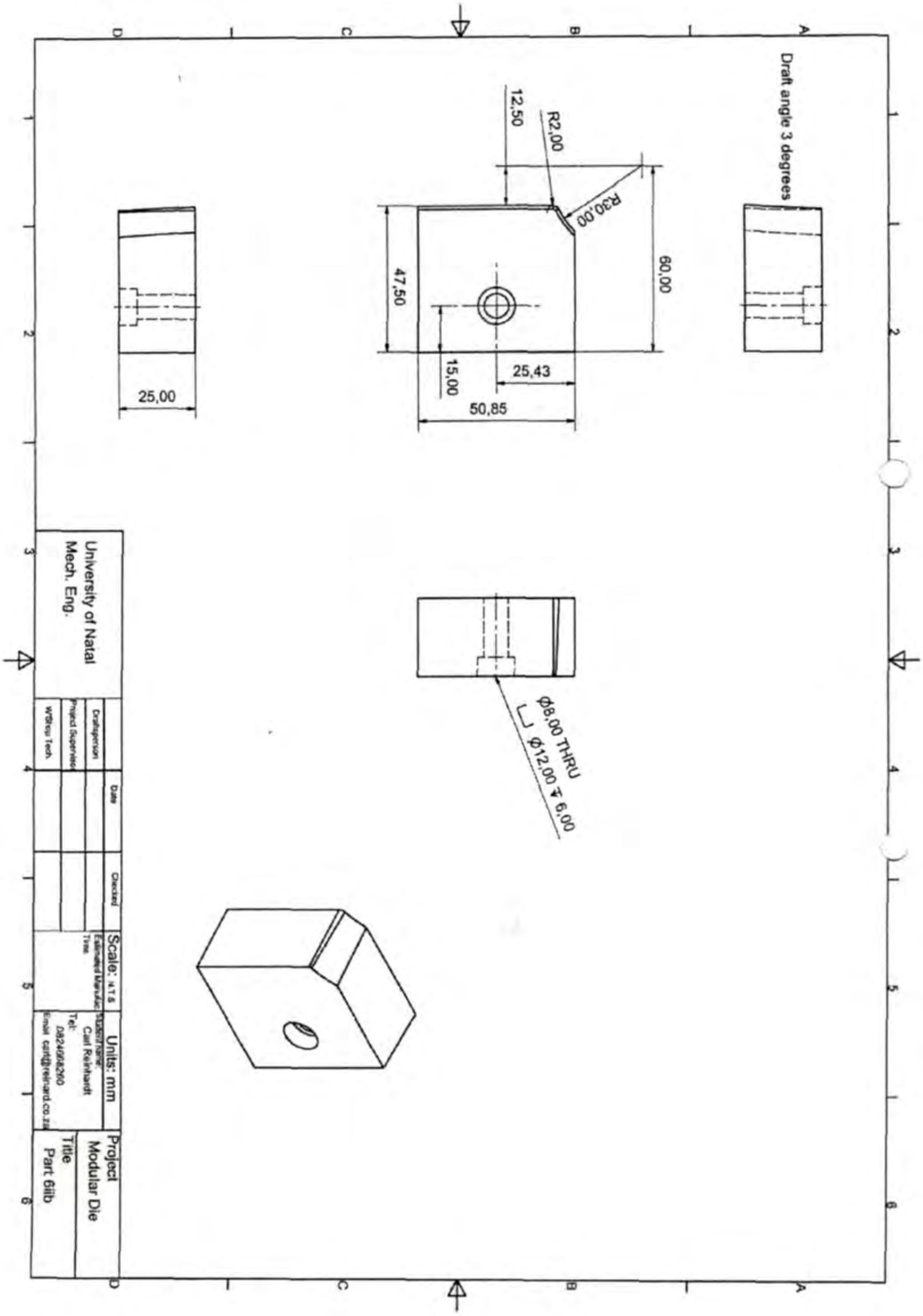Draft angle 3 degrees
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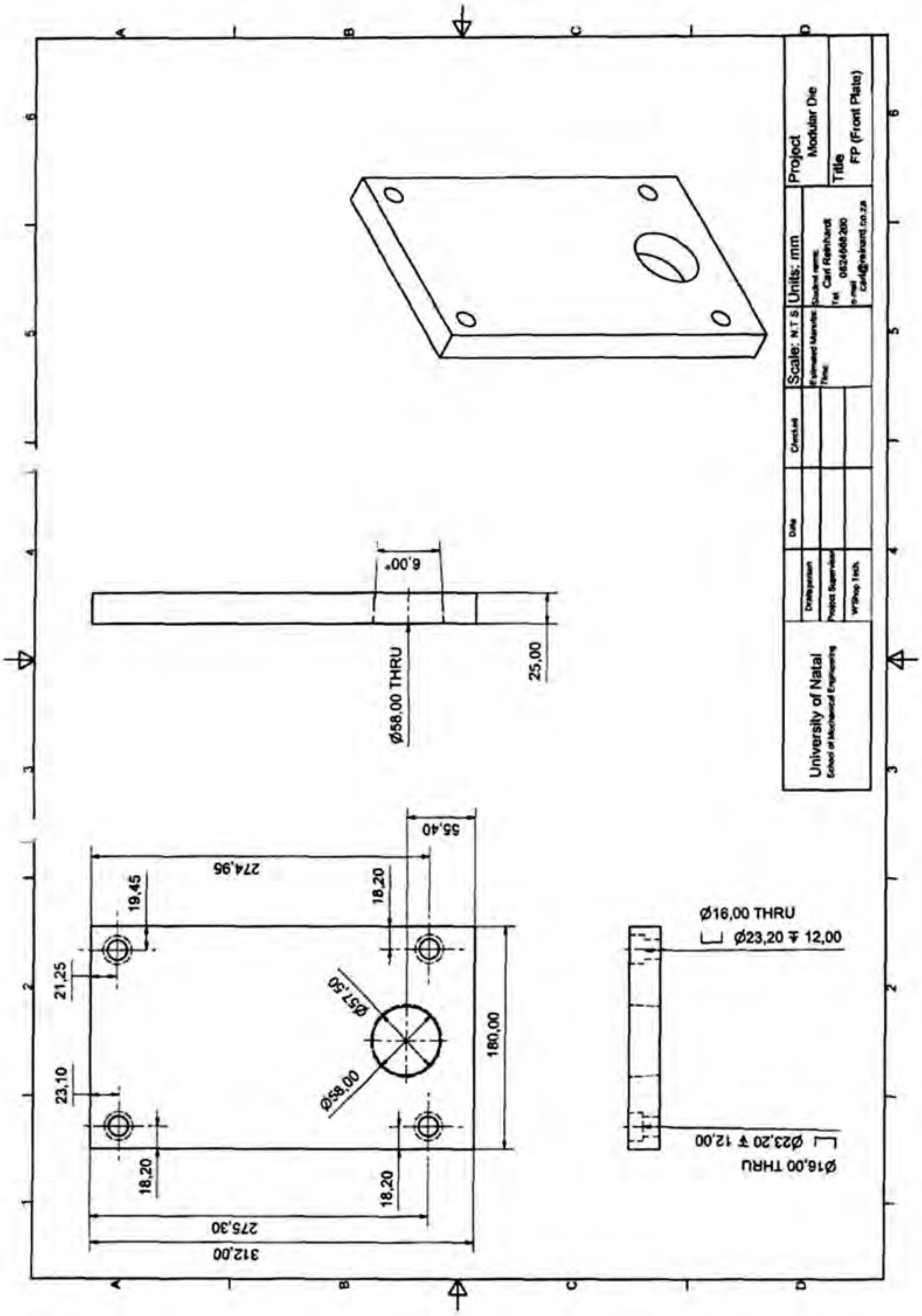
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University of Natal
School of Mechanical Engineering
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W'Shop Tech.
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Carl Reinhardt
Tel: 0824668200
e-mail: carl@reinhardt.co.za
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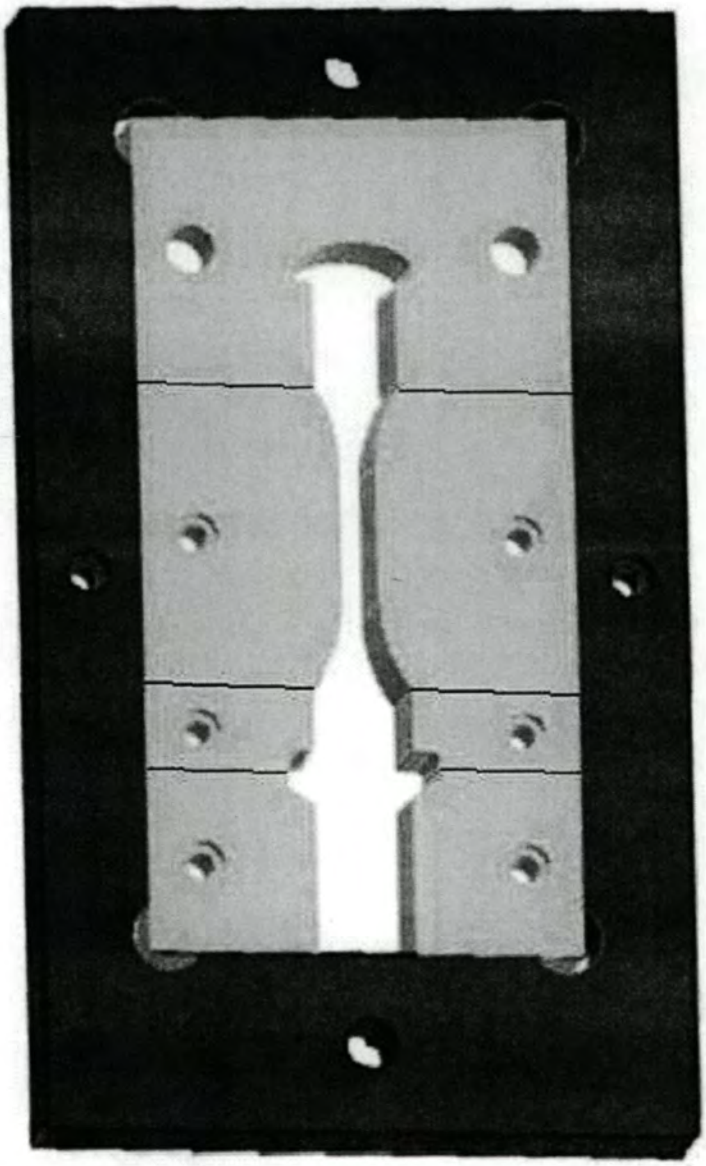

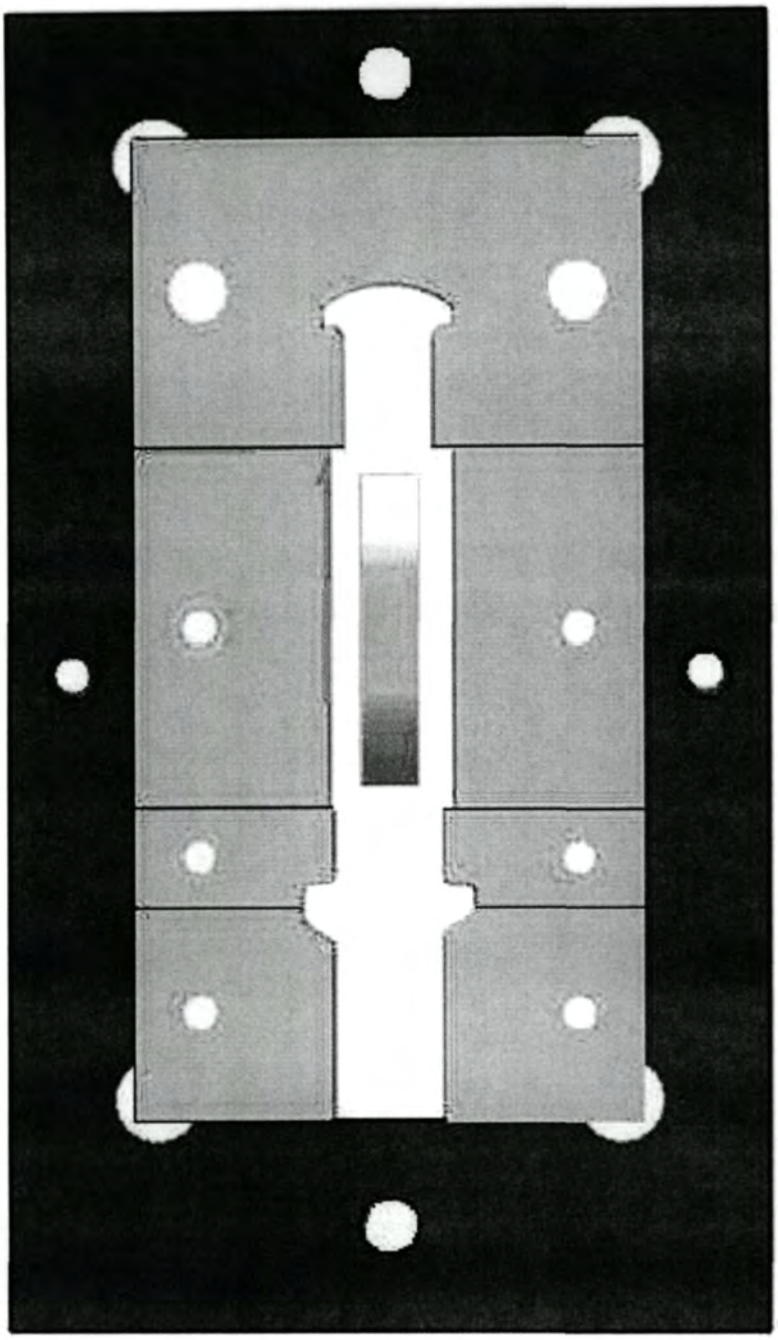

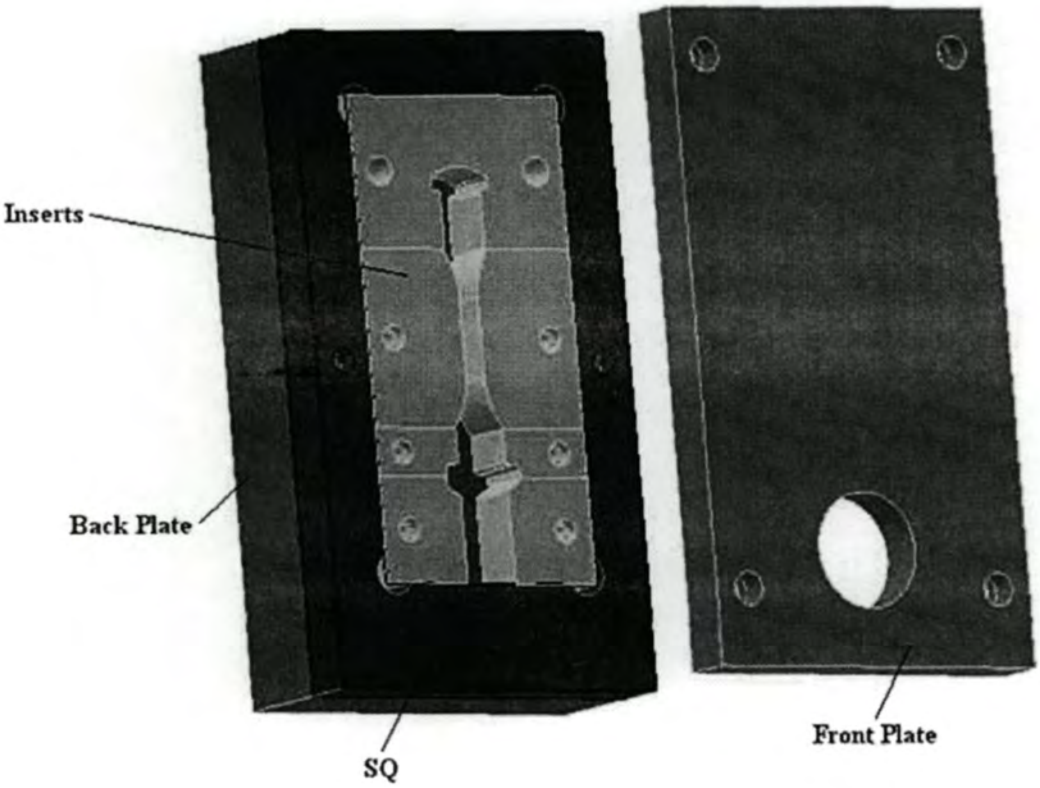
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Front Plate

Appendix 4

Paper for Japan, final.

SEMI-SOLID HIGH PRESSURE DIE CASTING OF COMPONENTS

***C Reinhardt and *G Govender**
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1 Abstract

Semi-solid Metal (SSM) forming has distinct advantages, strength, near net shape, thick and thin sections and the large scope of materials able to be cast[2,3,7]. The aim of this project is to produce a near net shape component using SSM casting in A356 primary Semi-Solid Aluminium feed stock from SAG. The selected Short Arm Component was identified as a suitable component for SSM forming[7], it is used as part of an insulated securing mechanism in overhead pylons, demands high strength and has relatively thick sections.A combination of full and short shot castings from the component and modular die were produced, on the real time shot controlled 50 ton high pressure die casting machine, at casting parameters of die temperature 250°C, Gate velocity 2.6ms-1 and a billet temperature of 580°C[4], to understand fluid flow and locate possible defects.X-ray radiography and naked eye surface observations of the castings were used to locate possible defects and irregularities which were cross sectioned and analysed using Optical microscopy and Scanning Electron Microscope with an Energy Dispersion Spectrophisy module. It was apparent from the current project and literature that increases in the die cross-sectional area reduces the shear surface area and increases the viscosity causing undesirable mould filling behaviour [1].

Keywords: SSM, near net shape, shear surface area, viscosity, high internal integrity

2 Introduction

The Short Arm Component which is used as part of an insulated securing mechanism in overhead electricity pylons, is currently manufactured out of a wrought alloy using traditional methods. The component's need for high strength, hence high internal integrity, and the relatively thick sections was the main criteria for selection of the component for research [3,7]. The loading is fatigue in nature demanding high internal integrity. A full casting of the Short Arm is shown in figure 1a. Research carried out on product and component development to date has shown the need for more than two shear surfaces [1], large gate areas [1,6], importance of directional solidification [3,5] and mould filling behaviour on internal integrity [3,5] as well as correct placement of overflows and venting [5,6]. This project will look at these topics with direct relation to the Short Arm Component this will be done as no steadfast complete robust methodology applicable to SSM component production has been formalised.

***Figure 1a:** Front View of a Casting of the Short Arm*

The aim of this project is to design a near net shape component using the semi-solid forming process, in the alloy, A356 primary Semi-Solid Aluminum feed stock from SAG. High internal integrity will be achieved by using directional solidification, reduce shrinkage porosity [5] and the placement of heating/cooling channels and overflows [6] will be predicted to enhance solidification, remove unwanted impurities and create different flow paths to achieve optimal mould filling behaviour by using the results found from the research.

3 Experimental Procedure

3.1 Criteria for Component Selection

The component's need for high strength, relatively thick sections and changing cross sectional area was the main criteria for selection of the component for research [3,7]. The loading is fatigue in nature demanding high internal integrity. The selection process involved looking at many candidate components. Using the methodology and rating system set out by NADCA [7] a comparison could be made between the various casting processes to evaluate components most suited to the SSM casting process. Two products were identified, both had thick sections and high strength requirements. The Short Arm was chosen above the second component due to its geometry having a changing cross sectional area, the changing cross sectional area of interest is the middle "hour glass" section seen in Figure 1a, which would provide opportunity for research.

3.2 Die Design

A conventional die and a modular die was designed and manufactured. The first has venting but no overflows and has a wide gate to aid directional solidification. The orientation of the component was selected to aid directional solidification and optimise the flow path to obtain high internal integrity, Figure 1a shows an as cast component and Figure 1b is a two dimensional drawing of one die half of the conventional die.

The component is symmetrical about two axes thus it was possible to break the component down into two, "two dimensional" planar models. The planar models have a constant thickness and only the cross sectional area is changed through the cavity to give the equivalent volume of the casting at each section hence the equivalent flow rate of the fluid. These planar models enabled the flow behaviour to be isolated to a particular plane. A modular die was designed with inserts. The inserts are interchangeable and allow both planar models to be built in the modular die. The small inserts are also easily machinable (made from mild steel) and hence can be easily modified to create different geometry as needed. Figure 2 shows the modular die with inserts.

3.3 Casting Procedure and Analysis Techniques

A short shot and ten full castings were performed using the convnetional die. The castings were all done at 0.6m/s plunger speed, 50mm diameter plunger, billet temperature 580°C and die temperature of 250°C [4].] X-ray radiography was performed on the full castings and defect locations were noted. The casting was then sectioned appropriately to analyse the defects using optical microscopes and a Scanning Electron Microscope (SEM) with an Energy Dispersion Spectrophisy Module (EDS).

Using the Modular die, six short shots were performed of one planar model at varying degrees of filling percentage, 20%, 30%, 35%, 45%, 50% and 80%. The percentages were decided upon due to the cross sectional changes which correspond to them. The short shots were done at the same process parameters mentioned for the conventional die above[4]. The short shots form a complete set for all the diverging and converging sections. Three full shots were performed. The experiments presented for this paper are for one model plane only.

The locations of possible cold shuts could be determined by analyzing the short shots, where secondary fluid flow occurs. The full shots were then analysed using X-Ray radiography to aid in the locating of internal defects in the casting, special attention was paid to the potential cold shut areas. The full shots were then sectioned in the hence selected areas. Analyses was then done on these samples using both optical microscopes and the SEM with EDS module which was used to monitor the levels of each element. The optical microscope was used to identify porosity and visible cracks, due to hot tearing and or cold shuts [8]. The results from the SEM EDS module was used to analyse the level of oxygen present which would indicate oxides, a sharp increase would indicate a cold shut. Using this process the full shots were analysed to indentify and study internal defects.

***Figure 1b**: Conventional Die, Back Half*

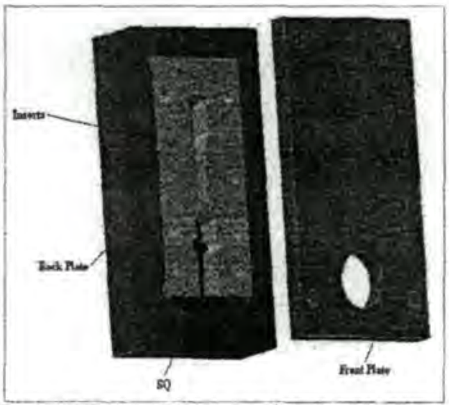

***Figure 2:** Isometric Diagram of the Modular Die*

4 Results and Discussion

4.1 Conventional Die Results and Discussion

The coventional Short Arm die produced a near net shape product which had good surface finish (figure 1) and low macro-porosity. Micro-porosity was detected in the top cylindrical section, this porosity was jagged in shape and hence was determined as shrinkage porosity. Thus directional solidification was not occurring in this area, further experiment with the modular die would show that this shrinkage porosity was caused by the narrowing of the cross sectional area in the centre, hour glass section of the casting. The short shot showed secondary flow and different flow fronts meeting. Secondary flow is defined as when a cavity partly fills and then the fluid, from a different flow front, passes over the metal surface of the partially filled cavity. Since there is a time delay between the two surfaces meeting there is a possibility of the original surface forming an oxide layer which will prevent homogeneous amalgamation of the two metal surfaces and hence a cold shut. By examining the ten full castings and the one short shot of the Short Arm the filling flow pattern was established.

Figure 3 shows the short shot of the Short Arm , the various flow fronts can be clearly seen. The flow separates when the hour glass obstruction is met. After the obstruction the flow fronts meet again. From examining the flow fronts it was postulated that there will be two cold shuts on either side of the upper cylinder section of the Short Arm.

***Figure 3** Short Shot of the Short Arm*

The X-ray radiographs of the full casting showed a crack in the upper cylindrical section of the Short Arm casting, figure 4. This crack is in the top left hand side. The reason for only one visible crack couldbe due to two reasons, firstly a distict line will only show up on the radiograph if there is also porosity along the cold shut. This often (but not always) takes place due to solidification shrinkage placing stress on the component and causing it to pull apart at the weakest point, in this case a cold shut where the metal did not fuse completely due to a layer of oxide. This process is known as hot tearing[8]. The second reason could be that the original cold shut on the right was pushed out of position and entrained during final filling and dispersed.

By Sectioning the component and using the EDS module of SEM it was possible to scan the cross section for sharp increases in oxide content. There was a sharp increase in oxide content on the side of the crack as anticipated (figure 5a & 5b), showing that the crack was formed due to a cold shut, here silicon oxide formed, scans at different regions of the same crack showed aluminium oxides to be present. Scanning the rest of the cross section gave rise to no sharp increases in oxide content, hinting at the fact that the oxide had been dispersed through out the component during final filling.

4.2 Modular Die Results and Discussion

The exact flow behaviour was picked up from the short shots of the planar model of the component. The short shots are shown in figure 6. Let us number the six short shots in figure 6 from left to right, left most as number one. In short shot number 6 (right most) the SSM fluid had already passed the bottom end cap diverging section, but did not fill it. Only once the fluid undergoes a constricting section change, short shot number 5, where an increase in internal fluid pressure takes place, at the start of the hour glass section, does the end cap begin to fill. The end cap fills uniformly from the main centre shaft by expanding outwards as a plug like flow front which travels at ninety degrees to the main centre shaft and is the size of the end cap cavity. The flow front fills each end cap uniformly extending from the bottom of the end cap cavity to the top. The next area of interest is at the top of the hour glass constriction where the profile diverges to form the top cylinder. Here again the fluid does not fill the diverged cavity until it is subjected to an increase in pressure, this can be seen by comparing short shot castings 1 and 2 (left most). As the flow front leave the hour glass constriction there are only two shear faces acting on it, thus the viscosity increases and the flow is seen to be paste like, undesirable filling takes place. Only once the fluid flow front, which is the width of the hour glass restriction, comes into contact with the top of the die cavity, and can no longer flow upwards, does the diverged cavity begin to fill. The cavity begins to fill from the bottom of the cavity upwards. The fluid flows up the hour glass restriction and then is confronted with the static fluid, which is still the width of the hour glass restriction but has an empty cavity on either side of the static fluid.

Figure 4

Figure 5a

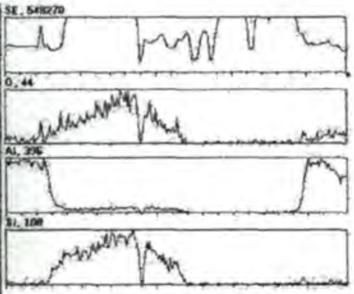

Figure 5b

X-Ray Radiograph of upper cylinder section showing crack on left the hand side.
SEM Electrograph with black line showing direction of EDS line scan, scale insert is 200μm
SEM EDS line scan result, SE Intensity, O Oxygen, Al Aluminium, Si Silicon

It was postulated that the fluid breaks the surface tension at the bottom of the diverging section and then travels upwards on either side of the static fluid. This could form a cold shut on either side of the static fluid where the "new" fluid flowed past on either side of the static fluid. The alternative was that the flow expanded from the static fluid outwards at ninety degrees starting from the bottom first and then expanding higher up as pressure built in the higher sections.

Figure 6

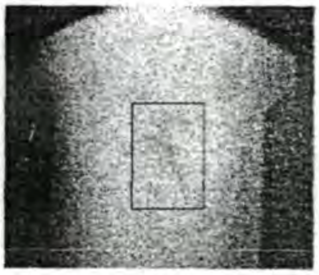

Figure 7

The Complete Set of Short Shots for each Diverging and Converging Section.
Copy of Radiograph, showing internal of top cylinder section of the Modular Die (full shot).

Investigation was carried out to ascertain the validity of the postulate. The cross section area where the flow is suspected to flow over either side of the static fluid was checked for cold shuts. First X-ray radiographs were taken of the full shot. The radiograph was examined and no visible cold shuts were seen in figure 7. Eventhough there was porosity (boxed) in the top cylindrical section, which increases shrinkage solidification stresses [8]. The EDS module of the SEM microscope then found no sharp increases in oxide content across the cross section. Given the decreased neck size of the hourglass and hence the increased tendency of hot tearing to occur (as discussed above) [5,8], this further suggests that no cold shuts are present. Hence the SSM fluid does not produce secondary flow in this area. When the fluid met the top of the die the new fluid was forced to flow towards to the side walls. As contact was made a new shear face acts on the fluid which decreases the viscosity and the fluid begins to fill the cavity in a desired manner [1].

5 Conclusion

In this model no overflows are necessary to remove the impurites caused by a possible cold shut, since no evidence of a cold shut occurred in this plane. The fluid path is acceptable to high internal integrity in this planar model. Directional solidification is not able to occur due to the thin cross section of the hour glass section. This will be compared with the second planar model, the second planar model has a larger cross sectional hour glass area. According to this model there will be cooling and hence cooling channels required next to the upper cylinder to induce earlier cooling before solidification of the hour glass neck so as to eliminate shrinkage porosity.

The research dictates to produce high integrity casting, three or more shear surfaces must be in contact with the fluid. This is not the case when fluid flows into an abrupt diverging section. Final placement of overflows and cooling/heating channels will be determined by results from the second planar model. For Directional solidification to occur, the ratio of the surface area in contact with the die surface and the volume of cast metal[8], must increase from the biscuit to the end points of the casting.

6 References

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