Cost Model for Bipolar Plate Manufacture

by

Juan Pablo Atkinson

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Supervisor: Prof Anton Basson

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DECLARATION

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Abstract

This thesis gives a cost model for the manufacture of bipolar plates in South Africa. The methods for the manufacture considered are machining, using a micro-milling machine, and compression moulding. The focus of this thesis is on compression moulding. Details of the work done towards developing and validating the models are described, and then the cost models are discussed in detail. The results of the analysis done using the cost model is given with attention paid to the effect of changing design parameters, such as channel size and flow field area, and of the cost of production for both methods over various production volumes.

The thesis concludes that compression moulding becomes the better option for production volumes greater than 324 bipolar plates, with a cost that eventually reaches close to R140 per plate for high enough production volumes (over 5000). The cost to produce 1000 plates using compression moulding is estimated at R294 per plate. An increase of the channel size gives a small reduction in the total cost, while the increase in cost with an increase in flow field area is large.

Uittreksel

Hierdie tesis gee 'n koste-model vir die vervaardiging van bipolêre plate in Suid-Afrika. Die vervaardigingsmetodes wat oorweeg word, is masjinering deur 'n mikro-freesmasjien en persvorming. Die fokus van hierdie tesis is op persvorming. Die besonderhede van die ontwikkeling en validering van die modelle word beskryf, en daarna word die modelle in besonderhede beskryf. Die resultate van 'n analise wat met die koste-model gedoen is, word daarna gegee, met die oorweging van die verandering van ontwerp-parameters soos die vloeikanaalgrootte en vloeiveld-area, en van die koste van vervaardiging vir beide metodes vir verskeie produksievolumes.

Die tesis kom tot die slotsom dat persvorming die voorkeurproses is vir produksievolumes groter as 324 bipolêre plate, met 'n koste wat tot naastenby R140 per plaat daal vir hoë produksievolumes (meer as 5000). Die koste om 1000 plate met persvorming te maak, word op R294 per plaat beraam. 'n Toename in kanaalgrootte gee 'n klein vermindering in die totale koste, terwyl die toename in koste groot is wanneer die vloeiveld-area toeneem.

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Nomenclature

A_c	Mould base cavity plate projected area
A_{ch}	Projected area of channels
A_{ff}	Area of flow field
ACR	Annual capital recovery
AP_{mach}	Annual production per micro-milling machine
B	Batch size
C	Taylor tool life constant
C_b	Mould base cost
C_{cavity}	Cavity material cost
C_{core}	Core material cost
$C_{Equipment}$	Cost of micro-milling equipment
C_{Import}	Import cost per plate, including VAT
C_i	Cost of material ingredient for one part
C_{Labour}	Labour cost
C_M	Cost per unit mass of Bohler M201
$C_{Major\ Tool}$	Cost of one tool for major channel machining on micro-milling machine
$C_{Major\ Tooling}$	Cost of all tools for major channel machining on micro-milling machine
$C_{Material}$	Total material cost including VAT from Schunk
$C_{Minor\ Tool}$	Cost of one tool for minor channel machining on micro-milling machine
$C_{Minor\ Tooling}$	Cost of all tools for minor channel machining on micro-milling machine
C_{mi}	Cost per unit mass of specific ingredient
$C_{Overheads}$	Cost of overheads
$C_{Periph\ Tool}$	Cost of one tool for peripheral machining on micro-milling machine

$C_{Periph\ Tooling}$	Cost of all tools for peripheral machining on micro-milling machine
C_{Plate}	Cost per blank plate, including VAT
$C_{Tooling}$	Total cost of all micro-milling machine tools
D	Tool diameter
d	Axial depth of cut
D^{*}	Adjusted tool diameter
D_{minor}	Tool diameter for machining minor channels
d_{minor}	Axial depth of cut for machining minor channels
F_A	Area scaling factor
F_L	Feed rate for lace cutting
F_R	Machining feed rate
F_{Rec}	Tool manufacturers recommended feed rate for specific tool size
F_0	ANOVA test statistic
f_t	Feed per tooth
FR_{periph}	Feed rate for machining peripheral features on micro-milling machine
h_p	Mould base cavity plate thickness
HR	Hourly rate of workshop, including all overheads
L_{BP}	Length of bipolar plate
L_{ch}	Total length of channels
L_{ch_major}	Total length of major channels
L_{ch_minor}	Total length of minor channels
$L_{outline}$	Length of the outline of the bipolar plate
L_P	Cutting length of peripheral features
L_{periph}	Length of the peripheral features
L^{*}_T	Adjusted tool life
L_T	Tool life for micro tools

L_{Taylor}	Taylor's tool life
l_c	Length from start of channel radius to middle of channel
l_s	Space left from edge of bipolar plate to side of insert
LR	Hourly labour rate for micro-milling
m_{tot}	Total material mass for one part
m_i	Mass of one ingredient for one part
MS_E	Error mean square
MS_R	Regression mean square
N	Number of plates machined at a time
n	Taylor tool life constant
N_c	Number of passes needed with one tool size
N_{mach}	Number of micro-milling machines used
$N_{mach/worker}$	Number of micro-milling machines operated by one worker
N_{pins}	Number of ejector pins
N_{tools}	Number of tools used of one size
n_{ch}	Number of channels on flow field
n_F	Number of points in the factorial part of the CCD
n_s	Number of sides with channels
P_{ch}	Proportion of flow field area taken up by channels
r_c	Radius of channel corner
r_i	Ratio of ingredient to total mass of one part
r_t	Radius of tool
T_{CM}	Channel machining time (micro-milling machine)
T_{close}	Time taken for mould halves to close
T_{comp}	Time taken to compress material in mould
T_{cure}	Time to cure thermoset
T_{ep}	Machining time of hole for ejector pin

T_{fix}	Time to fix blank plate to machining table
T_{flash}	Time to remove flash from moulded part
T_{flip}	Time to flip plate
T_{ins}	Time to inspect bipolar plate for faults
T_{Lace}	Time for channel lace machining of mould for one tool size
T_{mach}	Machining time for one tool size
T_{mix}	Total time to prepare material for moulding
T_{mould}	Time to mould one plate
T_{mp}	Total time to manufacture one bipolar plate
T_{open}	Time to open mould
T_{PM}	Time to machine peripheral features
T_{Prof}	Time for channel profile machining of mould for one tool size
T_p	Polishing time
T_{place}	Time to place material in open mould
T_{pp}	Total time for setup tasks that are performed on each plate
T_{refxyz}	Time to reference micro-milling machines x, y, and z axis
T_{refz}	Time to reference micro-milling machines z axis
T_{rem}	Time to remove cured part from mould
T_{remove}	Time to remove plate from micro-milling machine
T_S	Setup time
T_{sp}	Time to set micro-milling machines machining parameters
T_{tc}	Tool change time
T_{tool}	Total time taken to change a tool
TO	Total sundry overhead
v	Cutting speed
v_{max}	Machines maximum spindle speed

v_{rec}	Tool manufacturers recommended spindle speed for specific tool size
w_{BP}	Width of bipolar plate
w_{ch}	Width of channel
w_{ff}	Width of flow field
w_g	Width of gap in channels, between turns
wp	Width of blank plate
Z_{Major}	Number of tools used for machining major channels
Z_{Minor}	Number of tools used for machining minor channels
Z_{Periph}	Number of tools used for machining peripheral features
$z_{channel}$	Tool life multiplier for channels
z_{periph}	Tool life multiplier for peripheral features
z_t	Number of tools used for a specific tool size
α	Distance to axial points
ε	Error
ρ_M	Density of Bohler M201

Abbreviations

BMC	Bulk Moulding Compound
BP	Bipolar Plate
CCD	Central Composite Design
CHP	Combined Heat and Power
CM	Compression Moulding
CMM	Coordinate Measuring Machine
CNC	Computer Numerical Control
DFMA	Design for Manufacture and Assembly
DOE	Design of Experiments
HT-PEM	High Temperature PEM
HT-PEMFC	High Temperature PEM Fuel Cell
HySA	Hydrogen South Africa
MEA	Membrane Electrode Assembly
PEM	Proton Exchange Membrane
RSM	Response Surface Methodology

1. Introduction

This thesis deals with the development of a cost model for the manufacture of bipolar plates (BPs), a key component in hydrogen fuel cells. The aim of the thesis is to find whether it is feasible or even possible to manufacture BPs in South Africa and, if it is possible, what the best method to use is. The processes for the manufacture that will be considered are machining, using micro-milling, and compression moulding. The cost model is intended for use in the design phase and will be used in the optimization of the BPs in other research projects. This report will give some background on hydrogen fuel cells and BPs, then go on to discuss the experiments done to develop the cost models and give a detailed description of how they were generated. An analysis using the models is then done to compare the costs for selected test cases. The cost models will be used to estimate the cost per plate over a range of production volumes as well as assess the effect of design changes on the cost. The costs of both processes will be compared to find the best manufacturing method to use, and at what production volume one process becomes more effective than the other.

1.1. Background

With the shortage and increasing price of fossil fuels, there has been an increased interest in alternative fuels. There has also been a push towards more environmentally friendly sources of energy. One of the popular alternatives is hydrogen fuel cells. Of course for this to be effective, the hydrogen must first be generated from renewable power sources, which is a definite possibility. There are many different types of hydrogen fuel cells and they can be used for a wide range of purposes such as portable power, combined heat and power, and hydrogen powered vehicles.

The fuel cell industry is also an interesting prospect for South Africa since SA has about 75% of the world's platinum reserves and the fuel cells require a considerable amount of platinum as a catalyst. The supply of platinum is illustrated in Figure 1.1. For SA to take full advantage of the fuel cell industry, it is important that the technology is developed to the stage where fuel cells can be manufactured in the country instead of simply selling the platinum as a raw material.

To develop fuel cell technology in South Africa an organisation, Hydrogen South Africa (HySA), was set up. HySA is the national research, development and innovation centre for hydrogen and fuel cells. Its goals are (HySA, 2011):

- Create wealth for SA through manufacturing and development of the platinum group metals catalysis value chain. The aim is to supply 25% of the global catalyst demand by 2020.

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- Build on the knowledge of high temperature gas cooled nuclear reactors and coal gasification Fischer-Tropsch technology and to develop hydrogen generation solutions locally.
- Promote equity and inclusion in the economic benefits of South Africa's resources.
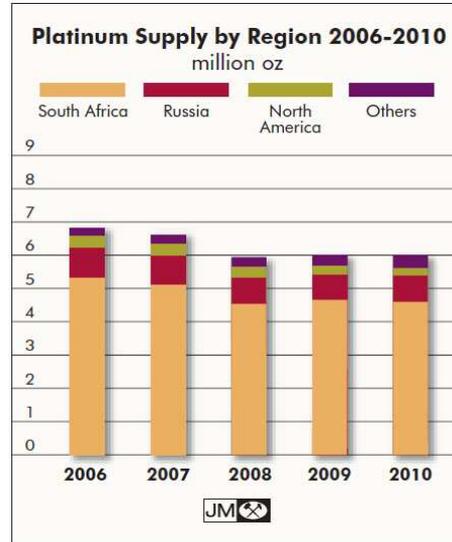
Figure 1.1: Platinum Supply Graph (Butler, J. 2010)

HySA has a number of Centres of Competence that focus on different areas of the project. These are HySA Systems, HySA Catalysts and HySA Infrastructure. Each centre is hosted by a different organisation or university. The centres each operate as a hub and each of these hubs has "spokes" that do some of the work for the overall project. The structure of HySA can be seen in Figure 1.2.
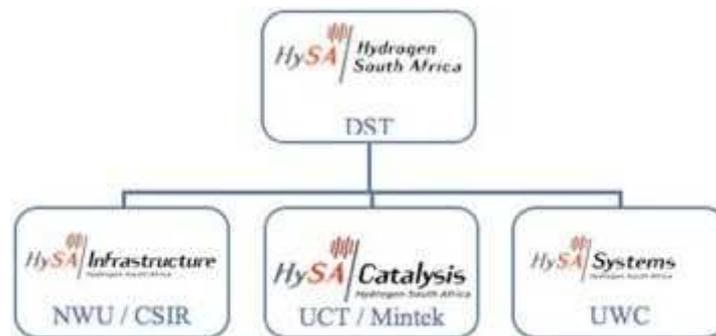
Figure 1.2: HySA Structure (HySA, 2011)

The work in this thesis is done for HySA Systems, of which Stellenbosch University is one of the spokes. HySA Systems is a technology validation and competence centre and is working on the development of hydrogen fuel cell technology. It receives funding from the Department of Science and Technology (DST) to do this research. HySA Systems has a few key areas in which it is doing research, i.e. combined heat and power (CHP) systems, portable power, hydrogen

fuelled vehicles and human capital development. This thesis will deal with CHP systems only.

There are a few technologies within the different fields mentioned above that are being developed and tested by HySA Systems. Some of these are Membrane Electrode Assemblies (MEA) for high temperature PEM cells, Metal Hydrides for hydrogen storage and palladium-base materials for reformers. HySA System's objective is to perform technology validation and systems integration in the areas discussed above (HySA, 2011).

For the CHP systems, high temperature PEM fuel cells (HT-PEMFC) are used. Therefore, within the field of CHPs, HySA Systems aims to develop MEAs for HT-PEM fuel cells, test HT-PEMFC stacks and develop full CHP systems (HySA, 2011). This thesis will provide information on the manufacture of the BP. Other members working on the project will focus on the design of the MEAs and chemical modelling of the fuel cells. There are still other parts of HySA that will focus on the catalyst and hydrogen storage.

The BP is a key component of the hydrogen fuel cell and can make up 80% of the weight of the cell in some cases (Larminie et al. 2003: 418). BPs are responsible for conducting electrical current, conducting heat out of the cell and as a pathway to distribute the fuel. In the past BPs where machined from graphite due to graphite's high electrical and thermal conductivity. However, this is not cost effective for production on higher levels. For this reason there has been interest in alternative materials that can be moulded and that perhaps even have better properties.

1.2. Objectives

The goal of this thesis is to investigate the manufacturing of BPs in South Africa. This includes determining whether it is feasible to manufacture the BPs in SA and finding the factors that contribute to the cost of the manufacture of a BP in the most attractive manufacturing processes. From there a cost model can be made for the processes and the costs compared for various production volumes. The individual objectives are:

1. Determine the different methods of making BPs for HT-PEMFCs in SA
2. Develop cost models for the most attractive manufacturing processes
3. Evaluate the cost model's ability to express the effect of design changes and the cost of producing different quantities

1.3. Motivation

The cost to produce a fuel cell is an important factor when deciding whether to enter the fuel cell industry. The BP is a major component and contributes significantly to the overall cost. It is also not a standard component and is likely to undergo some design changes as the cell is optimised. It must first be determined

whether it is possible to manufacture BPs in SA on a small to medium scale. It is also important to know how a change in the design will affect the cost to produce the BP.

Using the cost model, the BP can be optimised for performance and cost. It can also be used to determine which process to use once the design is finalised for specific production volumes. A related project is already underway on the optimisation of the thermo-fluid dynamics of the fuel cell.

BP manufacture is a new field for SA. It is therefore important to produce a BP to establish all the factors that affect the cost. As with any new process there will be costs and problems that were not originally anticipated. These could include problems associated with the design and the manufacturing process or the acquisition of the materials needed. This thesis will find these problems and hidden costs so that they can be considered during the design of the fuel cell.

It is also important to establish whether or not there is enough expertise to manufacture the BP in SA, as well as what materials and machinery may be needed from overseas. This will also be considered in the course of the research.

1.4. Scope

In the field of fuel cells, there are many different types for different applications. Within each type there are also different designs. Not every type of fuel cell is being investigated by HySA Systems as this would take far too long. It is also too early to compare many different designs. The specific design and the scope of the research will be discussed here.

This thesis will deal with high temperature PEM fuel cells (HT-PEMFC) for use in a CHP system. There are two types of PEM fuel cell, a regular type that operates at about 80°C and a high temperature type that operates at about 120°C to 180°C. The high temperature version has advantages in a CHP system as the CHP system uses the heat generated by the cell as a by-product of the chemical reaction, instead of it being wasted, and it is easier to capture the heat at the higher temperature. Thus the HT-PEMFC will be the focus for this thesis.

Within the HT-PEMFC there are still many different components that make up the cell. This thesis will look only at the BP. The design for the BP that will be used has been specified by HySA Systems. This design was developed by ZSW and only small design changes will be considered. The material for the BP has also been specified by HySA and is a graphite filled polymer. This is a thermoset resin with a graphite loading of 80% to 90%.

The cost model that will be developed will consider low to medium production volumes. The production volume is dictated by the demand and the market share SA will have. At this stage HySA only envisions producing fuel cell stacks in the low 100s, each with multiple BPs. This then puts the production volume of BPs in the 1000s.

2. Literature Review

2.1. Introduction

This chapter will describe how a fuel cell works and summarises the literature on the design and manufacture of BPs. It starts with a description of Design for Manufacture and Assembly (DFMA) concepts. The tools and theory used here is important for the formation of a cost model. A description of experimental methods will also be given as they are used to determine parts of the cost of the manufacturing of a BP. Some background on how a High Temperature PEM Fuel Cell (HT-PEMFC) works will then be given. Then the different designs for the BP will then be discussed, followed by the methods that can be used to manufacture it.

2.2. Design for Manufacture and Assembly

Design for Manufacture and Assembly or DFMA is a design philosophy whereby manufacture and assembly is considered during the design phase. It has been used successfully by many companies such as Ford Motor Company and IBM (Boothroyd et al, 2002). There are three main activities where DFMA is used. They are (Boothroyd et al, 2002):

1. To provide guidance to the design team to reduce manufacture and assembly costs in concurrent engineering studies.
2. As a benchmarking tool to study competitors products.
3. As a tool to estimate cost during the design phase.

The last point is most appropriate to this thesis. The emphasis here is to determine the cost of the manufacture of a BP and how changes in the design will affect the cost. Some of the advantages of using DFMA during the design stage are (Boothroyd et al, 2002):

- Time-to-market improvement
- Improved quality and reliability
- Reduction in assembly time
- Reduction in manufacturing cycle time
- Reduction in part count and costs

DFMA gives guidelines for the design of a part for different manufacturing processes and also a set of guidelines for assembly. If these are followed the part can be designed to be made cheaper. DFMA results in designs that are simpler and more reliable, which saves money at every step of the design and manufacture process (Boothroyd et al, 2002). Along with the guidelines there are also a number of formulas for estimating the cost of a part while it is still being designed. The figure below shows the steps that are taken when using DFMA philosophy in the design phase.
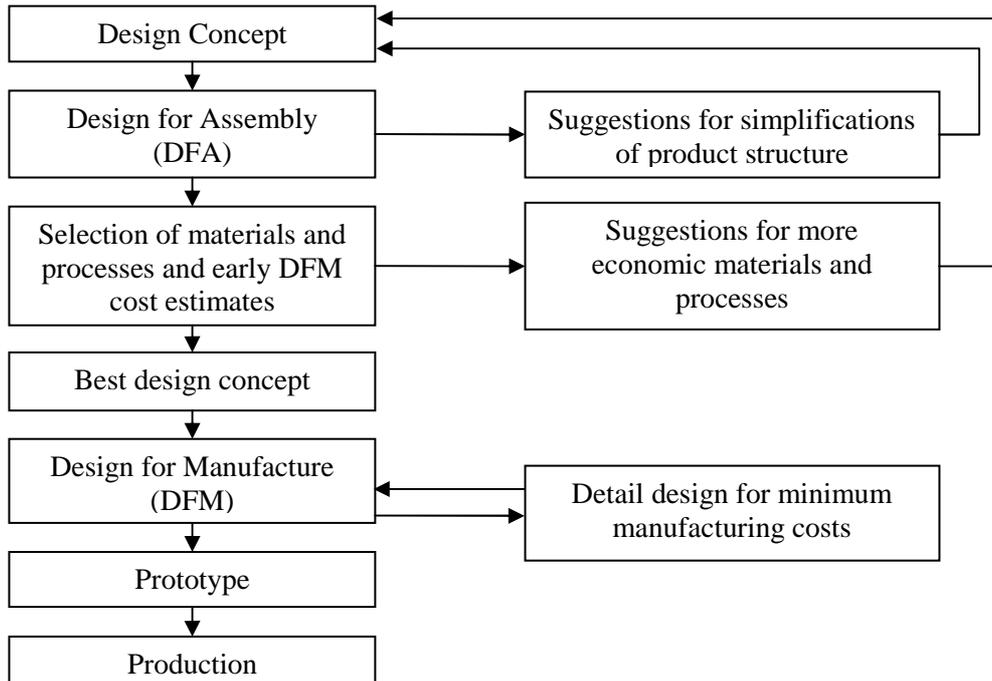
Figure 2.1: Steps in DFMA process (Boothroyd et al, 2002)

The most important part of DFMA for HySA Systems is to establish the cost to produce a fuel cell in South Africa. They are currently at the phase of finalising a detailed design and so the effect of design changes on cost is needed. This thesis will therefore use the methods and ideas of DFMA to construct a cost model for the manufacture of a BP. In this way the design can be optimised and different manufacturing methods can be compared. The cost model will eventually be used to determine whether SA can become a competitive player in the fuel cell industry.

2.3. Experimental Design

2.3.1. Common Terms

Experimental design and response surface methodology (RSM) use statistical methods to determine the effects of the various factors and to see which are significant. They are also used to fit models and to test how well the model fits the data. The terminology can become quite confusing so this section will give a brief description of the common terms.

When conducting experiments there is always some output for a process that the experimenter would like to control or optimise. This is called the response. There are also the variables that affect the response which are called factors. The aim of the experiment is then to determine the effect of the different factors on the response. The factors can either be quantitative or qualitative. In the field of statistics, quantitative is used to describe factors that are continuous, meaning that

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the factor can have any value in the region of experimental interest such as temperature. Factors that are qualitative can only have discrete values and are usually things like material. Before conducting the experiment, levels for the different factors are decided on. These are values within the region of interest that the factors will be set at during the experiment. If only linear effects are being investigated then normally only two levels are set. If one wishes to test for quadratic effects then three levels are set.

Factors can also have main effects and interaction effects. An interaction effect is where changing of two variables at the same time has a greater (or smaller) effect on the response than the addition of changing the variables one at a time. For example you may have an experiment with two factors, x_1 and x_2, which can each have a high or low level. Four experiments are then done, first one with x_1 and x_2 set on low, next one increasing x_1 with x_2 set on low, then increasing x_2 with x_1 set on low and finally increasing both. If an interaction effect was present then the fourth experiment would have a larger change on the response than that given by adding the effect of the second and third experiments. The effect on the response by a change in just x_1 or x_2 are called main effects.

Once the experiment had been run, the gathered data needs to be analysed. It is useful to look at the sample mean and variance of the response. The variance is a measure of the dispersion of the samples. It gives an idea of how much scatter there is in the data. A model must also be fit to the data. The common method used here is the least sum of squares. This uses Equation 2.1 below (for a second order function for two factors) and finds the values for the β's that minimises the sum of the square of the errors.

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{12} x_1 x_2 \qquad (2.1)$$

Once the data has been analysed and a model has been fitted to the data, it is important to see how well the model fits, as well as which factors are significant and should be included in the model. To see which factors have a significant effect, the p-value is used. If the p-value is lower than a set level of significance, α, then the factor is significant. Usually α is set at 0.05 (Montgomery, 2005: 637). The next useful statistic to check is the R^2_{adj} value. This is an indication of how well the model fits the experimental data. It shows the amount of variation in the experimental data that is explained by the predictors. The final step in the analysis is to do an analysis of variance (ANOVA). This tests to see whether the regression model is significant. Here the statistic that is used is the F_0 value. If the value for F_0 is greater than 3.11 (for 95% confidence) then the model is significant.

2.3.2. Response Surface Methodology

Response Surface Methodology (RSM) is a set of mathematical and statistical methods that are used to model problems that have a response that is determined by a number of factors (Montgomery, 2005: 637). It is also used when the response must be optimised. The problem can be expressed using Equation 2.2:

$$y = f(x_1, x_2, \ldots, x_n) + \epsilon \qquad\qquad (2.2)$$

In the formula y is the response that is to be determined, the x's are the variables that influence the response and ε is the error in the response. The form of the function above is not known initially in RSM problems and so experiments must be performed to find an estimation of the function. The use of a suitable experimental design will help with the RSM method. Some of the features of a desirable design according to (Montgomery, 2005: 637) are as follows:

- Provides reasonable distribution of data points in region of interest
- Allows model adequacy to be investigated
- Allows designs of higher orders to be built up sequentially
- Provides an internal estimate of error
- Provides precise estimates of model coefficients
- Provides a good profile of the prediction variance
- Does not require a large number of runs
- Ensures simplicity of calculation of model parameters

The most popular experimental design for RSM is the central composite design (CCD) as it meets most of the guidelines listed above. The different experimental designs considered for this thesis will be discussed below.

2.3.3. Experimental Designs

The proper choice of experimental design is important and there are various factors to consider. The design must work well with the RSM analysis discussed above. It must also not contain too many runs as this would take too much time and money. The methods considered for this thesis where the Taguchi method and a design of experiments (DOE). These methods will be discussed below. Both methods are designed to test for the main effects of the variables and for any interaction effects between variables.

The first method of experimental design that was considered was the Taguchi method. This method was created by engineers with the aim of design or process development and improvement. The Taguchi method therefore assumes that something is known about the process and this information is used to make the experiment more efficient by not investigating some of the interactions. This can cut the number of runs by a factor of 10 or 20 sometimes. Once the experiment is done the data can be analysed to determine the influence of each variable and the best values for the variables. There are specific statistical methods and formulas for this. It is recommended to then do a final confirming experiment at the optimal factor values (Cesarone, 2011). The methodical, laid out steps make the Taguchi method easy to use, however it is not always safe to make the assumption that some interactions would not be significant.

The second method is the design of experiments (DOE). DOEs were developed by statisticians. They assume that no knowledge of the process is known and that all factors and interactions must be tested (Cesarone, 2011). Within DOE there are

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various methods of conducting the experiments. The full factorial design tests all combinations of the factors at all levels. This can require a huge number of runs to complete, especially if you have many factors to consider. For example if you have three factors at three levels you need $3^3 = 27$ experiments, but if you have eight factors to consider the number of experiments is $3^8 = 656$. The other methods of conducting the experiments are all ways of cutting down the number of experiments that need to be done while keeping the experiment statistically valid. These are discussed below.

As mentioned above the number of experimental runs that are needed increases rapidly as the number of factors increases. Also, in the large factorial designs many of the degrees of freedom correspond to three-factor and higher interactions. These are normally negligible and so testing for them is not necessary. A fractional factorial design is then used to reduce the number of runs at the expense of losing information on the higher interactions. This happens as some effects become aliased, or combined, with each other. For example a main effect is mixed with a three-factor effect. It must then be assumed that the three-factor effect is negligible to obtain the main effect (Montgomery, 2005: 637). In the experiment in this thesis there are three factors at three levels each. If a fractional factorial design is used the main effects would be aliased (combined) with the two-factor interactions. This means that it would only be useful if it was assumed that all interaction effects were negligible. This was not the case so a fractional factorial design was not used.

Another possible design is the central composite design (CCD). This uses a full factorial design with all factors at two levels, and then adds centre and axial points to the design. When a two-level factorial design is conducted the assumption is made that all the effects are linear and no curvature can be tested for. This is problematic and so the centre and axial points are added to test for any quadratic effects. The CCD manages to keep the number of experiments down while still testing for quadratic effects. It also works well with the RSM. It was therefore used in this thesis. The shape of the design can be seen in Figure 2.2 below. In (a) the design is for two factors where (b) is for three. The points that lie on the corners of the cube are the normal two-factor full factorial runs, the point in the very centre is the centre run, and the points that extend beyond the cube are the axial runs.
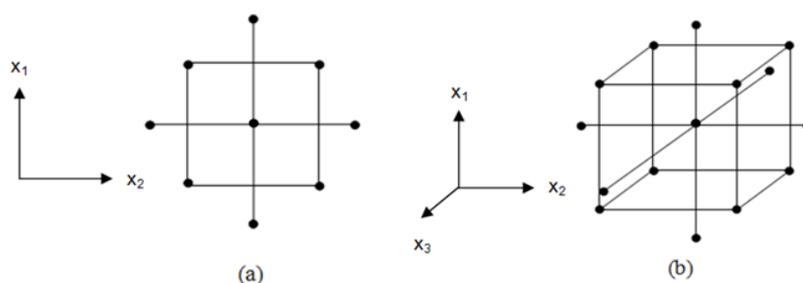
Figure 2.2: Central Composite Design

In the CCD, it is recommended that the centre run is repeated three to five times. This gives an indication of the variability in the process. The other points can be run once or also repeated depending on what the designer would like (Montgomery, 2005: 637). The distance of the axial point from the centre (denoted by α) can be set at any value, however Equation 2.3 below is recommended for determining α as it gives a rotatable design, meaning that all points that are the same distance from the centre point will have the same amount of prediction error. In the formula n_F is the number of points in the factorial part of the CCD. For a CCD with three factors the formula gives a value for α of 1.68. Then using the CCD a second order model can be fit to the data.

$$\alpha = (n_F)^{1/4} \qquad (2.3)$$

2.4. How the PEM Fuel Cell Works

The basic principle of how a hydrogen fuel cell works is that hydrogen is broken down into a proton and an electron in one reaction. The proton and electron then combine with oxygen to form water in another reaction. The formulas for this reaction are:

$$2H_2 \rightarrow 4H^+ + 4e^- \qquad (2.4)$$

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \qquad (2.5)$$

The way in which this reaction generates power is that the protons produced are allowed to travel through a membrane that allows only protons to pass through it, to the other side which contains the oxygen. This membrane is called the Proton Exchange Membrane (PEM) and is where the PEM fuel cell gets its name from. The electron is forced to flow through a circuit to meet the oxygen on the other side of the membrane. The proton, electron and oxygen then combine to make water. The electrons that are forced through the electrical circuit give us the electrical power needed.

The process that takes place in the fuel cell to generate power is illustrated in Figure 2.3: Hydrogen is channelled over the anode, the electrically negative terminal, where the H_2 molecule splits according to Equation 2.4. On the other side of the membrane, oxygen is passed over the cathode, the positively charged terminal, where the reaction in Equation 2.5 occurs, producing water. Another by-product of this process is heat.
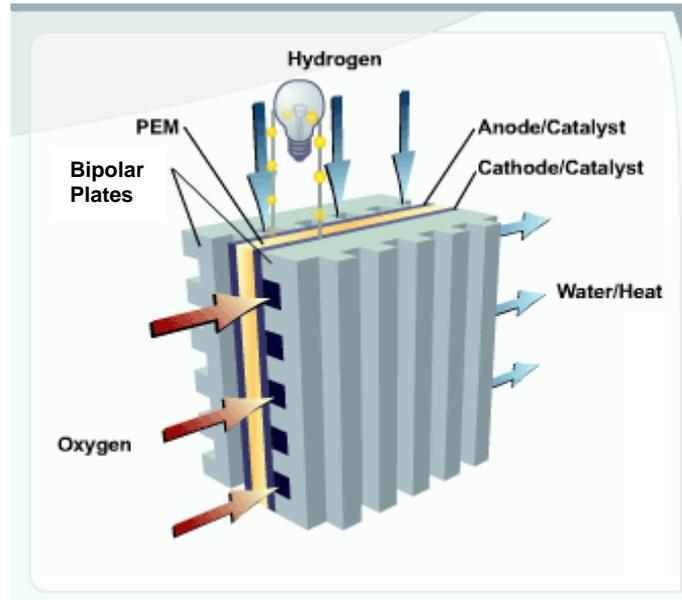
Figure 2.3: PEM Fuel Cell Diagram. (Adapted from U.S. Department of Energy, 2008)

Each cell produces only about 0.7 V, so many cells are connected in series to produce a stack. The number of cells in the stack is determined by the required voltage. The bipolar plates (BPs) connect the cells together. On the one side of the BP is the cathode of one cell and on the other is the anode of the next, hence the term bipolar. It also serves as flow channels for the oxygen and hydrogen (Larminie et al. 2003: 418). BPs are discussed in detail later in this chapter.

2.5. Combined Heat and Power

There is currently a worldwide emphasis on energy efficiency and reducing waste. Combined Heat and Power, or CHP, is a method of energy conversion where electricity and useful heat are generated and used simultaneously. It is also referred to as cogeneration. During operation of the high temperature PEM fuel cell, heat is generated as a by-product. This heat is used for heating purposes such as to heat water or for heating of a building, instead of being discarded as usual. It therefore lowers the amount of dedicated power that is needed for heating and improves the overall efficiency.

HT-PEM Fuel cells are ideal for use in CHP systems as they run at a high enough temperature (about 160 °C) for the heat to be easily removed and used elsewhere. This increases the efficiency of the system from about 35%, with only the electrical power being used, to about 60% with both electrical and thermal energy being used (35% electrical + 25% thermal).

2.6. Bipolar Plates

2.6.1. Function

BPs are one of the major components of the fuel cell stacks. They contribute the most to the volume and mass of the stack and therefore the design of the BP is an important consideration. The BPs can contribute about 80% of the weight of the stack (Larminie et al, 2003: 418). BPs have multiple functions within the fuel cell stack (Hermann et al, 2005: 1297):

- Connect neighbouring cells,
- Carry the current from cell to cell,
- Spread the hydrogen and air over the anode and cathode respectively,
- Carry heat out of the stack,
- Prevent leaks of either the reactants or the coolant and
- Assist with the expulsion of water from the cell.

To accomplish all of this, the BPs must have specific material properties. These properties are (Hermann et al, 2005: 1297):

- Low electrical resistance to minimise losses,
- High thermal conductivity for heat management,
- Low gas permeability so that the reactants are not lost,
- High corrosion resistance as the cell works at high humidity and heat which is a highly corrosive environment,
- It must be strong as it gives the stack its strength and
- It must be light weight as it comprises a large part of the mass of the stack.

The materials that are often used for BPs must comply with the requirements listed above but must also be inexpensive and suitable for whatever manufacturing method is to be used.

2.6.2. Designs

There are a few different designs for the BP. The main difference between them is the flow pattern that is used. This is the path that the fuel and air flows along. The various options for the design of the flow channels are: parallel, serpentine, parallel serpentine and a grid pattern. A figure of the different configurations can be seen in Figure 2.4 below. They each have their advantages and disadvantages. The parallel configuration gives good distribution of gasses without too much of a pressure drop, however if one of the channels is blocked that area of the electrode will not receive any gas. The serpentine channels will be sure to push any blockage out of the channel, but the pressure drop in such a long channel is high. The parallel serpentine is a trade-off between the two previous configurations. There is no real consensus over which is the best configuration, although parallel serpentine seems to be the most popular.

(a) Parallel

(b) Serpentine

(c) Parallel serpentine

(d) Grid
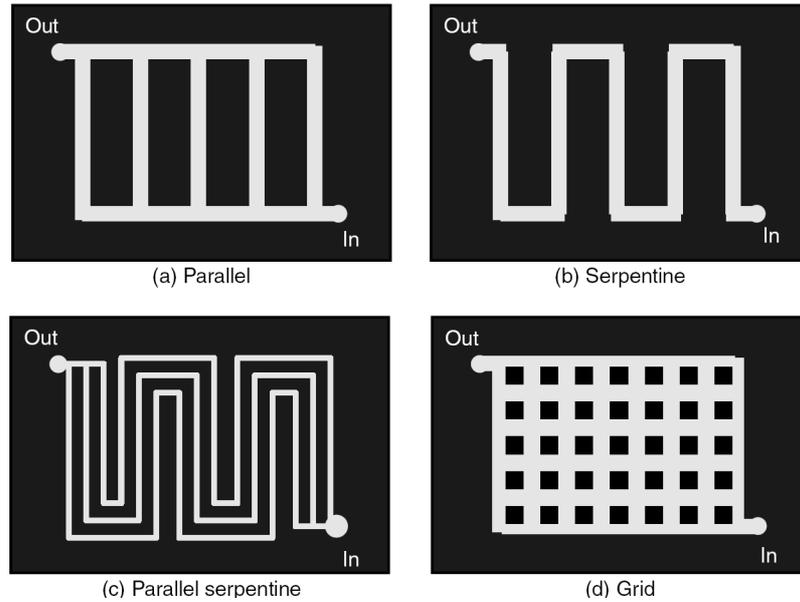
Figure 2.4: BP Flow Patterns (Larminie et al. 2003: 418)

For this thesis the design of the BP has been fixed. The plates will have a parallel serpentine configuration. HySA has decided on this configuration as it gives the best distribution of gasses over the electrodes while still making contact with the electrode to properly conduct the electrical current and heat out of the cell. A picture of HySAs design can be seen below. In the picture hydrogen flows through the opening in the top left corner, along the parallel channels and then out of the opening in the bottom right. There are also channels on the other side that run from the top right hole to the bottom left. These are for channelling the air. Figure 2.5 (a) shows a front view of the plate, (b) shows a view from front, right and below, while (c) shows a close up of the channel detail.

(a) (b) (c)
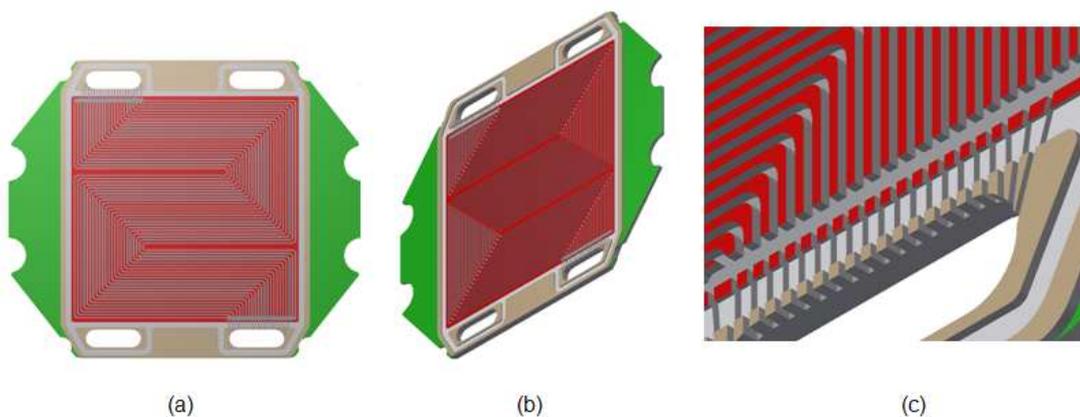
Figure 2.5: HySA Systems Bipolar Plate Design

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Another aspect of the BP design is the channel design. The channels can have either a square profile, as seen in Figure 2.6 (a), or have a radius on the corners as can be seen in (b). The square channel design is better if the BPs are to be machined while the rounded channels are better for compression moulding. This is discussed further later in this report. The land to channel ratio is also an important consideration. The land is the area between channels that makes contact with the electrode, and is shown in Figure 2.6. The design in this thesis kept the channel and land width the same, or as close as possible.
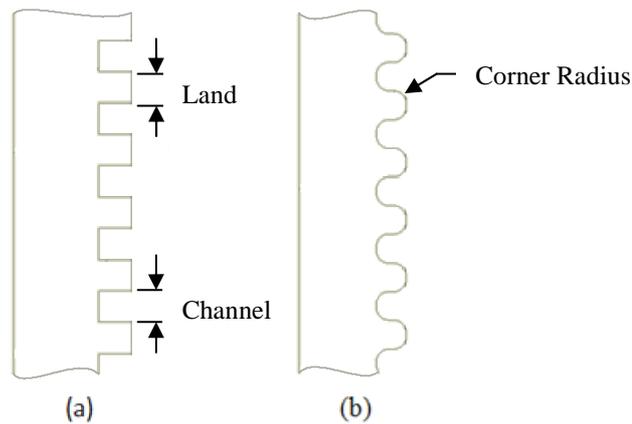
Figure 2.6: Channel Profile

2.6.3. Materials

Originally BPs where machined out of graphite. Graphite was used for its good electrical conductivity and corrosion resistance. However, if fuel cells are to be produced in higher volumes, the machining of graphite becomes too expensive and time consuming. For this reason there has been research done into alternatives. These will be discussed here.

The first alternative and possibly the most promising for higher production volumes is the use of a graphite or carbon filled polymer. The polymer falls either into the thermoset or thermoplastic categories. The difference between the two is that a thermoplastic melts when heated and then sets when cooled (it can be melted and re-set repeatedly) while a thermoset hardens by a chemical reaction called curing, that changes the structure of the polymer. A thermoset can therefore not be melted again after it has set. This generally makes it better for applications at high temperatures.

With graphite filled polymers it becomes possible to either compression mould or injection mould the plates. The injection moulding of BPs is still in its infancy and there are many problems with it, such as the proper filling of the small channels. The material will often harden in the small channels before the mould has been

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properly filled. Compression moulding is considered to be the better option and has already been used successfully (Lee et al, 2007b: 425).

The material to be used for this thesis will be a thermoset-graphite composite. The material to be used has been specified by HySA Systems. They require that the research is done using a material from Schunk Group, namely the FU4369HT which is ideal for use in high temperature fuel cells as it can handle the higher temperatures. It consists of a phenolic resin with a graphite loading of about 80% to 90%. The properties of the material can be seen in Table 2.1 below (Schunk Graphite Technology, [S.a]).

Table 2.1: Data Sheet for FU4369HT

Property			Unit	Value
Bulk density			g/cm^3	1.9
Flexural strength			MPa	40
Compressive strength			MPa	50
Young's Modulus	Dynamic		GPa	24
	Flexural			10
Hardness Rockwell HR10/40			N/A	100
Thermal conductivity			W/mK	55
Coefficient of thermal expansion α 20 – 140°C	xy plane		10^{-6}/K	15
	z through plane			38
Specific electrical resistance	xy plane		μΩm	90
	z through plane			190
Heat deflection temperature			°C	210

A new method that is under investigation is the use of stainless steel for BPs. They can be manufactured much more cost effectively by pressing and offer a higher electrical conductivity (Steele et al, 2001: 345). Other sheet metals have been proposed with various coatings. The problem with this process is that the complex flow fields such as the parallel serpentine cannot be used as the metal cannot be shaped into this pattern, leaving the parallel flow field as the only option. This method will therefore not be considered in this thesis.

2.7. Manufacturing Methods

There are several steps to manufacturing BPs. Each one of these steps has its own costs associated with it. Before any cost model can be formulated, the various steps must be understood so the cost can be determined for each step. This section will look at the various steps needed to produce BPs by compression moulding and machining.

2.7.1. Compression Moulding

The compression moulding (CM) process will have a higher initial cost than machining, but becomes cheaper at higher production volumes. The high initial cost is due to the high cost of the tooling. The faster cycle times make it cheaper

for higher volumes. The CM process is discussed below. It is assumed here that the selection of material and design of the BP is already known.

There are a number of different processes for compression moulding depending on the type of material and reinforcing fibres used. Some of the different materials that are used are bulk moulding compounds (BMC), sheet moulding compounds (SMC), glass mat reinforced thermoplastics (GMT) and long fibre reinforced thermoplastics (LFT) (Davis et al, 2003: 188). For this thesis the focus will be on compression moulding of BMCs.

With a BMC the raw materials are in powder form. The process for compression moulding a BMC is as follows: The material that is placed in the mould is called the charge. It is weighed out exactly before being placed in the cavity of the mould. The mould is heated and so the charge will start to heat up as it is placed in the mould. The mould then closes and the insert, which is also heated, presses down on the charge. This causes the charge to melt and flow to fill the mould cavity. A constant force is maintained on the part while the curing reaction takes place. Once the curing is almost done the part is ejected and allowed to cool (Davis et al, 2003: 188). The process then starts over again. The process is shown graphically in Figure 2.7 and the compression moulding cycle in Figure 2.8.
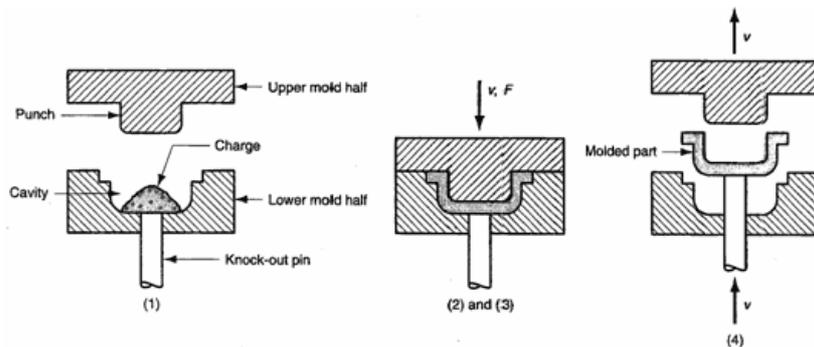
Figure 2.7: Compression Moulding Process (Sinotech Inc, 2010)
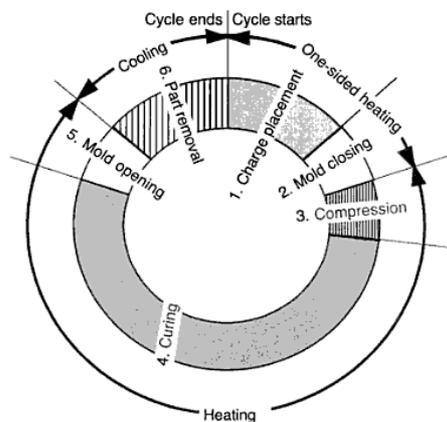
Figure 2.8: Compression Moulding Cycle (Davis et al, 2003)

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There are a number of guidelines for a part to be suitable for compression moulding, i.e. to ensure that the part is easy to manufacture and structurally sound. The mould must be designed so that material flows properly and heat transfer to the material is good. A brief summary of the "best practice" design guidelines for the part and the mould (Davis et al, 2003: 188) are given below.

Guidelines for part design:

- Constant wall thickness.
  A change in the part thickness will result in areas with more shrinkage and stress concentrations than others. It will also affect the way the material flows and can cause knit lines (where two material flow fronts meet during mould filling). Changes in thickness should therefore be gradual if possible.
- Minimize wall thickness.
  Wall thickness has a large influence on the cycle time as the material needs to heat up to initiate curing. The wall thickness should be kept as thin as possible while still satisfying the structural requirements
- Ribs and bosses.
  The addition of a rib creates a thick region at the base of the rib. This can be problematic and so some rules of thumb are used when designing a part with ribs. The thickness at the base of the rib should be 0.5T to 0.75T, the radius at the point of attachment should be 0.25T, the height of the rib should be less than 2.5T to 5T and a minimum taper of 0.5T is needed on the rib, where T is the thickness of the primary wall.
- Moulded in openings.
  Knit lines can form as the material passes around the cores for openings. If the part is structural, the holes should be placed at least 2D away from the edge and at least 1D away from each other. If the part is not loaded holes should be placed at 2T away from each other and the sides. Here D is the diameter of the hole and T is the thickness of the part.

Guidelines for mould design:

- Structural integrity.
  The pressures reached while moulding can be high and large stresses can be experienced especially if the charge placement is not well thought out. Narrow parts that stick out from the mould surface should be designed so that the height is less than twice the width to prevent them breaking.
- Part ejection.
  The placement and number of the ejector pins is crucial for proper release. The pins must be placed where the part is rigid enough to withstand the forces from ejection. Draft angles should be used to reduce the ejection forces
- Shear edge.
  When the mould closes the two halves should closely bypass each other so that air can escape while keeping the material in the mould.

2.7.2. Machining

The machining of BPs is simpler than compression moulding. For machining the initial cost is small but the production of one BP takes much longer, so the hourly rate charged becomes more significant. Other costs include the material, tools, several of which are needed, and other equipment.

The process for machining is simple. The blank plates are ordered as well as the appropriate tools. The plates are then machined in a milling machine. To machine the channels in the part, small diameter tools are needed and so high spindle speeds should be used to keep the feed rate from becoming too slow. This is because the feed per tooth (the amount of material removed by each tooth) needs to be kept below a certain amount. Therefore, if the spindle speed is slower, the feed rate must also be reduced. Micro-milling machines are ideal as they can achieve much higher spindle speeds (up to 60 000 rpm) than conventional CNC machines (only 20 000 rpm with a speed increaser).

Even using a micro-milling machine at high speeds, the cycle time to make one plate is much longer than with compression moulding. It is therefore suspected that while machining may be cheaper for small production volumes, compression moulding will be much more cost effective for higher volumes.

2.8.   Previous Studies

Some work has already been done on the manufacturing of BPs by machining and compression moulding, using various different materials. At least one study has compared the two methods of manufacture, similarly to this report. This section will give some of the results found by that study, done by Lee et al (2007a: 195), due to its relevance to this thesis.

The BP material used by Lee et al (2007a: 195) was an epoxy resin with a graphite filler, with graphite particles measuring 18.8 µm in diameter. 10% of the volume of the material was the epoxy resin while the rest was the graphite and a small amount of hardener. The dimensions of the channels where:

- Width: 2 mm
- Depth: 1 mm
- Land width: 1.5 mm
- Corner radius: 0 mm

The mould was made from aluminium, as opposed to the hardened steel used in this research. An aluminium mould will have a far lower mould life, but is still suitable to determine if proper mould filling can be achieved. The channel profile was machined into the mould using a 1 mm flat end mill.

For the machining trial, a blank BP was moulded and channels, of the same design as the moulded plates channels, where machined into this blank plate. A mould

was constructed out of aluminium for the production of the blank plates and the cost of this mould was included in the analysis.

The cost of machining and compression moulding was split into material cost, preparation cost, machining or moulding cost, and tool cost. The total cost, per part, for each process was then determined for different production volumes. Lee et al (2007a: 195) determined that the cost to produce one part would be $40.87 and $18.87 for compression moulding and machining respectively. However if 1000 parts where produced, the cost per part comes down to $2.02 and $5.28 for compression moulding and machining respectively. Thus it can be seen that for low production volumes the machining has the lower cost, while compression moulding is more suitable for higher production volumes. Lee et al (2007a: 195) found that compression moulding became more cost effective at a production volume of about 10 plates.

The study by Lee et al (2007a: 195) is interesting to consider due to its similarity to the research being done in this thesis. However, there are some issues with comparing their research with that done in this thesis. The first issue is that they used a very simple aluminium mould. This mould is useful to test if mould filling can be achieved, however, in a production setting a mould made from hardened tool steel would be more appropriate. An ejection system for the easy removal of the moulded part would also be needed. The mould cost estimated by Lee et al (2007a: 195) is therefore far too low.

The channel design used by Lee et al (2007a: 195) is also different to the channels used in this thesis. They used larger channels with no radius, which are easier to machine, and mould filling is less of a concern.

The costs estimated by Lee et al (2007a: 195) are useful for comparing the manufacturing and machining process, however they underestimate the overall cost in both processes due to the simple mould design. Although the overall costs cannot be used, it is useful to note that the compression moulding costs are higher than machining for small volumes, but lower for high volumes, which is intuitive.

3. Machining Cost Model

3.1. Introduction

One of the objectives of this thesis is to compare the costs of machining and compression moulding bipolar plates for various production volumes. A cost model for each of these processes is therefore needed. This chapter will discuss the machining cost model that was developed. All the work in this chapter, except Section 3.5, was done by Essmann (2011) from the Industrial Engineering Department at Stellenbosch University as part of his thesis: *A Cost Model for the Manufacture of Bipolar Plates using Micro Milling*. He conducted experiments to build a tool life model and then used the tool life model, combined with a manufacturing time model, to build a cost model. This chapter will summarise his experimental results and the tool model he developed. It will describe the manufacturing process to produce BPs and finally discuss the cost model he constructed. The last part of this chapter will discuss the adaptations made to Essmann's model so that it could be used in this thesis.

3.2. Tool Life Experiment

In order to develop cost models for machining, the factors that influence the cost must first be determined. The major factor that will influence the cost of the BP is the serpentine channel that runs along the plate. It will use the most tools and take the longest to machine. An experiment was therefore done to determine the tool life for the machining of these channels.

The function for the tool life will ultimately be used in the overall cost model for the BP. The cost model must also be valid for various designs. This means that the tool life formula must be valid over a range of tool sizes. The experiment for the machining was done using only one tool size, but it was adjusted later to apply for different sizes. This section will discuss those experiments and the tool life model that was generated.

For the experiments, response surface methodology (RSM) was used to convert the data into a meaningful tool life model. In this way the experiment's factors become the input variables for the tool life model. The experiment also used the central composite design (CCD) method of design of experiments (DOE). Using this method the resulting tool life model can account for second order factors and interaction effects.

The material used in the experiment was FU4369HT from Schunk, the material specified by HySA. This material is suitable for moulding and machining. The experiments where performed on a high speed micro-milling machine located in the Industrial Engineering Department at Stellenbosch University. The details of the machine are given later in this chapter.

3.2.1. Determining Experiment Factors

The purpose of this experiment was to develop a tool life model for the machining of BPs. The tool life model must predict the tool life for an end mill given various machining parameters. Three parameters where selected as having the highest influence on tool life. They are:

- Feed per tooth - f_t (μm)
- Cutting speed – v (m/min)
- Axial depth of cut – d (mm)

The tool life model will be of the form:

$$L_T = f(f_t, v, d) \tag{3.1}$$

In a CCD experiment in three factors, each factor can have five possible levels. The values for these levels where selected by finding the region of interest and the region of operability. The region of interest is the range over which the variable will be used in practice or is determined by the design of the BP. The region of operability depends on the physical constraints of the equipment such as the maximum feed rate. The tool suppliers recommended cutting parameters where used as the centre point for the factors. The other factor to consider in setting the factor levels is the axial distance α (as discussed in Section 2.3.3. This is the distance the axial runs are from the centre run. There is some flexibility when choosing α, but according to Myers et al (2009: 130) an ideal value for a CCD with three factors is $\alpha = 1.682$. The table below gives the levels used in the experiment.

Table 3.1: Factor Variables

	-α	-1	0	1	α
Cutting speed (m/min)	47.5	56.621	70	83.379	92.5
Feed per tooth (μm)	10	13.04	17.5	21.96	25
Depth of cut (mm)	0.2	0.5649	1.1	1.6351	2

A definition for the end of the tool's life is needed. A tool's life can end in two ways: The tool either fails catastrophically by breaking or wears down gradually. There are two problems with tool wear: the tool becomes blunt and the surface finish of the machined surface deteriorates, with chips of material being removed, or the tool becomes thinner as it wears down causing the channel to thin out. The end of tool life therefore comes when the surface finish of the channel is no longer suitable or when the channel becomes too narrow and goes below the lower tolerance limit specified in the design of the BP, whichever comes first. It was found that the reductions in diameter or catastrophic failure always occurred first, and so were used as the criterion for determining tool life. A reduction of 100 μm was used as the end of the tool life if it did not fail catastrophically.

3.2.2. Experimental Setup

Blank plates of about 160x160x3 mm were ordered from Schunk for the experiments. The micro-milling machine used was the Minitech 12528 from the Minitech Machine Corporation. The plates where held on to the machine using mechanical clamps on two sides. A portable vacuum cleaner was used to remove the cutting chips. This is important as the graphite in the material forms fine dust when machined and this dust could reduce tool life if it is allowed to build up in the cutting path. The figure below shows the machine with plate and vacuum cleaner in place.

Figure 3.1: Machining Setup (Essmann, 2011)

The cutting path followed was a zigzag shape similar to that of the serpentine channels on the BP. The cutting path was also at 45 degrees to the edge of the plate as this allows for a higher feed rate. This is because the milling machine has two motors to control the feed, one for the y-axis and one for the x-axis. The feed rate is limited by the top speed of the motor. However, if the cutter moves diagonally then both motors are used and a higher feed rate can be achieved. The figure below shows the cutting path.

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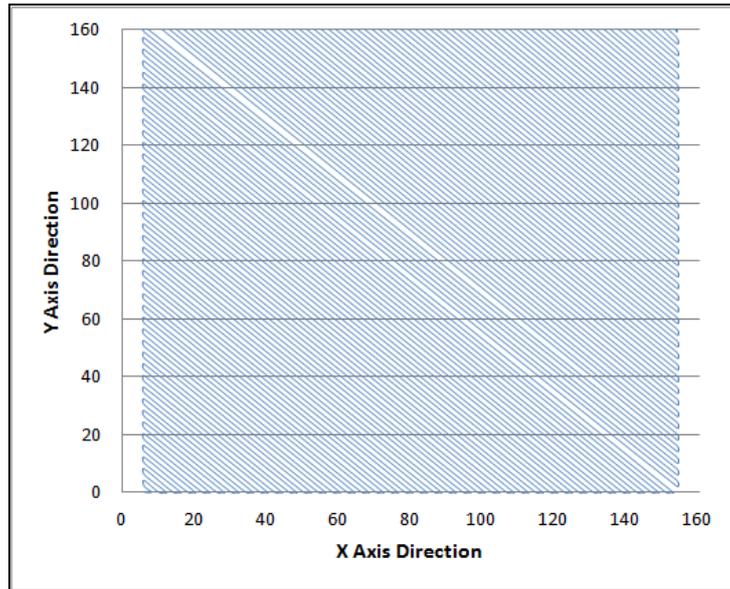
Figure 3.2: Cutting Path (Essmann, 2011)

3.2.3. Procedure

The plates to be machined where first clamped to the worktable and the machine parameters, feed rate and spindle rotational speed and depth of cut were input into the control program. The program was then run and the channel was cut into the plate. This procedure was repeated for each run of the experiment.

Once the plate was finished being machined and had been removed from the machine, it was analysed to find the end of the tool life. The tool diameter was used as the criterion for the end of tool life, as mentioned above, unless the tool failed catastrophically before the lower tolerance limit for the tool diameter was reached. The tool life was found by measuring the width of the channel. The tool life is therefore the length of cut till the width of the channel is less than the lower tolerance limit of a reduction of 100 μm.

3.2.4. Experimental Results

The main results of the experiments are given below, while detailed results are given by Essmann (2011). The results of the regression analysis are given first including the final formula for tool life. The results of the analysis that was done to determine how well the model fits the experimental data is then given.

Once the experimental data was obtained, it was analysed to fit a formula for the tool life. It was decided that a second order regression model would be used to fit the data. The coefficients of regression were found using a least squares estimation. The formula for the tool life is expresses in natural variables as follows:

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$$L_T = f(f_t, v, d) + \varepsilon \tag{3.2}$$

where: f_t is feed per tooth (µm), v is cutting speed (m/min), d is depth of cut (mm) and ε is the error. It can also be expressed in non-dimensional variables, x_1, x_2, x_3, which are cutting speed, feed per tooth and depth of cut respectively. The formula for tool life is then as follows:

$$L_T = f(x_1, x_2, x_3) \tag{3.3}$$

The transformations from the natural variables to the dimensionless variables can be done using the following equations, where the natural variables come from Table 3.1:

$$x_1 = \frac{v - 70\ m/min}{13.3786\ m/min} \tag{3.4}$$

$$x_2 = \frac{f_t - 17.5 \mu m}{4.4595 \mu m} \tag{3.5}$$

$$x_3 = \frac{d - 1.1 mm}{0.5351432 mm} \tag{3.6}$$

After an initial analysis it was found that a better fit was obtained if the response variable was transformed. The decided upon transformation was to take the natural logarithm. This gives the formula in Equation 3.7 and 3.8.

$$\ln(L_T) = f(f_t, v, d) + \varepsilon \tag{3.7}$$

Or in terms of L_T:

$$L_T = e^{f(f_t, v, d) + \varepsilon} \tag{3.8}$$

With the three first order effects (v, f_t, d), three second order effects (v^2, f_t^2, d^2) and three interaction effects ($v*f_t$, $v*d$, f_t*d), there are 511 possible combinations of regressor variables. All combinations where tested and the best one selected. The criteria used for the selection was the R^2_{adj} statistic, which gives an indication of the amount of the variation in the data that is accounted for by the model. The definition for tool life used was volume of material removed.

The final formula for the tool life, in terms of the volume of material removed, is as follows:

$$L_T = e^{5.842 + 5.275d - 0.000348v^2 - 0.00506f_t^2 - 1.724d^2 + 0.0027vf_t} \tag{3.9}$$

The model in Equation 3.9 gave an R^2_{adj} statistic of 0.8405. From this number it can be said that there is an 84% fit of the model to the data. This is a good fit. When using Equation 3.9, the values for the variables used should not fall outside of the ranges used in the experiment. These ranges can be seen in Table 3.1 on page 21. The accuracy of Equation 3.9 is unknown if extrapolated.

The final step in the analysis of the data was to do an analysis of variance (ANOVA). This tests for the significance of regression. The test statistic is:

$$F_0 = \frac{MS_R}{MS_E}$$
(3.10)

In the formula above MS_R and MS_E are the regression and error mean squares. For this experiment and working at 95% confidence, if F_0 is greater than 3.11 we can say that the response variable is related to at least one of the regression coefficients. The value found was: $F_0 = 18.9 > 3.11$. Therefore the response variable is related to at least one of the regression coefficients. However it is not an absolute judgement on whether the model really does fit the data. Looking at all the statistics presented, it was decided that the model does fit the data.

The final step of developing the tool life model was to account for different tool diameters. The formula to modify tool life is:

$$L_T^* = L_T \times \frac{D^*}{D}$$
(3.11)

In Equation 3.11 L_T^* is the adjusted tool life (mm^3/tool), D^* the new tool diameter (mm) and D the original tool diameter (0.71 mm). An experiment was conducted and the error from extrapolating the model to include different tool sizes was found to be 14.64%. The range for D used in the experiment was 0.5588 mm to 0.7248 mm. Equation 3.11 should not be used outside of this range.

3.3.   Machining and Setup Times

Now that the tool life model has been established, a model for the time taken to manufacture the bipolar plates (BPs) is needed. This section will discuss the times for the setup of the blank plate and tools, as well as the actual machining. To establish the setup times a time study was conducted. The machining times are calculated using the cutting length and machining parameters. The times for setup and machining will be discussed below. The equipment and materials used for the time modelling was the same as that used in the experiments for tool life.

3.3.1. Setup Time

The setup time constitutes most of the non-productive time of the entire process. The setup includes various steps and the times for each step must be determined to estimate the non-productive time spent on each plate. The time to flip, remove and inspect the BP will also be included in the setup times. The time study conducted to establish the time for the different steps took the average over 10 repetitions. A description of each of the steps of the setup is given below.

- Fixing the plate to the worktable: (T_{fix})
  It is assumed that the plate is held by a vacuum workpiece holding

system as using the clamps from the experiments would make the setup time too long.

- Tool changing: (T_{tc})
  The tool changes are performed manually
- Referencing the axes: (T_{refxyz})
  The referencing is done using an electrical continuity tester. This tests whether two points are electrically connected. The tester is connected to the plate and the tool, and the tool is moved until it makes contact with the plate. This is done for each axis.
- Setting machine parameters: (T_{sp})
  This is the setting of the correct feed rate, spindle speed and depth.
- Flipping the plate: (T_{flip})
  After one side is machined the plate needs to be flipped to machine the other side. This includes the unfastening of the plate, turning it over, and clamping it in place again.
- Removing the plate: (T_{remove})
  Once the machining is done on both sides the plate is removed from the machine.
- Inspecting plate: (T_{ins})
  This is the checking of the plate for errors in the machining.

The values for each of the steps of the setup found in the time study are given in Table 3.2 below:

Table 3.2: Setup Times

Setup	Time Estimates (seconds)
Tool Change (T_{tc})	34
Reference x,y and z-axes (T_{refxyz})	135
Reference z-axis (T_{refz})	46
Set Machine Parameters (T_{sp})	24
Plate Fixing (T_{fix})	17
Plate Flipping (T_{flip})	19
Plate Removing (T_{remove})	17
Plate Inspecting (T_{ins})	30

There are two possible methods for the process of manufacturing a batch of plates. Either one side of a plate can have all features machined before turning it over and

doing the same on the other side. The other method is to machine one feature on both sides of all plates and then machine the next feature. The method that is faster will depend on whether tool changing or plate handling takes longer. The time to set up is given by the equations below for both scenarios. Equation 4.1 is for machining all features before moving on to the next plate, while Equation 4.2 is for the second scenario.

$$T_S = \frac{5T_{tc} + 6NT_{refxyz} + 5T_{sp} + N\left(T_{fix} + T_{flip} + T_{remove}\right)}{N} + T_{ins} \tag{3.12}$$

$$T_S = \frac{3T_{tc} + 6NT_{refxyz} + 3T_{sp} + N(T_{fix} + 3T_{flip} + T_{remove})}{N} + T_{ins} \tag{3.13}$$

In Equations 3.11 and 3.12, N is the number of plates that are machined in a single setup, or the number of plates loaded onto the machine at the same time.

3.3.2. Cutting Time

There are various features on the plate and therefore different tools are needed. The process of machining is quite straight forward once machine parameters have been set and the plate loaded on the machine. The machining is done by the machine as it follows a predefined cutting path. The only interruption to this is if a tool breaks. A new tool must then be put in the machine and the z-axis re-referenced. There are also tool changes between machining features.

Due to the different features, the machining is split up into a few different processes, each with its own way of estimating the time to complete the process. The different processes are:

- Channel machining: This includes the machining of the main channels that run over the surface of the plate as well as the smaller channels that lead from the inlet hole to the manifold (See Figure 2.5, page 13).
- Peripheral features: This is the machining of the outline of the plate as well as the other features such as the holes and seals.

The methods of determining the machining times for the various features will be discussed here. One set of formulas is used for the machining of the channels (main channels and smaller channels), while another set is used for the various peripheral features.

To find the channel machining time, some factors need to be considered: Firstly the time to machine the actual channels needs to be determined. Then there is also the time taken when the tool moves from place to place while not cutting. This traverse time is most apparent when machining more than one plate on the machine at a time. The final consideration is time spent changing tools and re-referencing the z-axis that needs to be done if a tool breaks or has worn too much. The equation below is used to determine the machining time. It takes all the factors mentioned here into account.

$$T_{CM} = \frac{L_{ch}}{F_R} + \frac{wp(N-1)}{F_R\,N} + (T_{tc} + T_{refz})z_{channel} \qquad (3.14)$$

In the formula above the first term is for the time to machine the channels, the second for the travel time and the third for tool change time if a tool breaks. The variables in the formula are:

- T_{CM} – channel machining time (min)
- L_{ch} – total length of a channels (mm)
- F_R – Feed rate (mm/min)
- wp – plate width (mm)
- N – number of plates machined at a time
- T_{tc} – tool change time (min)
- T_{refz} – z-axis referencing time (min)
- $z_{channel}$ – tool life multiplier

The machining of the channels is done at the maximum feed rate of the machine, so the traverse feed rate and machining feed rate are the same, and represented by the same symbol (F_R). The tool life multiplier ($z_{channel}$) uses the tool life model established in Section 3.2. It establishes the number of tools that will be used for the machining so that the number of tool changes is known. The formula for $z_{channel}$ is:

$$z_{channel} = L_{ch}\frac{d\,D}{L_T} \qquad (3.15)$$

Here L_T is calculated using Equation 3.9, in mm³/tool. D is the tool diameter (mm). The tool life is also adjusted for tool diameter using Equation 3.11. This gives the number of tools that will be used for designs where the channel width is changed. The method for adjusting the tool life will be discussed later.

The next consideration is the machining of peripheral features. Unlike the channels, the peripheral features are not on the micro scale. Thus the Taylor's tool life model can be used to determine the tool life used for these features. The equation is:

$$L_{Taylor} = \left(\frac{C}{v}\right)^{1/n} \qquad (3.16)$$

Here v must be in m/min, and C and n are empirical constants. In this model the value for C is 170 and n is 0.14. These values are used in literature for a similar material (Essmann. 2011). The time for the peripheral machining is also split up into parts in the same way the channel machining time model has been split. The time to machine peripheral features is:

$$T_{PM} = \frac{L_P}{F_R} + \frac{wp(N-1)}{F_R\,N} + (T_{tc} + T_{refz})z_{periph} \qquad (3.17)$$

The terms in this formula are:

- T_{PM} – peripheral machining time (min)
- L_p – effective cutting length (mm)
- z_{periph} – tool life multiplier

The tool life multiplier is similar to the one used above for channel machining, but it uses the Taylor tool life model. The value for z is found according to the following formula:

$$z_{peripheral} = \frac{L_P/F_R}{L_{taylor}} \qquad (3.18)$$

The formulas above can now be used to establish the time for machining the BPs. These formulas will be used later when determining the cost to machine BPs.

3.4.   Machining Cost Model

The previous section discussed the manufacturing process and the times associated with each step. This information can now be used to determine the cost of machining BPs and develop a cost model. This section will discuss the cost model developed by Essmann (2011). Each part of the cost will be considered separately and then combined to give an estimate of the cost for the overall machining of the BP. The optimal machining parameters will discussed as well as the effect of design changes on cost. The cost for various production volumes will then be discussed.

3.4.1. Material Costs

The material cost is only the cost of the blank plates that are ordered from Schunk in Germany as well as the import costs. A formula for the material cost is given below.

$$C_{Material} = C_{Plate} + C_{Import} \qquad (3.19)$$

The import cost includes the cost of transport and all import duties. All the costs are in R/plate. All that is needed now is to estimate the values for C_{Plate} and C_{Import}. Plates were ordered for the project and so the cost of those blank plates shall be used. The costs where:

- C_{Plate} = R397.18 per plate
- C_{Import} = R10 per plate

This is for plates 160x136x3 mm in size. The import cost is actually a function of the number of plates ordered, but this amount gives a good enough estimate without complicating the cost too much, and will remain accurate for orders of plates in the low 100s. VAT is included in the material cost.

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3.4.2. Labour Costs

One of the major costs to consider is that of labour. Here the cost of labour (C_{Labour}) is determined using the time models to determine the length of time to machine a plate and the labour rate. This cost assumes for simplicity that a plate is made using only one machine and one operator. The possibility that an operator may work on more than one machine is taken into account. The formula for labour cost is then given as:

$$C_{Labour} = \frac{T_{mp}}{60} \times LR \times \frac{1}{N_{mach/worker}} \qquad (3.20)$$

Here $N_{mach/worker}$ is the number of machines that an operator can work at the same time. LR is the labour rate and is taken to be R71/hour. This is obtained from the annual average remuneration figures for employees in the manufacturing sector in 2010 from the Department of Trade and Industry. The labour rate includes only the cost of labour and no overheads. For the cost estimating here it is assumed that an operator will only operate one machine since the machining requires constant monitoring. Half of the machining time is actually non-productive time, and the machine must be monitored for tool wear. Thus a value of $N_{mach/worker} = 1$ is used.

3.4.3. Tooling Costs

The tooling costs are the costs of the cutting tools and machining fixtures needed to machine the BPs. The fixtures are a small part of the cost and so only the cutting tools will be considered here. Different tools are used for the different parts of the BP, namely the major channels, minor channels and peripheral features, each with their own cost formulas. The cost is the product of the number of tools used (from the tool life model from Section 3.2) multiplied by the cost per tool. The total tooling cost is given by:

$$C_{Tooling} = C_{Major\,Tooling} + C_{Minor\,Tooling} + C_{Periph\,Tooling} \qquad (3.21)$$

Here the major, minor and peripheral tooling costs are the costs to machine those features. Each one of these costs is determined using the following formulas:

$$C_{Major\,Tooling} = C_{Major\,Tool} \times Z_{Major} \qquad (3.22)$$

$$C_{Minor\,Tooling} = C_{Minor\,Tool} \times Z_{Minor} \qquad (3.23)$$

$$C_{Periph\,Tooling} = C_{Periph\,Tool} \times Z_{Periph} \qquad (3.24)$$

Here $C_{Major\,Tool}$, $C_{Minor\,Tool}$ and $C_{Periph\,Tool}$ are the cost per tool (R/tool) and Z_{Major}, Z_{Minor} and Z_{Periph} are the number of tools for each of those features. For the major channels the number of tools is determined by:

$$Z_{Major} = L_{ch\_major} \frac{d\,D}{L_T} \qquad (3.25)$$

Here L_{ch_major} is the total length of the major channels (mm). It is assumed that the channels are cut in one pass and so the depth of cut is also the channel depth.

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Using the tool size transformation the formula for the minor channels becomes:

$$Z_{Minor} = \frac{L_{ch\_minor}}{(L_T \times \frac{D_{minor}}{D})/(d_{minor} \times D_{minor})} \tag{3.26}$$

Now the number of tools for the peripheral machining must be determined. The tool life for the peripheral tools uses Taylor's tool life which is shown in Equation 3.16. The tool life (L_{Taylor}) is measured in time (mins). The number of tools needed can then be calculated using the following formula:

$$Z_{Periph} = \frac{\frac{L_{outline}+2\times L_{periph}}{FR_{periph}}}{L_{Taylor}} \tag{3.27}$$

Here $L_{outline}$ and L_{periph} are the lengths of the outline and the cutting length of the peripheral features on one side of the plate respectively (mm), FR_{periph} is the feed rate for machining the peripheral features (mm/min).

The tools used for this project where obtained from PMT (Performance Micro Tools) and so the costs for the tools where determined from the tool supplier's website, where the prices are readily available. There is also a delivery cost that was included by adding R5 to the cost of each tool. The prices listed on the website are also in dollars and so the exchange rate on 31/08/2011 (R7.06/$) is used. The costs for the tools in Rands (including delivery and import costs) then come to:

- $C_{Major\ Tool}$ = R87.25
- $C_{Minor\ Tool}$ = R101.37
- $C_{Periph\ Tool}$ = R80.19

3.4.4. Equipment Costs

The equipment cost includes the cost of the machinery, workpiece holding system and installation costs. Typically a loan is taken out on machinery and so the equipment cost is not a lump sum but a payment over a number of years. The cost of equipment is then a capital recovery cost or a contribution per plate to repay the loan or the equipment. The equipment cost, $C_{Equipment}$ (R) is therefore defined as follows:

$$C_{Equipment} = \frac{ACR}{AP_{mach} \times N_{mach}} \tag{3.28}$$

Here ACR is the annual capital recovery (R/year), AP_{mach} the annual production per machine (plates/machine-year) and N_{mach} the number of machines. This formula is appropriate when a company produces only one product. AP_{mach} is actually a forecasted value as the production volume may not be known before the end of the period in question. The ACR is the annual cost of owning the equipment. There are more formulas for the calculation of the ACR based on the

number of years it will be used and the interest rate but they will not be discussed here. The value is determined to be about $ACR = $ R40 600.

3.4.5. Overhead Costs

The sundry overhead costs are estimated in a similar way to the equipment cost. A blanket overhead rate is used and once again this is best suited to a plant that only manufactures BPs. The formula for the sundry overhead costs is as follows:

$$C_{Overheads} = \frac{TO}{N_{mach} \times AP_{mach}} \tag{3.29}$$

Here TO is the total sundry overhead (R/year) and the other terms are the same as above. A value of $TO = $ R100 000 was taken for this cost model.

3.5. Machining Model Adaptation

In the first part of Chapter 3, a detailed description of a cost model developed by Essmann (2011) for the production of BPs by machining was given. It was necessary to adapt the model to be able to compare the machining of bipolar plates with compression moulding. This section will first discuss the reasons for the adaptation to the model presented by Essmann, and then go on to give the adaptations made to it. An argument for its validity will also be given here. The adapted model will be used later in the thesis to estimate the effect of design changes and the cost of manufacturing over a range of production volumes.

3.5.1. Model Adaptation

In Essmann's model, the methods for estimating the tooling costs are acceptable and will therefore not be modified. The main changes will be to the parts that estimate setup time, labour, equipment and overhead costs. There are also small changes to the way that the material cost is calculated

The main limitation of the estimation of the equipment and overhead costs is that the model assumes that there is a company whose sole purpose is to machine BPs. This is not a reasonable assumption to make and inflates the cost, especially at lower production volumes. All the cost for the equipment and overheads is placed on the number of BPs made. If only one plate were to be made, it estimates that it would cost over R100 000 which is clearly inaccurate. Essmann's model is also unnecessarily complicated and attempts to use information that may not be available in the design stage.

In Essmann's model a value for the overhead and labour was guessed, while the equipment cost was determined from the cost of the machinery and clamping setup. The total of all these costs where spread over the cost of the number of BPs used. In the new model, an hourly rate for the workshop making the plate is used, which includes the overhead, labour and equipment costs. After consulting

engineering workshops, it was seen that this is the method used for quoting in industry and so will be used in the cost model.

To determine a reasonable hourly rate, the hourly rate from an engineering workshop was used. However, this was the rate for machining done on a large CNC machining centre, which is much more expensive than a micro-milling machine. The hourly rate was therefore adjusted down by considering the difference in cost of the equipment and the repayment period, as well as the utilisation of the machine. The hourly rate used for micro-milling was then taken as R310/hour.

The other change that was made to Essmann's model was the method to determine setup time. In Essmann's model time to enter the machining parameters into the machine and reference the x, y and z-axis was added to every plate made. In practice this would only be done once for the production of a batch of plates and so the setup time is inflated in his model. The modified model takes the time to reference the axis only once for a batch, then the times to set the machining parameters and reference the z-axis is added on every time a tool is changed. Finally the times for fixing, flipping, removing and inspecting the BP are added. Equations 3.31 to 3.33 show how the setup times where calculated. The inspection and removal times are also included here.

$$T_{tool} = (2n_s + 1)(T_{tc} + T_{sp} + T_{refz})$$ (3.30)

$$T_{pp} = T_{tool} + T_{fix} + T_{flip} + T_{remove} + T_{ins}$$ (3.31)

$$T_S = \frac{T_{refxyz}}{B} + T_{pp}$$ (3.32)

T_{tool} refers to the time taken for the tool changing time to machine one plate. There are three tool changes needed for an end plate and five needed for a bipolar plate (channels on both sides). The first term in Equation 3.31 accounts for this. T_{pp} is the time for all the tasks that must be performed on every plate, while T_S is the total setup time. T_S includes the referencing of the axis, which is done once per batch, and T_{pp} to give the total time per plate.

A change was also made to the method of estimating the machining time. The machining would always be done at the max feed rate as discussed in Section 3.3.2, however the machine slows down while changing direction and moving the tool from point to point over the plate without machining. Thus an effective feed rate of 950 mm/minute was used that is lower than the machine's maximum feed rate. Also, it was assumed that only one plate will be machined at a time and so the second term in Equation 3.17 is not needed. Equation 3.33 shows how the machining time was calculated for a tool size. Note that the full channel depth is machined in one pass. The process used can also be seen step-by-step in the sample calculation in Appendix A.1.

$$T_{mach} = \frac{L_{ch}}{F_R} + (T_{tc} + T_{refz})z_t \qquad (3.33)$$

T_{mach} is the machining time for a tool size, the tool sizes being the ones for the major channel, minor channel and peripheral features and is used instead of T_{CM} and T_{PM} from Essmann's (2011) model. The feed rate and length of channel for that tool are used to calculate the machining time. The second term calculates the time for tool changing using the number of tools used, z_t, which has the same value as Z_{Major}, Z_{Minor} or Z_{Periph} depending on the tool being used. The z-axis is referenced for every new tool inserted into the machine. Figure 3.3 gives an overall picture of how the adapted cost model predicts the cost to machine BPs.
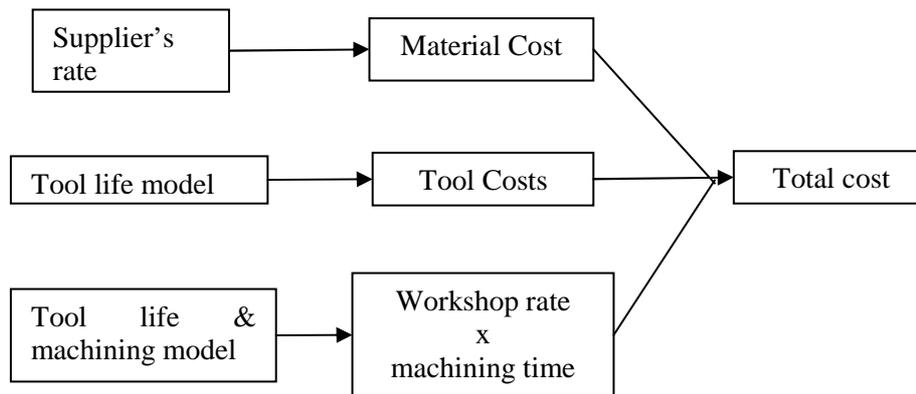
Figure 3.3: New Machining Cost Model

3.5.2. Model Analysis

A model for the machining of BPs has been described above. This model will be used later in this thesis to analyse the cost of machining BPs. The effect of changes in the design on the cost was analysed by Essmann (2011) and a similar analysis for the adapted model will be done in Chapter 5. This section will give an argument for the validity of the adapted machining model so that it can be used with confidence later.

The adapted machining model was used to do an analysis with typical design parameters and a batch size of 100 plates. The total cost was determined and then broken down into the material, micro-milling tools and labour costs to determine what the main cost drivers are. The costs for the different aspects of machining are given in Table 3.3 below. From the table it can be seen that the biggest cost is the material cost which makes up about 60% of the total cost. Next is the labour which makes up 24% of the total, and the lowest cost was the tools which were 16%.

Table 3.3: Machining Model Cost Drivers

Cost Driver	Cost (R)
Material	408
Tools	106
Labour	161
Total	675

The major cost, material, was determined from the actual purchase of blank plates from Schunk and so is accurate. A part of the material cost is for importing it and so would decrease with larger batch sizes, however it is only a small part of the cost and so would not make a significant difference.

The labour cost is derived from the machining and set up times determined by Essmann. The cost of tools also relies on the tool life model developed by Essmann. The accuracy of the set up times and are discussed by Essmann (2011), and this thesis must rely on this. The tool life model is discussed in Section 3.2.4 and does fit well for a tool size of 0.71 mm, but loses accuracy at other values of tool size. Even with the reduction in accuracy, the model is still suitable for cost estimating.

3.5.3. Model Evaluation

As with any cost model, some assumptions have been made and there is still room for the model to improve. There are also potential problems with the model that could give inaccurate results. These issues will be discussed here.

The first assumption that is made is that only one plate is loaded onto the machine at a time. If the worktable of the machine is big enough, it would be possible to load more than one plate and have the micro-milling machine do both. This could reduce the setup times and make the process faster. However factoring this in requires knowledge of the manufacturing that might not be available in the design stage. It should also not make a major difference as the setup time is only a small part of the cost.

Another assumption made is that a tool can be found that is the same diameter as the channel. If this proves not to be true, the machining time would be increased as two passes would be needed to get the channel width with a smaller tool. The tool supplier used was Performance Micro Tools, who have a wide range of tool sizes. They supply tools in inches and so there are no round figures for mm. However, often a tool can be found that is within the tolerance of the design. A selection of their tool sizes can be seen in Table 3.4 (in mm).

Table 3.4: Available Tool Sizes [mm]

0.5842	0.79248
0.6096	0.889
0.635	1.016
0.6604	1.143
0.6858	1.1938
0.7112	1.27
0.7366	1.397
0.762	1.524

From Table 3.4 above it can be seen that there is a wide selection to choose from and the designer of the BP should aim for a channel width that matches one of the tool sizes available. The need to do two passes will increase the machining time and therefore the cost. This is not factored into the model as there is not enough data on the tool life for this kind of machining.

Another improvement that can be made to the model is to factor in the change in cost for the change in tool size. Larger tools are less expensive and so would bring the cost down. The current model assumes a fixed price for all tools used for the channel machining. This would not change the cost significantly however as the change is not big. For example the change in cost between the smallest and biggest tool in Table 3.4 is less than 14% at the time of writing.

The reduction in import cost for importing larger volumes of the blank plates is also not factored into the material cost. This would also not make a big difference as the import cost is only a small part of the total cost.

The last issue to consider is the changes in material costs and exchange rates over time, as well as possible changes to import costs. The costs and exchange rates used were up to date as of the end of 2011, and so the cost model may need to be adapted to reflect these changes if there are major changes with the costs over time. This will only cause the calculated cost to be inaccurate and will not affect the comparisons made using the model.

4. Manufacturing by Compression Moulding

The main task of this thesis is to determine the costs of two different manufacturing methods for bipolar plates (BPs). The machining of BPs is discussed, along with the associated cost model, in Chapter 3. Before the cost model for compression moulding (CM) is discussed, a detailed look at the process is needed. This section will describe the process for compression moulding of BPs, from the design of the BP to a moulded plate. The changes necessary to mould a BP, compared to a machined one, will also be considered here.

4.1. Finding a Partner in Industry

Since compression moulding is a specialised process, it was necessary to find a company with the equipment and expertise to do the mould design and compression moulding. As this thesis will deal with a cost model for the manufacture of BPs in industry in South Africa, it is necessary to conduct the project with companies that would ultimately do the manufacturing. If not, the cost model developed may not be valid. However, due to the complex design and unusual material of the BPs, most compression moulding companies were either unwilling or unable to undertake the project.

The first step was to find the companies that worked with compression moulding or the processing of thermosetting materials. This was done by contacting the Institute of Polymer Science and using the Plastics and Packaging Industry Directory for South Africa (Plastixportal, 2011). Companies identified in this way were contacted to determine their interest.

Not all the companies that do routine compression moulding production were willing to help. This was for a number of reasons: some companies were small and where not interested in R&D, while the adverse economic environment meant that companies were only interested in work that would definitely be profitable.

Further potential industry partners were identified through the Plastics Institute of Southern Africa (PISA). Through contacting these companies, contact was made with Mr. L. van Niekerk of Plascom Consultants and his assistance was obtained.

Mr. Van Niekerk has many years of experience in the field and is used to the R&D process. Plascom Consultants works closely with Rheinmetall-Denel Munitions in Somerset West and the latter's equipment was used for this project. Some of the mould design and material development was also done by them. It was decided that Plascom Consultants and Rheinmetall-Denel would be used for this thesis, since they were used to a culture of R&D and the use of novel materials and designs. They are also very experienced in the process of compression moulding, as well as the designing of the moulds. They can also help with material selection and finding a company to do the mould manufacturing.

4.2. Bipolar Plate Design

The design of the BP had been specified by HySA Systems. The design is discussed in Section 2.6.2. A picture of the design is given again below for convenience. This design, however, would cause problems if used for compression moulding. The design specified by HySA is clearly for machined BPs. For a mould, the negative of the BP is needed. There are some design features on the BP that would be difficult to machine into the mould and the main problem is the circled feature in Figure 4.1 (c). The area between the channels would be machined in the mould, however this would not be possible as it goes to a point. The sharp corners on the edges of the channels are also a problem. The moulding occurs at high pressures and there would be stress concentrations on the sharp corners. The sharp edges are also not good for material flow, potentially causing incomplete mould filling.

(a)   (b)   (c)
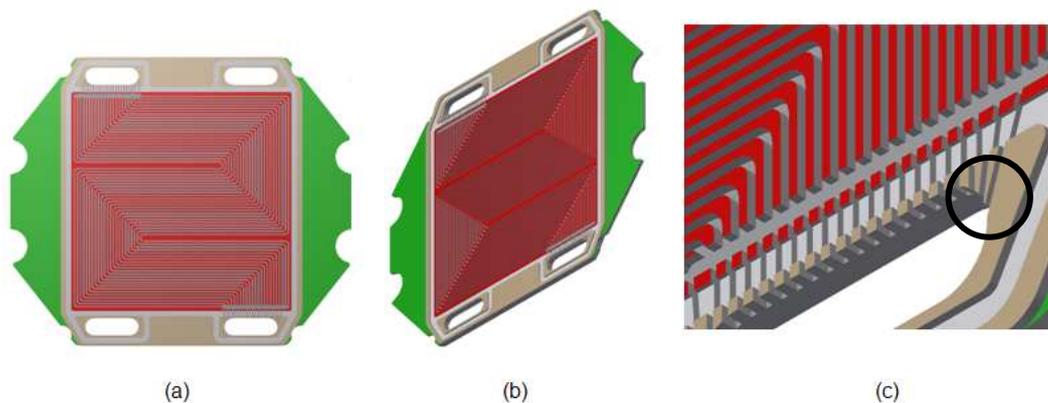
Figure 4.1: HySA BP Design

The design of the mould had to be changed to accommodate moulding. It was requested by HySA that the design be changed as little as possible, and therefore only the essential changes were made, i.e. a radius was put on all the sharp edges in the mould design. The design for the end plate (discussed below) with the rounded edges is shown in Figure 2.6 on page 14 where (a) is a cross section of the original channel design and (b) is the cross section for the moulded design.

There was a limited budget for the thesis and so, after consulting Mr. van Niekerk, it was decided that it was not necessary to mould a plate with channels on both sides. This would not change the cycle times of the moulding and the mould filling could be determined with the channels on the one side. It would, however, reduce the cost of the mould making considerably. The design used was then for the end plate, the last plate in the stack which only has channels on one side.

4.3. Mould Design

Once the design of the BP is finalised, the first step towards compression moulding is to design and build the mould. The mould must be designed for the specific CM machine it will be used in as well as the material used for the moulding, which is necessary to account for material shrinkage. Once the design is done, it can be sent off to a mould maker or engineering workshop. The design of the mould is quite intricate since it comprises many parts. The design for the mould was done by Rheinmetall-Denel for their machine.

The major parts of the mould and the parts that require the most machining are the cavity and the core inserts. The core (or plug) is the part that fits into the cavity when the mould closes and has the pattern of the channels on it. It therefore will require the most machining as the machining of the channels is time consuming. The outer edge of the cavity and core must be done to tight tolerances as they must fit together closely so that the material does not flow out, but air is allowed to escape. The cavity must also have holes in the bottom for the ejector pins that will be used to push the cured part out of the cavity. Both the cavity and core must also be polished to a mirror finish so that the BP does not stick to the surface. The surface finish of this design requires a *Ra* value of 0.2 μm. In Figure 4.2 (a) the mould core is shown and in (b) the cavity.

(a)   (b)
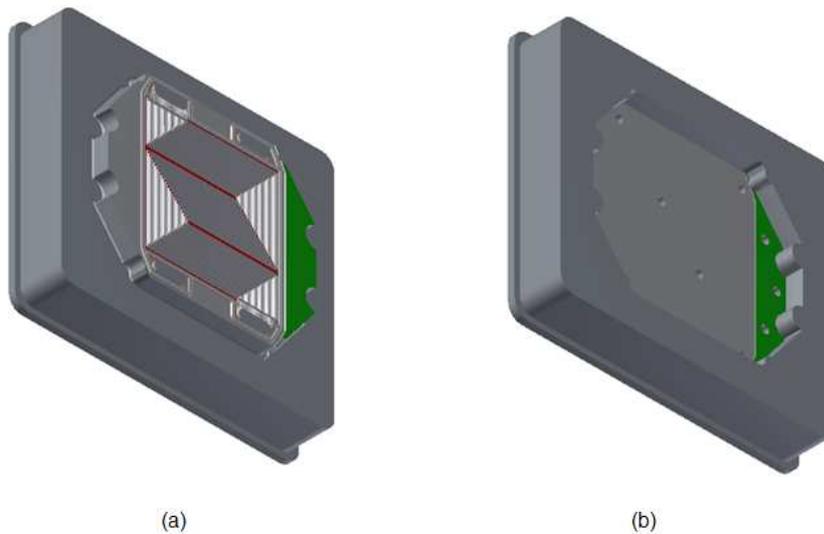
Figure 4.2: Mould Insert and Cavity Design

There are many other components in the mould such as mould plates, bushing, pins, springs and cap screws. Most of these are standard components and can be purchased already complete or need only a small amount of machining. These standard components can be obtained from DME, whose distributer is South Africa is Hestico. A list of all the components is given below with their catalogue codes. A description of the function of the components is then given.

Table 4.1: Mould Components

Item	Title	Code	QTY
1	Support Plate	DME N20-3035-46/1	1
2	Mould Plate, Lower	DME N10-3035-36B/1	1
3	Cavity Insert	NA	1
4	Mould Plate, Upper	DME N10-3035-36A/1	1
5	Force Insert	NA	1
6	Riser Plate	DME N30-86-3035/1	2
7	Clamping Plate, Top	DME N01-3035-26/1	1
8	Clamping Plate, Bottom	DME N01-3035-26/1	1
9	Ejector Plate	DME N50-26-3035/1	1
10	Ejector Retainer Plate	DME N40-26-3035/1	1
11	E/Plate Spacer	DME SB4-16	4
12	Cap Screw, Hex SKT HD	DIN 912:1983 M8x30LG	4
13	Centerhead Bushing	DME FBC16-26	2
14	Leader Pin	DME FSC24-36-36	4
15	Centerhead Bushing	DME FBC24-36	4
16	Cap Screw, Hex SKT HD	DIN 912:1983 M12x30LG	4
17	Cap Screw, Hex SKT HD	DIN 912:1983 M12x170LG	4
18	Locating Sleeve	DME TD32-140	4
19	Ejector Pin, DIA 6	DME AH06x125	6
20	Ejector Pin, Vented, DIA 6	DME AH06X125	6
21	Leader Pin	DME FSN16-26-86	2
22	Ejector Spring	DME WZ8031 TB 076	4

The components named in the table above can be seen in Figure 4.3. The item number in the table corresponds with the numbers in the figure. For a clearer understanding of how the components fit together an exploded view of the mould can be seen in Figure 4.4. The purpose of the components will be discussed here.

The support plate simply goes under the cavity insert. It gives support so that the cavity does not distort under the force of the core. It also has the holes for the ejector pins to go through it. The upper and lower mould plates support the core and cavity respectively. The inserts fit into the mould plates which then have the holes for screws and leader pins. The bottom mould plate has a hole in the side for a thermocouple so that the temperature of the insert can be monitored. The two riser plates are to raise the top part of the mould. This then gives space for the ejector pins so that they do not sit in the cavity, but can be pushed up at the appropriate time. The top and bottom clamping plates hold the mould together and serve as the interface between the mould and the moulding machine.
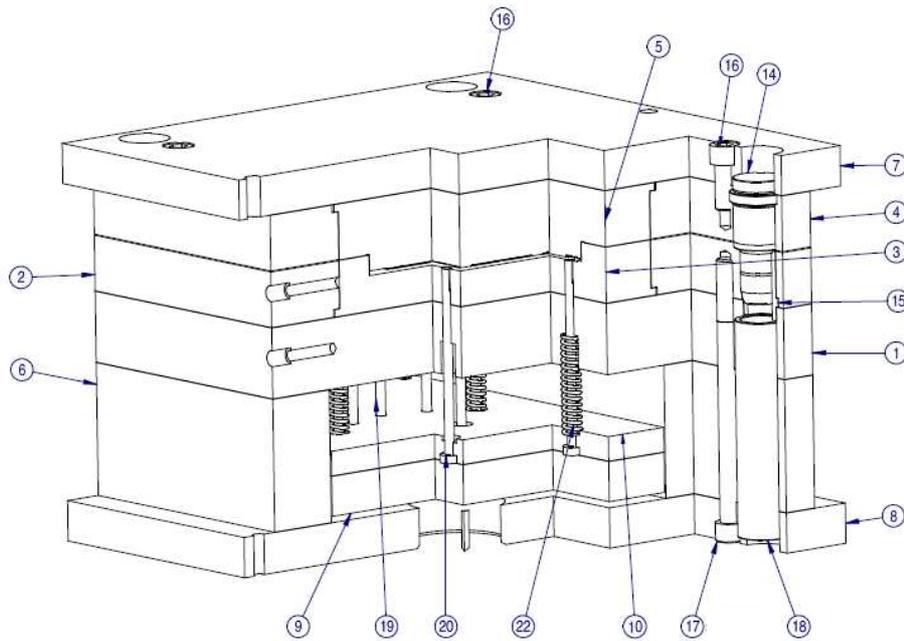
Figure 4.3: Mould Design

The top clamping plate keeps the upper mould plate and force insert together, while the bottom clamping plate keeps the risers, support plate, bottom mould plate and cavity insert together. The ejector and ejector retainer plates are to keep the ejector pins in place as well as the ejector springs. These two plates are pushed up in order to move the ejector pins into the cavity. The ejector pins' function is to remove the product from the mould once it has cured. Some are vented to allow for air to escape while the mould is filling. The ejector springs fit over the pins and are to keep the ejector plate down and the pins out of the cavity while the curing is in progress.

There are still other components such as the leader pins and bushings which make sure the mould halves fit together properly. The locating sleeves also ensure that components that fit together are correctly aligned. Finally there are the cap screws that hold the components together.

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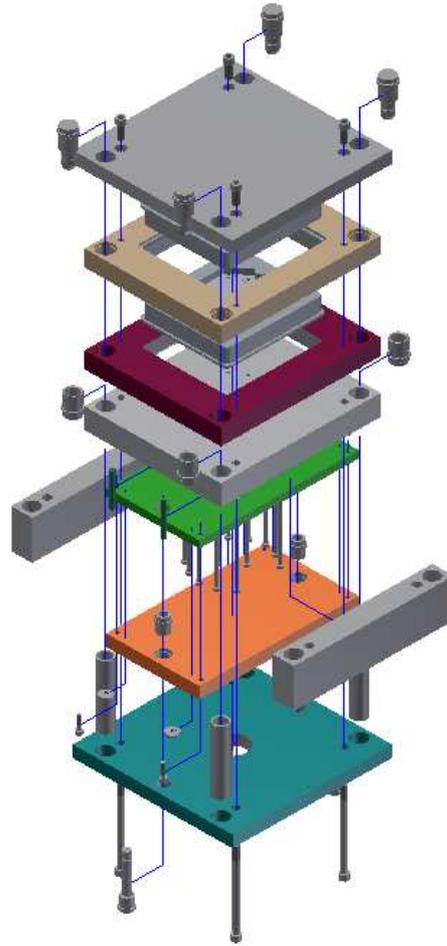
Figure 4.4: Mould Exploded View

The final consideration in the design of the mould is the material to use. The material for the mould needs to be strong steel that can support the temperatures and pressures it will be subjected to during the compression moulding. The material for the cavity and core also need to be very hard so that it does not scratch or deform. The material that was used was from Bohler and was their M201 tool steel. The properties for this material are given in Table 4.2 below (Bohler-Uddeholm South Africa, [S.a]). The steel is then also hardened for the cavity and core. This will be discussed in more detail in the next section.

Table 4.2: Properties of Bohler M201

Property (at 20°C)	Units	Value
Density	kg/dm^3	7,85
Thermal conductivity	W/(m.K)	33
Specific heat	J/(kg.K)	460
Modulus of elasticity	N/mm^2	210 x 10^3

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4.4. Mould Manufacturing

Once the design of the mould is finished the mould must be manufactured. Mr. van Niekerk recommended the use of a professional mould maker and not a regular engineering workshop. This is as the mould makers have a better understanding of how the mould will fit together and work, and so have a better feel for the tolerances and surface finishes that are required. For the making of this mould, the company Mould Shop in Cape Town was used. A discussion of the mould making will be given in this section. First the process of making the mould will be discussed and then the costs will be analysed.

Most of the components of the mould are standard parts, and can be ordered complete or almost complete, with only a small amount of custom work needed. However, Mould Shop chooses to machine some of these standard components themselves as they can do it cheaper than acquiring the parts already made. The most time consuming part of the mould is the core. This is due to the long process of machining all the small channels.

4.4.1. Mould Making Process

Here the steps taken by Mould Shop to produce the mould are given as well as the machinery that was used. The problems they encountered will also be discussed. Mould Shop has a number of years experience in mould making and, even though they usually make moulds for injection moulding, they have done compression moulds before. They where therefore able to raise some concerns with the design that will also be given here.

Mould Shop started by ordering the material required, including the standard parts as well as the material for the cavity and core. The standard components are mostly DME parts and where obtained through Hestico. The material for the cavity and core is Bohler M201 steel. The cutting tools necessary for the machining of the channels (2 mm, 1 mm and 0.6 mm ball nose cutters) where obtained from Mitsubishi.

The next step was to machine the rough outline of the cavity and core. The material around the core insert was machined away giving the basic shape while still leaving a layer of material to be removed. The channel profile was not machined at this stage. The same was done for the cavity insert. The cavity and core where then sent off for hardening. The hardening was done by Bohler and a vacuum hardening process was used. The design specified a hardness of 52 – 55 HRc.

While the core and cavity inserts where away being hardened, the standard components where machined. The work that was done on the standard components was as follows:

- Machining the openings in the upper and lower mould plates where the cavities fit in.

- Machining the holes for the ejector pins and springs, in the support plate and ejector retainer plate.
- Machining the hole for the ejector piston in the bottom clamping plate.

The following images show the machined mould plates. Figure 4.5 shows the upper mould plate, with the cavity for the insert already machined. Figure 4.6 below shows the support plate, with the holes for the ejector pins machined into it. The wider holes are for the pins that will have springs on them and are blind. Finally, Figure 4.7 shows the ejector retainer plate with the pins and springs assembled.

Figure 4.5: Machined Mould Plate

Figure 4.6: Machined Support Plate

Figure 4.7: Ejector Retainer Plate with Ejector Pins and Springs

Once the core and cavity had returned from hardening, the finishing machining was done on the outline of the core and cavity to give the final shape. The machining of the channels was then done. The machining of the channels was the most time consuming part of the machining process. The profile of the channels is given in Figure 4.8 for reference. The machining was first done with a 2 mm ball nose cutter, followed by a 1 mm cutter, and finally a cutter 0.6 mm cutter was used to remove the rest of the material from in the channels. All cutters first did a profile cut which followed the channels and other features. Then a lace cutting was done which started at the back of the plate and moved back and forth. This was to get the radii on the top of the channels.
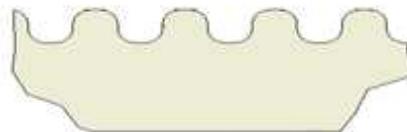

Figure 4.8: Channel Profile

Once all the machining had been completed the final step of the manufacturing was the polishing to get the required surface finish. The surface finish specified on the design was $Ra = 0.2\ \mu m$ on all the surfaces that come in contact with the moulding material. The surface finish was achieved by polishing first with a super

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stone and then with diamond paste. This is a lengthy procedure as the polishing in the channels takes time, thus a week was spent on the polishing. Figure 4.9 and Figure 4.10 show the cavity and core inserts. After this the mould was assembled and checked to make sure the two mould halves fit together properly.

Figure 4.9: Core Insert
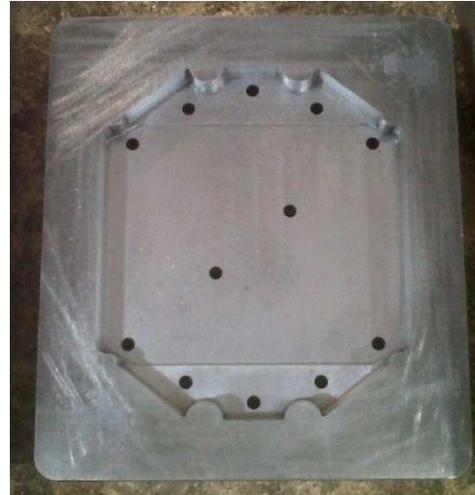
Figure 4.10: Cavity Insert

4.4.2. Mould Making Costs

The moulding process has the high initial cost of the mould manufacture, which makes up a substantial part of the cost for lower production volumes. An estimate of the cost for the mould is therefore important. Estimating the cost to make a mould is difficult and even mould makers have expressed difficulty in estimating cost. It is interesting to note that Mould Shop spent more on the manufacturing of this mould than expected and would give a higher quote for the same mould in future.

The quote from Mould Shop, as well as the observations made there during the construction of the mould, will be discussed in this section and then used later in the construction of the cost model.

The quote from Mould Shop (see Appendix B.1.) came to a total of R120 800 excluding VAT, comprising R34 000 for material and R86 800 for labour. The time to complete the project was quoted as 6 to 8 weeks. These amounts will now be split up further into their parts.

The largest contributor to the material cost is the mould base material, which includes the main components of the mould base as well as the bushes, guides and ejector pins. The other parts of the material cost are: the cavity and core material, the cost of material hardening and the tools for the milling of the channels. The tools would normally not be included, but with this mould they make up a bigger part of the cost than is usual. A breakdown of the costs can be seen in Table 4.3 below.

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Table 4.3: Material Costs

Item	Cost (R) (excl VAT)	Source
Mould Base	21 399	Hestico Quote
Cavity and Core	2 230	Bohler (R80/kg)
Hardening	1 190	Bohler (R42,50/kg)
Tools	5 600	Mitsubishi (R700/tool)
Total	30 419	

From the table above it can be seen that the total for the material comes to R30 419. This is about 10.5% less than the quoted amount.

The labour can be broken down into the separate tasks in a similar way to the material costs. The labour was quoted at R86 800, which is worked out using the time taken to make the mould times an hourly rate of R450. The time estimated to make the mould was therefore 193 hours. The total amount of time spent working on the mould should be close to this amount. The quoted 6 to 8 weeks also accounts for time waiting for material and tools, the hardening of the material to be done and other such tasks. The breakdown for the labour can be seen below. The times given below are taken from what was observed at Mould Shop as well as from interviews with the employees.

Table 4.4: Labour Costs

Item	Time (hours)
Mould base machining	40
Cavity and core profile machining	Unknown
Channel machining	35
Ejection system machining	Unknown
Polishing	40
Mould assembly	8
Total known	123

There is some uncertainty with the times given above, while the times for the profile machining and ejection system machining are unknown. Of the 193 hours quoted, there are 70 hours remaining to be allocated to the two unknowns. Boothroyd et al (2002: 698) recommends using 2.5 hours per pin for the machining of the holes for ejector pins in injection moulding. The machining for the 12 ejector pins for this design would therefore take 30 hours. This then leaves 40 hours for the profile machining, as well as some margin for error.

The manufacture of the mould at Mould Shop gave insight into the process, as well as the tasks that drive the cost of the mould. This knowledge can be used in the construction of the cost model which will be discussed later. Although there is uncertainty with the times and costs, enough is known to make the cost model accurate enough to fall within the uncertainty that is always present with cost estimating.

4.4.3. Checking the Mould

After the mould manufacturing had been finished and the mould was delivered, it was checked to see that it met the design specifications. The only detail check that was done was on the channel profile. This was the hardest part to machine and has the most chance of going wrong. A description of the method used to check the channel profile is given in this section. The remaining aspects of the mould were visually inspected and were found to agree with the design.

To measure the channels, a coordinate measuring machine (CMM) was used. This machine can make very accurate readings of a point in 3D space. It uses a probe which is lowered towards the part to be measured and records the point at which contact is made with the part. Many measurements can be taken to get the profile of the part. The CMM used for measuring the mould was a Mitutoyo Bright STRATO 710. It has an accuracy of 7.5 µm over 500 mm and a repeatability of 4 µm (ANSI/ASME B89. 1.12M). This is more than enough for the measuring of the channel profile. A stylus of 0.3 mm was used for the measurements.

To determine whether the channel profile of the mould matched that of the design, three scans of the mould where taken. They were all straight lines across the channels. Figure 4.11 below shows where the scans were taken. The probe took measurements every 0.1495 mm along the lines shown, in the direction of the arrow.
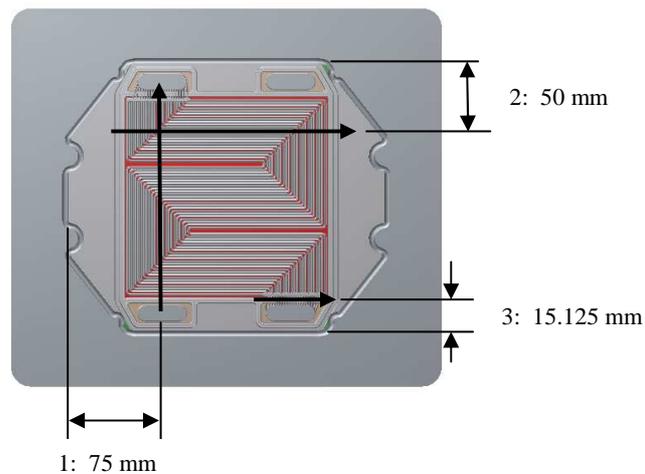
Figure 4.11: CMM Probe Scans

Using the measurements taken with the CMM, a profile of the mould was created for the areas measured. This was then compared to the profile of the design for the corresponding area. The comparison showed that there was a good fit between the measured data and the design. There was some discrepancy on the tops of all the channels where the mould is flatter than the design. This can be seen in Figure 4.12 below which is taken from scan 2. The black line is the CMM measurements, with a measurement taken at each dot, which has been offset by the radius of the

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stylus (0.15 mm). The gray area is a cross section of the mould design. There is an error at the top of the channel of about 50 µm, which should not affect the results from the moulding experiment.
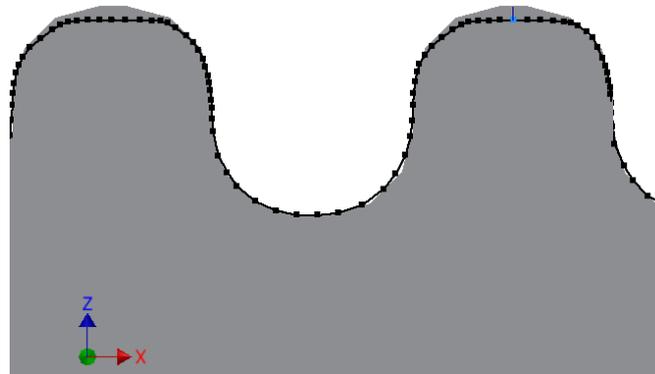
Figure 4.12: CMM Scan 2

There was also a discrepancy in the third scan as the design has square edges at the bottom of the channels and this obviously could not be cut with a ball nose cutter. This was an oversight in the design and these corners should have had fillet radii. The discrepancy can be seen in Figure 4.13 below. Again the offset for the CMM profile was 0.15 mm.
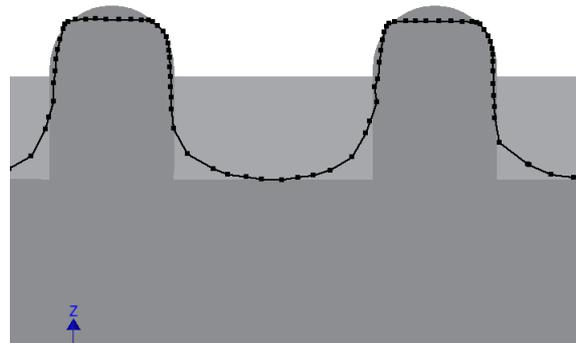
Figure 4.13: CMM Scan 3

In the first scan, the CMM data showed a kink on the one side of every channel. It was uncertain whether this was due to a measurement error, as the CMM did struggle to measure in the channels at times, or whether it was due to an error on the mould. These kinks are circled in Figure 4.14. The CMM data for this measurement is for the centre of the ball on the stylus used to make the measurements, and has not been offset as it was in the previous figures. Therefore the profile of the design has also been offset (the blue line). Thus the CMM data should follow the blue line. It was attempted to use a microscope to see if the cause for the discrepancy could be seen, but the images from the microscope where unclear. It does appear as though there is a scratch on one of the images.

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Figure 4.15 shows one of the photographs taken with the microscope in which it appears that there is a scratch on the surface.
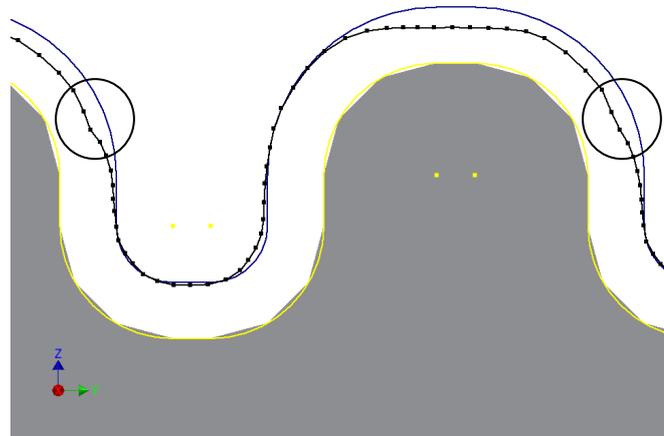
Figure 4.14: CMM Scan 1
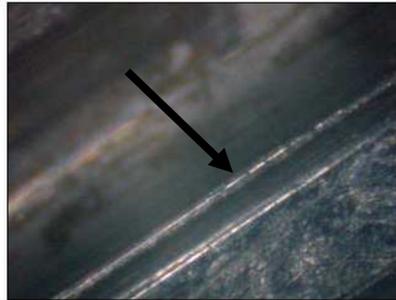
Figure 4.15: Microscope Close up of Channel

From the measurements made, it can be seen that the mould is close to the design, and within the tolerance specified. The flattening out of the top of the channels, as well as the kink in the side, should not affect the moulding of the plate. The data from the moulding experiments will therefore be reliable.

4.5. Bipolar Plate Moulding

Now that the design and construction of the mould has been discussed, the actual moulding of a BP must be considered. There are a few different steps to this process. First the raw material must be prepared, then the press and mould must be set up and allowed to heat up to the moulding temperature. Once the machine and material are ready, the moulding can begin. This section of the report will discuss the work that was done on the material development in order to get a usable material and the preparation that is required for the material. It will then go on to the actual moulding process and discuss the times associated with the moulding.

4.5.1. Material Development and Preparation

The material for the BPs was specified by HySA to be Schunk's FU4369HT. The details of the material are given in Section 2.6.3. This raised a problem for the moulding as Schunk was unwilling to supply the raw material in powder form, and only supplies already moulded plates. They also keep the processing information, such as constituents and mixing methods, confidential. The only information they give is the properties of an already moulded plate. A material that was equivalent for the moulding was needed for this thesis. Thus a material that was close to that of Schunk's FU4369HT was developed. This section will discuss how that material was decided upon as well as how the development of the material was done. The process of mixing the material for the actual moulding process will also be discussed.

The material used by Schunk is a highly filled graphite composite. This is similar to other materials used in literature. It was attempted to get as close to their material as possible for the material used in this thesis. It is also important that the material is decided upon before the mould is designed, as the mould needs to account for shrinkage. To get a material, one of Schunk's moulded plates was given to Plascom Consultants to analyse. They performed a number of tests to determine the resin type and weight, and the filler type and weight. The table below shows the tests that where done as well as the results they showed.

Table 4.5: Material Analysis

Criteria	Analysis	Result
Resin type	FTIR Spectroscopy	Phenolic Resin
Resin weight	DSC-TGA (N_2)	12.5%
Filler type	EDX	Graphite flakes
Filler weight	DSC-TGA (N_2)	87.5%
Filler particle size	SEM	4 to 6 μm

From the results it can be seen that the material Schunk uses is a Phenolic resin with a graphite flake filler of 87.5%. It was possible to get the exact same resin as Schunk as their supplier was known. The resin that was used was a Cellobond 1008p. That leaves only the graphite flakes which became problematic to find. Unfortunately suppliers for graphite flakes only sell the graphite in large quantities. It was not in the budget to buy such a large batch of graphite and finding suppliers that deal in small amounts was very difficult, causing large delays in the project. Eventually the graphite was obtained from JFJ Industries in Johannesburg, who were willing to supply a minimum of 25 kg. The graphite supplied by JFJ Industries was a FC99 5MY graphite natural flake from Fochem International. The flakes are 3 to 6 μm.

Now that a material almost exactly the same as Schunk's has been sourced, the material compounding needed to be developed before it is ready for moulding. This is a lengthy process. The aim of the material development is to get a mouldable material, which means getting proper wet out (explained below) and

getting the material into granular form. Before the development can be discussed, the preparation method must be given. The preparation is as follows: First the resin and a solvent are mixed together for approximately 2 minutes. Then the graphite is added and mixed for a further 3 minutes. The resulting mixture comes out as a paste, and is spread into a tray and baked for exactly 20 minutes. The baking is to evaporate off the solvent and partially cure the resin (B-stage curing). The final step is to break up the material into granular form, ready to be placed into the mould.

Wet out refers to the mixing of the graphite and resin, and proper wet out is obtained when each graphite particle is coated in a thin layer of the resin. The ratio of solvent to resin will determine whether proper wet out is achieved, as well as the mixing time. To determine the correct ratio, a small batch of material is prepared with a guess at the ratio. The material is then checked and the ratio is adjusted and the process is repeated until proper wet out is achieved.

The other important factor is getting all the solvent to evaporate off. This is done in the baking stage and the time the mixture is baked is important. If it is too short, some solvent will remain, forming bubbles when the part is moulded. If it is too long, the material will cure in the oven, making it useless.

The material also needs to be ground back into powder form, so it can be poured into the mould and easily spread. After it has been baked, the material is broken up by lightly grinding it. Too much force during the grinding can compact the material which is undesirable. During the grinding, the wet out can be determined as clumps of dry graphite will be found if proper wet out was not achieved. The solvent ratio or mixing time must then be adjusted. During the granulating it was found that proper wet out was achieved and the material was easy to break down into powder form.

After the granulating the material development was complete. The next step was to test the material to determine whether it was mouldable. This will determine if the material releases from the mould, or in other words, does not stick to the surface of the mould. It will also determine whether the material has sufficient cohesion, and does not break apart. If the material does not perform as required, more material development is done and the trial is attempted again.

For the first round of material development, a ratio of solvent to resin was established by starting with 60% solvent and ended with a final formulation of 600% solvent. The correct baking time was then found to be exactly 20 minutes, to evaporate off the solvent and achieve the B-stage curing. The material was then tested in a simple cup mould, with a diameter of 50 mm. This moulding was successful, and proper release and cohesion was achieved. The final test would be to test the material in the actual BP mould.

In the first trial moulding at Rheinmetall-Denel, the part was not ejected successfully. A cohesive failure occurred causing the moulded end plate to break apart and stick to both the top and the bottom of the mould. Figure 4.16 shows the

core immediately after the first trial moulding, with the material stuck to it. The material development was then continued to find an improved material. Possible adjustments were to increase the amount of resin in the mixture so that there is more binding, as well as to increase the amount of solvent used, to achieve a better wet out.

Figure 4.16: First Moulding Trial

The second round of material development found that increasing the solvent to 3000% of the resin produced better wet out. The baking time then needed to be increased to 30 minutes. An additional release agent was also added to the mixture to help prevent the moulding material sticking to the mould. This second material mix had not yet undergone a trial moulding at the time of this writing.

4.5.2. Moulding Process

Once the material is properly mixed, the actual moulding process can be started. The first step is to prepare and test the mould. The preparation involves taking the mould apart and applying an anti-corrosion layer. Then 5 layers of release agent are applied to make sure the material does not stick in the mould. Finally the moving parts are greased and the mould is re-assembled. The mould is then loaded into the moulding press and is tested cold to make sure it operates properly and all moving parts move smoothly. Next the mould is heated to the correct temperature and tested again to see that it operates hot. The mould is then ready for a trial moulding. It was found that the ejection system did function properly at the moulding temperature.

The first moulding attempted with the BP mould was with the material from the first development. The process was as follows: First the mould was heated to the moulding temperature of 169°C. This can take many hours and was done overnight. Once the mould was ready, the material was heated to 80°C in an oven for 5 minutes so that the heating in the mould is quicker. The material was then placed into the mould cavity and spread evenly. Next the mould was closed in two

stages: first the top part moved down quickly until it made contact with the material in the cavity, second it compressed the material slowly until the mould was completely closed. The resin in the composite material then melted and underwent a curing reaction. The mould was left closed for 20 minutes to allow ample time for the curing. Once the curing was complete, the mould was opened and the part was ejected.

The first trial moulding did not eject a complete part, as explained above. It was then decided to test whether the mould did work as expected with a material that is less likely to fail. Two mouldings were done, each with a different thermoset plastic material. The second material was a cotton phenolic, which was chosen for its similarity to the graphite composite that will eventually be used. Both mouldings were successful, and proper mould filling was achieved. This shows that the mould does work as it should, and once a mouldable material is developed, it should also give an intact moulded plate.

In the moulding process, once a part has been ejected, the material for the next part can be placed into the cavity and the process repeats. The moulding cycle can be seen in Figure 2.8 on Page 16. The process and the times for each step will be discussed in more detail below.

Although the trial moulding was not successful, times for the different steps of the process are still representative of a successful moulding, and therefore the times observed for the trial moulding can be used in the model later. The only exception to this is the curing time, which would most likely be reduced substantially. More tests would have to be done to find the minimum curing time. Typical times for the process are given by Davis et al (2003: 188), and are summarised in Table 4.6 below.

Table 4.6: Moulding Process Times

Step	Time (s)
Charge placement	10
Mould closing	5
Compression	5
Curing	> 20
Mould opening	5
Part removal	10

These times are close to what was observed at Rheinmetall-Denel, except for the curing time which was 20 minutes. This extended curing time was to ensure that the material had cured properly and would not be used once the process is established. According to Van Niekerk (2012) a reasonable curing time would be 12 minutes. Also, the part removal time was not observed as no complete part was ejected. However, it is clear that the times listed in Table 4.6 are similar to what will be experienced in the moulding of BPs.

5. Compression Moulding Cost Model

The processes for machining and compression moulding of bipolar plates (BPs) have been discussed in Chapters 3 and 4. The times for the various steps, as well as some of the costs, have been considered for both processes. The cost model for machining proposed by Essmann (2011) was also given, as well as an adaptation of the model. In this section a cost model for compression moulding will be developed. The moulding costs will be considered, including the cost of the mould making.

5.1.   Mould Making Cost Model

The mould making is a major part of the cost and is affected by changes in the design of the BP. The mould making contributes a large initial cost for the moulding process. It is therefore important to be able to determine the cost of the mould and the changes to the cost associated with changes in design variables. A model to determine the cost of mould making was programmed in Matlab and the methods used to determine the various costs will be discussed in this section. It is split into the material and labour costs. For a better understanding of how the cost model works, a sample calculation can be seen in Appendix A.2.

5.1.1. Material Costs

The first part of the mould to consider will be the mould base costs. This includes the entire mould except for the cavity and core, and is relative to the size of the BP. According to Boothroyd et al (2002: 698) the mould base costs in injection moulding can be estimated using the following formula:

$$C_b = 1000 + 0.45 A_c h_p^{0.4} \qquad (5.1)$$

Here C_b is the mould base cost (\$), A_c is the area of mould base cavity plate (cm^2) and h_p is the combined thickness of cavity and core plate (cm). This formula needs to be scaled to the current costs in South Africa. This can be done by comparing the quotes for mould bases from Hestico to the cost predicted by Equation 5.1. Amounts estimated by Equation 5.1 for different sized moulds are given in Table 5.1 below, along with amounts obtained by Hestico. Using this information the formula can be scaled, giving Equation 5.2.

Table 5.1: Mould Base Costs

Flow Field Area (cm)	Ac (cm)	Ac hp$^{0.4}$	Amount (\$)	Hestico Amount (R)
10x10	34.6 x 29.6	2 255.8	2 015.11	21 399
20x20	44.6 x 39.6	3 890.12	2 750.55	32 029
30x30	49.6 x 54.6	5 964.96	3 684.23	41 787

$$C_b = 9689.70 + 5.462 A_c h_p^{0.4} \qquad (5.2)$$

Here C_b is in ZAR. This gives an average error of 2.5% when compared to the quotes from Hestico. This is a good fit when considering the amount of uncertainty in cost estimation.

The mould base area, A_c, must be larger than the cavity area to provide the necessary rigidity. Van Niekerk (2012) recommended that there be 8 cm between the cavity and each side of the mould base, which is shown in Figure 5.1 for clarity. Once the size of the BP is known, the size of the mould base plates can be determined using this guideline, and Equation 5.2 can be used to estimate the cost of the base. The mould base comes in standard sizes, so the closest size that fits the recommendation should be used. The thickness of the cavity and core plate will remain constant as long as the thickness of the BP does not change by too much. In the mould produced for this research A_c has a value of 0.102 m^2, and h_p is 7.2 cm.

The material for the cavity and core insert also needs to be determined. This cost was obtained from Bohler as a cost per mass for their Bohler M201 steel (R80/kg). The material cost can now be determined for any size BP using Equations 5.3 and 5.4 for the core and cavity costs respectively. These formulas work by determining the volume of steel needed for the cavity and core, and then multiplying it by the density and cost per mass.

$$C_{core} = 4.8(L_{BP} + l_s)(W_{BP} + l_s)\, \rho_M\, C_M \qquad (5.3)$$

$$C_{cavity} = 3.6(L_{BP} + l_s)(W_{BP} + l_s)\, \rho_M\, C_M \qquad (5.4)$$

Here L_{BP} is the length of the BP (cm), w_{BP} the width of the BP (cm), ρ_M the density of Bohler M201 ($\rho_M = 7.85\text{x}10^{-3}$ kg/cm^3) and C_M the cost of the material (R/kg). To account for the material that is added around the BP, l_s is used and has a value of 5.8 cm for the mould made in this thesis. The values 4.8 and 3.6 are the respective heights of the inserts. The variables from Equations 5.3 and 5.4 can be seen in Figure 5.1 below. Pictures of the components of the mould shown in Figure 5.1 can be seen in Section 4.4.1. Figure 4.5 shows the mould plate and Figure 4.10 shows the insert with the cavity.
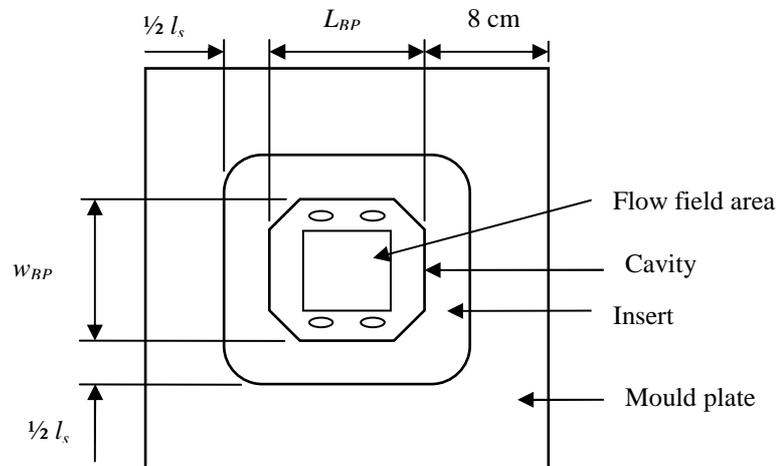

Figure 5.1: Mould Plate Diagram

The material for the cavity and core inserts also needs to be hardened. The hardening is done by Bohler and they charge R42.50 per kilogram. This is multiplied by the mass of the cavity and core to establish the total cost for hardening.

5.1.2. Machining Costs

The next cost to consider is the machining of the mould. This includes the machining of the base. However, the biggest consideration is the cavity and core machining. The machining of the mould base will be considered first and then the cavity and core will be discussed. The time for each step is calculated, which is then used to determine the cost of labour. The other costs, such as tools, are then added to the labour cost.

For the mould base, the items that need machining have been given in Section 4.4.1. However, it is not worth breaking down the cost of the work on the mould base into its individual parts as it is not a large part of the total cost and breaking it down would be overly complicated. Boothroyd et al (2002: 698) recommend for injection moulding to use the amount calculated for the material cost, also for the custom work that is needed on the mould base. This is a simple way to estimate the cost of mould base custom work and should still be valid for compression moulding. Thus the value calculated by Equation 5.2 for the material cost is also used for the cost of machining.

One part of the manufacturing that can be separated is that of the ejection system. This refers to the machining of the holes for the ejector pins. The time for the machining of one hole for an ejector pin is estimated to be 2.5 hours by Boothroyd et al (2002: 698), therefore:

$$T_{ep} = 2.5N_{pins} \qquad (5.5)$$

The number of pins will change depending on the size of the part. It is intuitive that the change will be proportional to the change in part area. Boothroyd et al (2002:698) also propose calculating the number of pins using the projected area of the part, therefore:

$$N_{pins} = ceil\left(\frac{A_{ff}}{850}\right) \qquad (5.6)$$

For BPs, A_{ff} is the projected area of the BP active flow field area (mm^2). This formula was obtained using the current design of the mould, which has an ejector pin for every 850 mm^2 of flow field area. Using the two formulas above, the time for machining the pins can be calculated.

The machining of the cavity and core inserts can now be considered. They are much more time consuming to machine than the mould base. The channel machining takes up most of the time for the core. The cavity for a BP would also be dominated by the machining of the channels, however, the mould for an end plate does not have channels on the cavity side. The channel machining will be

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separated from the profile machining for this analysis. The channel machining can then be doubled for an estimate of the cost of a BP, as opposed to an end plate.

The first aspect to consider is the machining of the channels. As explained in Section 4.4.1, a number of different size tools are used to cut the channels. The final tool is the only one smaller than the channel width and so removes the majority of the material from within the channels. The purpose of the bigger tools is to remove some of the material faster than the small tool can. The current design used 2 mm, 1 mm and 0.6 mm ball nose cutters. A change in the channel design will result in a change in tools used. A method for determining the tools used and the amount of time to machine using each tool will be presented here.

First it is necessary to determine the tools that will be used. This is done in industry simply by using the machine operator's intuition. If the channels were wider and bigger tools were to be used, it would go up according to the sizes available from the tool supplier. Also, only three tool sizes would be used and be spread evenly in size. An algorithm was therefore formulated to determine the tool sizes used for various channel widths. It chooses the biggest tool by taking a tool that has a diameter 3 times the channel width or the closest standard tool size to that. The next tool is the closest tool to 1.5 times the channel width and the final tool is taken to be the tool size that is equal to, or just smaller than the channel width. The for-loop used in the model is described below.

An excerpt from the code that finds the tool can be seen below, and is explained here. First the ideal tool size (`T_ideal`) is found by multiplying the channel size by a factor, as explained above. This ideal size is then compared to the available tool sizes, which are stored in a vector (`Tool_sizes`). In lines 1 to 3 below, each tool size is subtracted from the ideal size, and saved in a new vector (`find_T`). The smallest value in this vector corresponds to the tool that is the closest to the ideal size. In line 4, the position of this smallest value is saved (`In`), and the tool that is in this same position in the standard tool sizes vector, is the tool that is the closest to the ideal. This tool size is saved in line 5. It is then returned for the rest of the analysis.

```
for i = 1:8                                             (1)
    find_T(i) = size - Tool_sizes(i);                   (2)
end                                                     (3)
[Y, In] = min(abs(find_T));                             (4)
Tool = Tool_sizes(In);                                  (5)
```

The machining is assumed to be done in two parts. First a profile cut is done, which removes most of the material from within the channels. Then a lace cut is done, which is needed to get the radii at the top of the channels. The times for both these processes are needed. The depth that can be cut with the larger tools must also be determined so that the number of passes that is needed with them can be calculated. The algorithm to calculate this depth uses the equations given below in Equations 5.7 and 5.8. Figure 5.2 illustrates the symbols in the equations.

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$$p = \sqrt{(r_t + r_c)^2 - l_c^2} \qquad\qquad (5.7)$$

$$d = r_t + r_c - p \qquad\qquad (5.8)$$
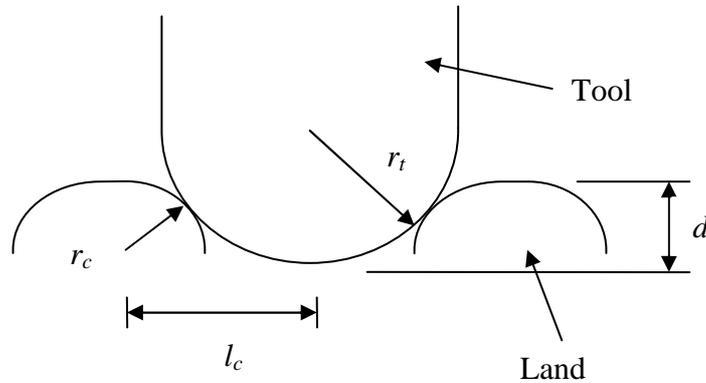
Figure 5.2: Machining Depth Calculation

To determine the time to machine the channels for each tool, the length of cut and feed rate are considered. The recommended depth of cut is also considered to determine the number of passes. These parameters are obtained from the supplier recommendations (Table 5.2), as well as the channel design. The maximum spindle speed for all mould makers in the Cape Town area this author found was about 20 000 rpm. Where the recommended spindle speed could not be reached, the feed rate should be adjusted. Table 5.3 shows the feed rates after being adjusted to a maximum spindle speed of 20 000 rpm.

Table 5.2: Recommended Machining Parameters

Tool size (mm)	Feed (mm/min)	Spindle Speed (rpm)	Depth of Cut (mm)
0.6	1 300	40 000	0.025
0.8	1 900	40 000	0.04
1	3 000	40 000	0.05
2	3 500	31 000	0.11
3	3 400	22 000	0.13
4	2 700	16 000	0.15

Table 5.3: Feed Rates Adjusted to Spindle Speed

Tool size (mm)	Spindle Speed (rpm)	Corresponding Feed (mm/min)
0.6	20 000	650
0.8	20 000	950
1	20 000	1 500
2	20 000	2 200
3	20 000	3 000
4	16 000	2 700

The tool path length for the channels is determined by first using the size of the flow field area, and calculating the number of channels that will fit. It is assumed that the channels go back and forth across the flow field three times, and that the gaps between passes are the same, as in the design from HySA. It is further assumed that the flow field is square, and the channel width is the same, or near to, the land width. Once the number of channels is determined, the proportion of flow field area that is taken up by the channels is calculated, and this divided by the channel width gives the total length of the channels. Equations 5.9 to 5.12 show the steps to determine the channel length. This calculation can also be seen in Appendix A.2.

$$n_{ch} = floor(\frac{w_{ff} - 2w_g}{6w_{ch}}) \tag{5.9}$$

$$P_{ch} = \frac{n_{ch}w_{ch}}{w_{ff}} \tag{5.10}$$

$$A_{ch} = A_{ff}P_{ch} \tag{5.11}$$

$$L_{ch} = \frac{A_{ch}}{w_{ch}} \tag{5.12}$$

In the equations above n_{ch} is the number of channels, while w_{ff}, w_{ch} and w_g are the widths of the flow field, channels and the gap between separate passes of the channels respectively. P_{ch} is the proportion of flow field taken up by the channels. A_{ch} and L_{ch} are the area and length of the channels respectively. Figure 5.3 shows the flow field area with the w_{ff} and w_g for clarity.
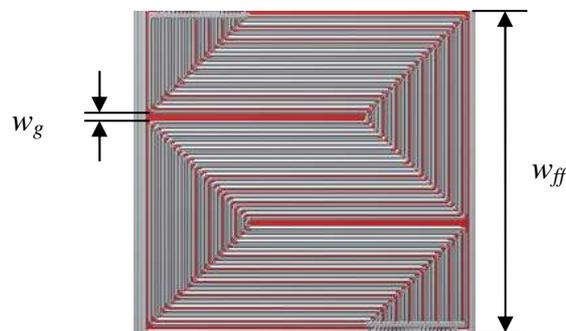
Figure 5.3: Flow Field Area

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Combining the channel length with the feed and depth of cut above, the time for the profile machining can be calculated. This can be seen in Equation 5.13. This gives a close approximation to the machining times observed at Mould Shop for the larger tools. The machining time for the smallest tool, however, is underestimated since when a tool breaks, there is additional time spent changing the tool and time is wasted while the machine runs with a broken tool. The machining time for the smallest tool is therefore adjusted by multiplying it with a factor of 1.6 to account for this. The machining time then fits closely with the observations made at Mould Shop.

For the lace cutting, the cutting length is calculated using the tool size, the step over recommended by the manufacturer, the size of the flow field area and the number of passes needed. The number of passes, N_c, is calculated using the depth of cut required, determined by Equation 5.8, and the maximum depth of cut from the tool manufacturers recommendations. The recommended step over is $0.2r_t$, where r_t is the radius of the tool. The time to cut can then be calculated using the cutting length as well as the feed rate, as shown in Equation 5.14. As mentioned before the CNC machine cannot sustain a high feed rate while moving along the z-axis (up and down), therefore during the lace cutting the feed rate reduces when the cutter moves up and down over the channels. The observed feed rate was about 300 mm/min and this was the feed rate used in the model during lace cutting.

$$T_{Prof} = \frac{L_{ch}N_c}{F_R} n_s \tag{5.13}$$

$$T_{Lace} = ceil\left(\frac{\sqrt{A_{ff}}}{0.2r_t}\right)\frac{\sqrt{A_{ff}}}{F_L} n_s \tag{5.14}$$

Here T_{Prof} and T_{Lace} are the profile and lace machining times respectively, per cutter (in minutes). For the smallest cutter, T_{Prof} and T_{Lace} will be multiplied by a factor of 1.6 to account for tool breakage, as discussed above. The number of passes needed is given by N_c. F_R is the feed rate (mm/min), already adjusted for spindle speed and F_L the achieved lace cutting feed rate (300 mm/min). The channel multiplier, n_s, has a value of 2 for a BP, with channels on both sides, or 1 for an end plate. The equation used to adjust the spindle speed can be seen in Equation 5.15 below.

$$F_R = \left(\frac{v_{max}}{v_{rec}}\right)F_{Rec} \tag{5.15}$$

In Equation 5.15, v_{max} and v_{rec} are respectively the machine's maximum and the tool supplier's recommended spindle speeds (rpm). F_{Rec} is the tool supplier's recommended feed rate (mm/min).

The cost of the tools must also be accounted for. For this the tool life is needed, which was estimated using the number of tools used while making the mould, described in Chapter 4.4. Only one of each of the 2 mm and 1 mm tools was used,

while 6 of the 0.6 mm tool were used. In the model, the 6 tools used will be scaled by the area of the BP for predicting the number of small tools used. The time for machining of channels on both the cavity and core will be the same, and the factor n_s is used to double the tool cost for the manufacture of a BP, assuming that each side starts with a new tool. Equation 5.16 shows how the number of tools used is calculated. The term F_A is used to scale the number of tools used by the area of the flow field, using the design of the mould that was made for this thesis. The flow field area, A_{ff}, must be in mm^2.

$$F_A = \frac{A_{ff}}{10000} \tag{5.16}$$

$$N_{tools} = ceil\left(\frac{N_c}{6}F_A\right)n_s \tag{5.17}$$

The final part of the machining of the mould is the peripheral machining. This is all the machining for the cavity and core that is not included in the channel or ejector pin machining. The time taken for this machining was derived from the observations made at Mould Shop as well as discussions with the machine operator. The majority of the peripheral machining is the machining of the general shape, or outline of the core and cavity. This remains the same whether an end plate or BP is machined. The other part is the groove for the seal and the inlet holes on the BP. This is then doubled for the production of a mould for a BP as opposed to an end plate. It is also scaled for the size of the BP. The equation can be seen below in Equation 5.17, were the machining time is given in hours. Again, A_{ff} must be in mm^2.

$$T_{PM} = (20 + 12n_s)F_A \tag{5.18}$$

5.1.3. Other Costs

The remaining costs to consider are the cost of polishing the mould, which is a lengthy procedure, and the assembly of the mould components. There are also overhead costs, but these are included in the labour rate and machine rate, and will not be discussed further.

The polishing takes a long time and is labour intensive as it is done by hand. The time to polish the BP is dominated by the polishing of the channels. The polishing time is also relative to the surface area that needs to be polished. The projected surface area of the flow field is used to calculate the polishing times, as most of the time is spent on the channel polishing. A formula to predict the polishing time was obtained using the time it took to polish the prototype mould at Mould Shop. It is shown in Equation 5.18 below. As discussed previously, the term F_A is used to scale the polishing by the area of the flow field.

$$T_p = 40F_An_s \tag{5.19}$$

Here T_p is the time to polish the mould (hrs), A_{ff} is the flow field area (mm^2) and n_s doubles the time for polishing a BP. It has a value of 1 for an end plate and 2 for a BP. This time, multiplied by the labour rate, gives the cost of the polishing.

The final cost to consider is the assembly of the mould and the final adjustments. When the mould is put together, it is checked to see that the two mould halves fit together properly. Any point at which they scrape together must be filed down. The assembly and adjusting is not a lengthy procedure and will remain more or less constant no matter what the size of the mould. Therefore a time of 1 day (8 hours) is allocated to this task. This is what was observed from Mould Shop.

5.2. Moulding Cost Model

The cost for a mould for BPs has been given in the previous section. This is the first step in determining the cost for compression moulding BPs, and forms part of the total cost. The process of material preparation and compression moulding has also been given in Section 4.5. The cost model for the moulding process is developed here. This will be used to compare the costs of machining and compression moulding later in this report. For a better understanding of how the cost model works, a sample calculation can be seen in Appendix A.3.

5.2.1. Material Costs

The first cost to consider is that of the material. This includes the cost of purchasing and delivering the material, as well as the mixing and preparation to get it to a mouldable form. The material consists of the resin and graphite filler, while a solvent is also used during the preparation, but does not form part of the final composition. The costs for the various ingredients can be seen in Table 5.4, including tax and import costs.

Table 5.4: Material Costs

Material	Order Size (kg)	Cost (R)	Cost per mass (R/kg)
Phenolic Resin	25	3800	152
Graphite flakes	25	6555	262
Solvent	NA	NA	50

Using the prices given in Table 5.4, along with the ratio of the ingredients and the volume of the mould, the cost for the material per BP can be determined. To estimate the BP volume a simplified model is used which is split into parts of constant thickness. Figure 5.4 shows this simplified model, and the calculations for the volume can be seen in Appendix A.3. The sum of the volumes of these parts is the total volume of the BP. From this, the amount of each of the ingredients can be calculated, by calculating the mass of the moulded material using the density (1.9 g/cm^3). Once the mass of the mixture is known, the mass of each ingredient can be found by multiplying by the ratio of that ingredient to the total, i.e. 88% graphite and 12% resin. The amount of solvent used is 3000% the

resin content. The mass of the specific ingredient is then multiplied by the cost per unit mass for that ingredient. The cost for the release agent was not included as it is negligible. These formulas can be seen below in Equation 5.19 to 5.21.
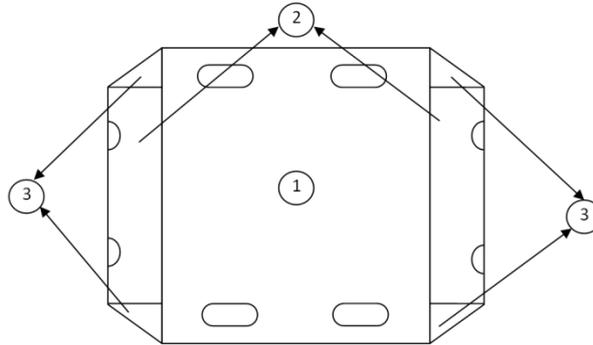

Figure 5.4: Simplified BP Diagram

$$m_{tot} = V_m \rho_{tot} \qquad (5.20)$$

$$m_i = r_i m_{tot} \qquad (5.21)$$

$$C_i = m_i C_{mi} \qquad (5.22)$$

Here m_{tot} and m_i are the mass of the total and ingredient for one part (kg). V_m is the volume of the unmoulded part (cm^3). The ratio of the ingredient to the total is given by r_i. C_i is the cost of the ingredient for one part (R), and C_{mi} is the cost of the material per unit weight (R/kg).

The material preparation includes the measuring out of each of the ingredients, mixing, baking and granulating. The cost of this is determined by calculating the time for each step and multiplying this by the hourly rate. The times for each step are given in Table 5.5. It is possible to make 25kg of material at a time.

Table 5.5: Material Preparation Times

Step	Time (min)
Mixing ingredients	3 – 4
Laying in pan	2
Baking	30
Granulating	15

The cost of the mould must also be considered at this stage. The cost of the mould is a once off cost that is spread over the number of BPs made. The mould does deteriorate and will eventually need to be replaced, so the cost per plate will be determined by first deciding on a production volume, and then finding the number of moulds needed. The cost per plate will be spread over the amount for all the moulds.

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The lifetime for the mould could not be determined experimentally as that would require moulding enough BPs to wear out the mould. An expert's opinion was therefore used to determine the mould life. Van Niekerk (2012) proposed a value of 10 000 as the mould life. Graphite is a relatively soft material to mould and so does not wear the mould much. There is also little movement of the material during the compressing of the mould, and therefore little shear to wear out the mould. These two factors give the mould its high life.

5.2.2. Moulding Costs

Now that the cost of the material preparation has been determined the cost model for the actual moulding can be developed. The moulding process was discussed in Section 4.5.2 and the times for each of the steps can be seen in Table 4.6 on page 54. The method of determining the cost of the process will be discussed here. The cost is determined simply by finding the total time to mould the plate and then multiplying that time by the hourly rate. Not shown in Table 4.6 is the time to remove any flash from the part and inspect it. From the trial moulding it was found that there was very little flash, due to the low resin content. There was also no data obtained for flash removal times. Van Niekerk (2012) advised a time for the flash removal and inspection of 2 minutes. Equation 5.22 below shows the formula for determining the moulding time.

$$T_{mould} = T_{place} + T_{close} + T_{comp} + T_{cure} + T_{open} + T_{rem} \qquad (5.23)$$

Here T_{place}, T_{close}, T_{comp}, T_{cure}, T_{open}, T_{rem} are the times for placing the material, closing the mould, compressing the material, curing the material, opening the mould and removing the moulded part, respectively. The flash removal and inspection time must still be added to this.

The total time of each step can now be multiplied by the hourly rate to determine the cost of labour for the moulding process. Equation 5.23 below is used for this final step.

$$C_{Labour} = (T_{mix} + T_{mould} + T_{flash})HR \qquad (5.24)$$

Here C_{labour} is the cost of labour (ZAR), T_{mix}, T_{mould}, T_{flash} are the times for material mixing, moulding and flash removal respectively. *HR* is the workshop's hourly rate. This labour cost can then be added to the cost of the materials and the mould to determine the total cost. A sample calculation can be seen in Appendix A.3.

5.2.3. Model Analysis

This section will argue the validity of the moulding model so that it may be used to estimate the cost for moulding BPs with confidence. The cost model first uses the mould making cost model for the mould cost, and then predicts the overall cost of the moulding process. The results from the mould making cost model will therefore be separated from the overall model results to clearly illustrate the effect of changing the design on the mould making cost. The mould making results will be given first, with the results from the overall model shown after.

The first step was to test the accuracy of the mould making model. This is done by comparing the cost to make an end plate estimated by the model to the cost incurred by Mould Shop. Thus the parameters for the mould that were used at Mould Shop where input into the model and the resulting cost estimate was compared to the quote from mould shop, as well as what was observed during the manufacturing of the mould. The resulting comparison can be seen in Table 5.6 below.

Table 5.6: Comparison of Estimated Cost to Observed Cost

	Cost Model	Mould Shop
Material Cost	R 30 100	R 34 000
Labour Cost	R 85 520	R 86 800
Total	R 115 620	R 120 800

From Table 5.6 it can be seen that the estimate of the material cost is just over 10% off. This is acceptable for cost estimating and shows that the model does a good job of predicting the material cost. The cost of the labour is almost exactly the same, however the labour cost was calibrated using the observations from Mould Shop and so the two costs should match up closely. This analysis has shown that the model is suitably accurate for cost estimation.

The validity for the moulding model must now be established. This is harder to do as there is no comparison that can be made as with the mould making. The moulding model relies on expert opinions and observations on what parts of the process could be replicated.

The major cost drivers for the moulding process are the material costs and labour. The material costs have been established fairly accurately as they are based on the actual purchase price for the graphite, resin and solvent used for the trial moulding.

To establish the labour cost, the material preparation and moulding time is needed. The times for the material preparation where obtained from the mixing of the material for the trial moulding. It is hoped that this mixing gives an accurate representation compared to what might happen on a larger scale. Typical times for the moulding process have been discussed in Section 4.5.2. These times are similar to that observed during the trial moulding with the exception of the curing time. The curing time was taken to be 12 minutes based on an expert's opinion (Van Niekerk, 2012).

The mould making and moulding models' validity has been argued in this section. Considering these arguments, it was decided that the models are accurate enough for the purposes of cost estimation. In the next section the possible issues with the models will be discussed.

5.2.4. Model Evaluation

As with the machining model, there are various assumptions that have to be made as well as other problems that could cause inaccurate cost estimates. These will be discussed here. First the potential problems with the mould making cost model will be discussed, followed by a discussion of the moulding model's flaws.

The model for mould making is based on the making of one mould at Mould Shop, which was a mould for an end plate. The model has been extended to estimate the cost of a BP, however, which can be problematic. There are some unknowns with the making of a mould for a BP that cannot be accounted for. There will be changes to the design of the mould that will change the cost, making the estimate uncertain. However the major costs of the material and channel machining can be accurately estimated for a BP and so it is believed that the model will not be far off. The unknown changes are in the peripheral machining, which is not a major part of the total cost. More work is needed to accurately determine the cost of making a mould for a BP, which was not possible in this thesis.

It is also assumed in the model that of the three tools sizes used to machine the channels, eight tools will be used in total; one each of the bigger tools and six of the smallest. This may not be true for all channel sizes and it is expected that fewer tools will be needed for machining larger channels. There is not enough data on the tool life for the various tool sizes and more work will have to be done to get this data. Once again this should not have a major influence on the model as the tool costs are small when compared to the total. The cost for all three sizes is also assumed to be the same, even though the larger tools should cost less. This difference is also small.

The cost for the work on the mould base is taken to be the same as the material cost. This is a rule of thumb and does not give the actual cost of the work on the mould base. Breaking the mould base machining into its various parts and calculating the actual cost is complicated and may not be much more accurate than the estimation made above. It was therefore decided to use the method of doubling the material cost.

The times for the various tasks taken form Mould Shop may not always be accurate. It was also imposable to observe every part of the mould making and so the machine operator's statements had to be used. Therefore there may be some inaccuracies in parts of the model. However, the model does fit what was observed as well as what was quoted to a reasonable extent.

There are also issues with the moulding model. The main issue is that there is no data to validate the model. It was not possible to do a production run and so the model relies on expert opinions at times.

The other issue with the moulding model is that it uses costs for materials that could change over time, and change with the volume of material ordered. This will affect the accuracy of an estimate, but if the model is used for comparisons of

different designs, or to compare with the machining process, this should not be an issue. These figures can also be adjusted in future to try and maintain accuracy in the estimated costs.

Now that the model for compression moulding has been discussed and its validation argued, it may be used to estimate the cost of manufacturing BPs. The following section will use the model developed here to analyse the effect of design changes and to compare compression moulding with machining.

6. Cost Model Results

6.1. Introduction

In Section 3.5 and Chapter 5 the machining and compression moulding cost models have been developed and their validity argued. This section will assume the validity of the models and use them to determine the effects of design changes, as well as make a comparison of the two manufacturing methods. The results of the models have already been shown while demonstrating their validity and so not all the results will be repeated here. This section will focus on aspects that were not discussed previously, especially the comparison between the costs between the machining and compression moulding processes. More detail on how the costs are calculated can be found in Appendix A.

6.2. Machining Model Results

The first model to be considered is the machining model. The model has been described and evaluated in Chapter 3 and will now be used to analyse the effects of design changes, as well as the cost for different production volumes. In the last section of this chapter the cost of making bipolar plates (BPs) by machining will be compared to the cost of compression moulding.

The first aspect to consider is the effect of changing the channel size. An increase in channel size will improve the tool life which means that fewer tools are used and that there is a small reduction in the machining time as there is less time wasted on changing tools. With a big enough increase, less channels will fit on the flow field area and so the machining time is less as the total channel length is reduced. There is no increase in feed rate when using larger tool sizes, however, as the maximum feed rate for the machine is always used. Figure 6.1 below shows the cost of machining BPs for various channel sizes. The parameters other than channel size, such as flow field area size, were kept constant. Also it should be noted that the analysis was for a BP and so the channel machining was done on both sides. The analysis was done for a batch size of 100 plates.

From Figure 6.1 it can be seen that there is a significant reduction in cost with an increase in channel size. The cost changes from around R800 for a channel size of 0.5 mm to about R665 for a channel size of 0.73 mm. The cost of the BPs is therefore quite sensitive to channel size, which is to be expected. The maximum channel size used was 0.73 mm as above this the tool life model developed by Essmann (2011) may not be valid. Even though the increasing in channel size does have a significant effect, the material cost of over R400 per plate dominates the cost.
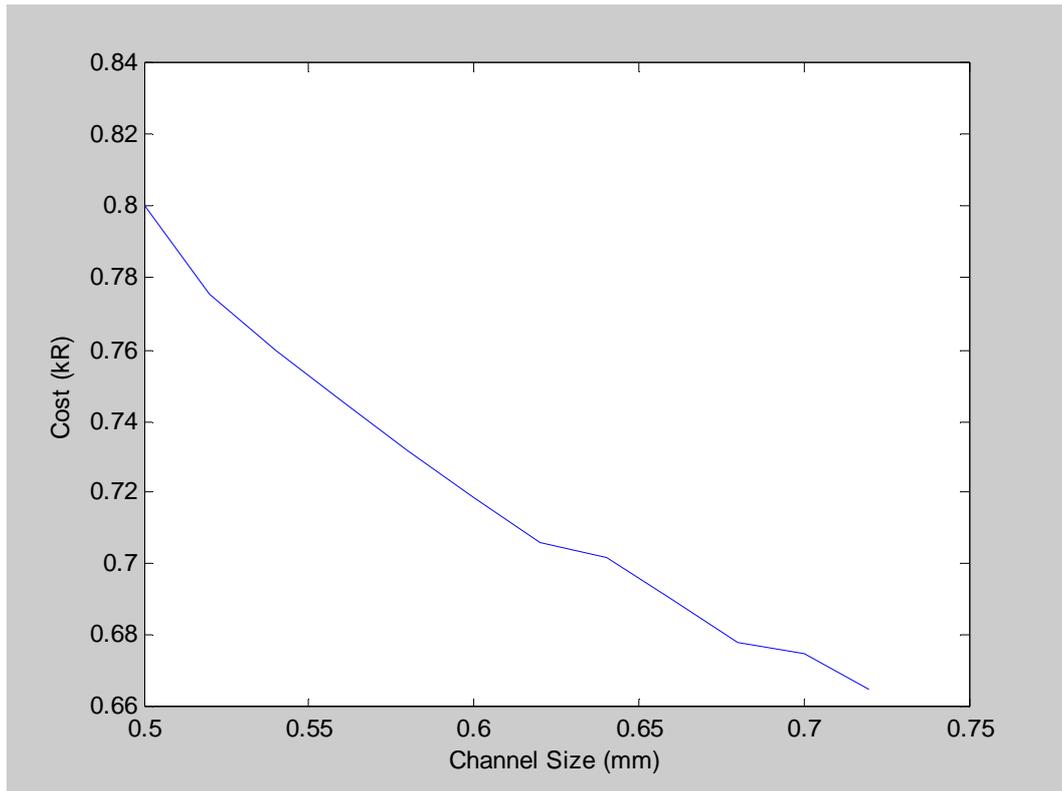
Figure 6.1: Graph Showing Cost vs. Channel Size for Machined BPs

In Figure 6.1 above, a number of discontinuities can be seen, where the model predicts that the difference in cost sometimes changes little between steps up in tool size, while at other points the change is more significant. The reason for this is that some changes in tool size will cause the number of channels in the flow field to be reduced by one, reducing the machining time and in turn the cost. At two points the number of channels does not decrease and so the cost changes little.

The other possible design change is the increase in the plate size, for the production of a bigger fuel cell. This increase in the flow field area means an increase in the channel length and so more time is spent machining and more tools are used. There is also an increase in material costs as larger blank plates must be ordered. Figure 6.2 below shows how the cost increases with an increase in BP flow field area. Once again the other parameters where kept constant at typical values, and the batch size was taken to be 100 plates.

The graph shows that there is a major increase in cost with flow field area. The main cost driver, material cost, increases linearly with the increase in area. This is also true for the machining time. The increase in cost for an increase in flow field area is therefore linear. The cost goes from about R680 for a plate of 100x100 mm to about R5 350 at 300x300 mm. This analysis is for a BP and so the effect would not be as significant for an end plate as the machining time would be halved. However the main increase due to the material so it would not have a major effect.

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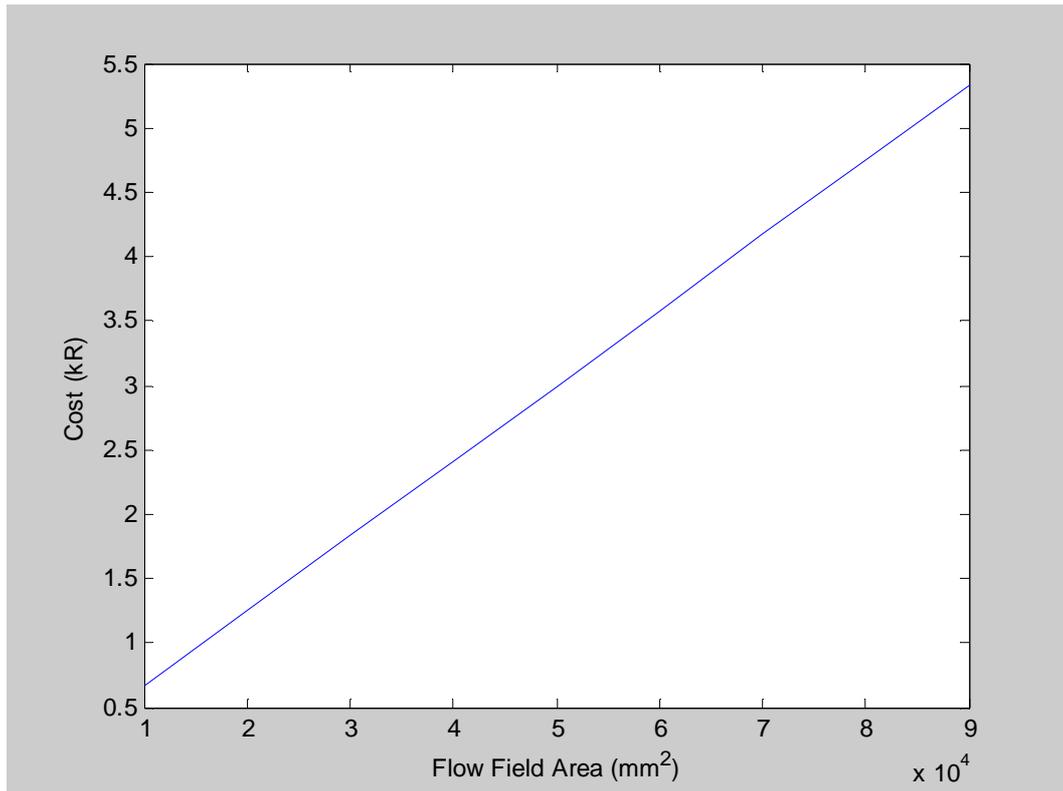
Figure 6.2: Graph of Cost vs. Flow Field Area for Machined BPs

The final factor to consider is the effect of batch size on the cost of a BP. This will be most important when comparing machining against compression moulding. A BP design close to that of the mould made for the compression moulding experiments was used and the cost for various batch sizes was calculated. The analysis used a channel width of about 0.71mm, and a flow field area of 100 mm by 100 mm. The resulting costs can be seen in the graph below. The range used for production volume goes from 5 plates, less than the absolute minimum one would have to make for a complete cell, to 1000 plates.

From Figure 6.3 it can be seen that the cost drops from almost R740 for the production of five plates to about R682 for 200 plates. This is not a very big difference, as is expected with the machining process. It can also be seen that after a batch size of 50 plates there is hardly any change in the cost per plate. The difference in cost that does occur is accounted for by the cost of the tools. At least one each of all three tools (major channel, minor channel and peripheral) is needed for the production of a plate. However, the tools for the minor channels and peripheral features can be used on more than one plate before breaking, thereby reducing the cost per plate for higher production volumes.

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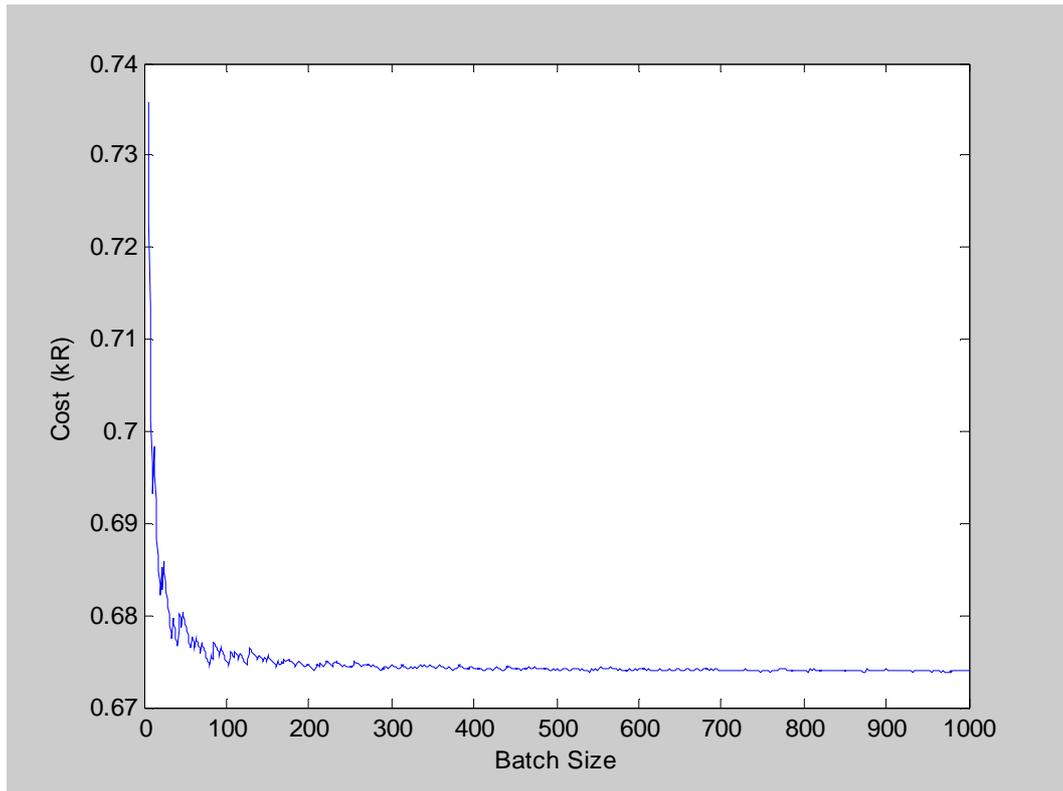
Figure 6.3: Graph of Cost vs. Batch Size for Machined BPs

6.3.   Compression Moulding Model Results

In Chapter 5 the model for the compression moulding of BPs was described. This section of the report will discuss the results of that model and give the effects of design changes and production volume on cost for BPs made by compression moulding. Later in this chapter a comparison between the machining and compression moulding methods will be given.

Part of the reason for constructing the cost model is to determine the effect of design changes. Thus the model was used to estimate the cost for various channel sizes. The cost to construct a mould for a BP (channels on both sides) was considered for channel sizes from 0.5 mm to 1.4 mm in increments of 0.01 mm. The results can be seen in Figure 6.4 below.

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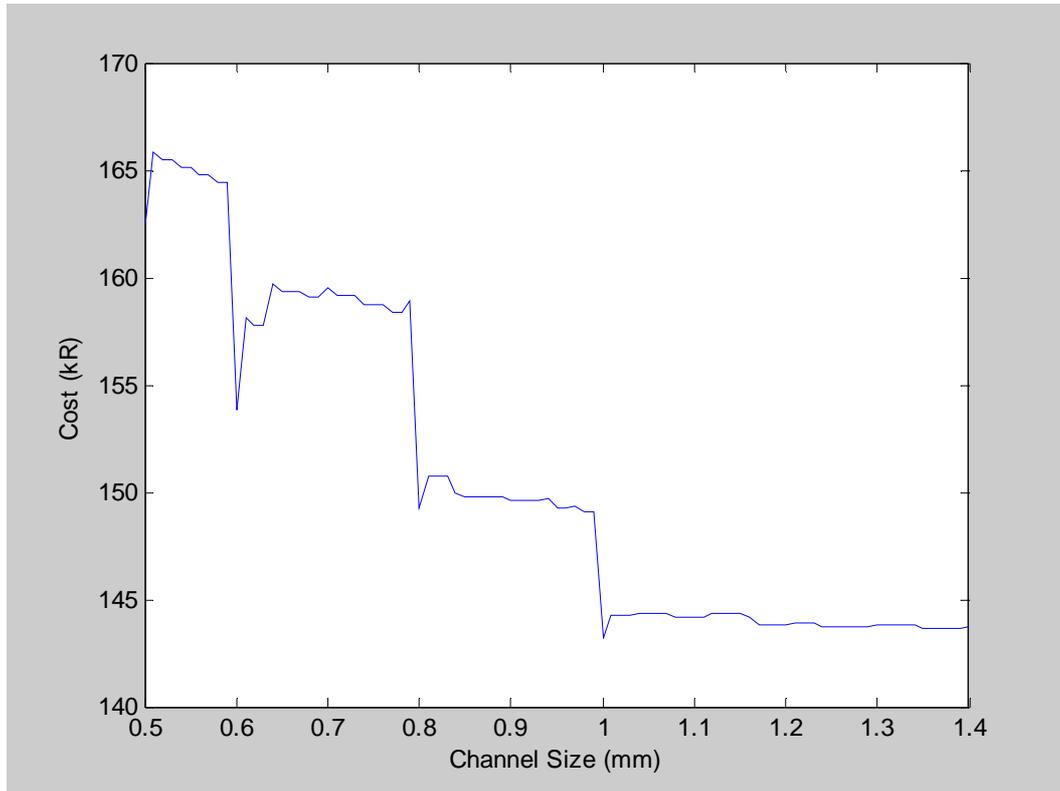
Figure 6.4: Graph of Mould Cost vs. Channel Size

Figure 6.4 above requires some explanation so that the factors that cause the cost to change can be understood. The large drops in cost on the graph correspond to the tool sizes available for the channel machining. As explained in Section 5.1.2, three tools are used for the channel machining. As the final tool needed becomes larger, the machining time drops as the feed rate for that tool is faster. The other factor reducing the cost is that as the channels get larger, fewer can fit on the BP, which reduces the machining length. Table 6.1 below shows the size of the tools used as well as the number of cuts made with each tool for a selection of channel sizes. It can be seen that there is a jump in machining time as the channel becomes bigger than the 3rd tool due to the increased number of cuts needed. There is then a drop in time as the 1st tool changes to larger size, due to a reduction in the lace cutting time. The number of channels that are on the plate also drops as the channels get larger, giving a small decrease in machining time.

Table 6.1: Channel Machining Parameters

Channel size	1st Tool		2nd Tool		3rd Tool		# Channels	Machining time (hrs)
	Size	# cuts	Size	# cuts	Size	# cuts		
0.8	2	2	1	5	0.8	11	21	23.77
0.82	2	2	1	5	0.8	22	20	24.89
0.84	3	2	1	7	0.8	22	20	23.89
0.86	3	2	1	7	0.8	22	19	23.74
0.88	3	2	1	7	0.8	22	19	23.74
0.9	3	2	1	8	0.8	22	18	23.65

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From Figure 6.4 it can be seen that there is a cost saving to be made by widening the channel size, however it is not a large saving compared to the total cost. The drop from 0.7 mm to 0.9 mm channels is about R10 000, or only 6%. It can also be seen from the graph that the advantage gained from widening the channels becomes less as they become wider, as the reduction in machining time becomes less. The cost goes from a maximum of about R165 500 to a minimum of about R143 700.

The next design change to consider is the change in size of the BP. A bigger plate would need a bigger mould increasing the material costs. The channels would also be longer, increasing the machining time. The model was used to estimate the cost for end plates of various sizes, with constant channel width. The costs can be seen in Figure 6.5 below.
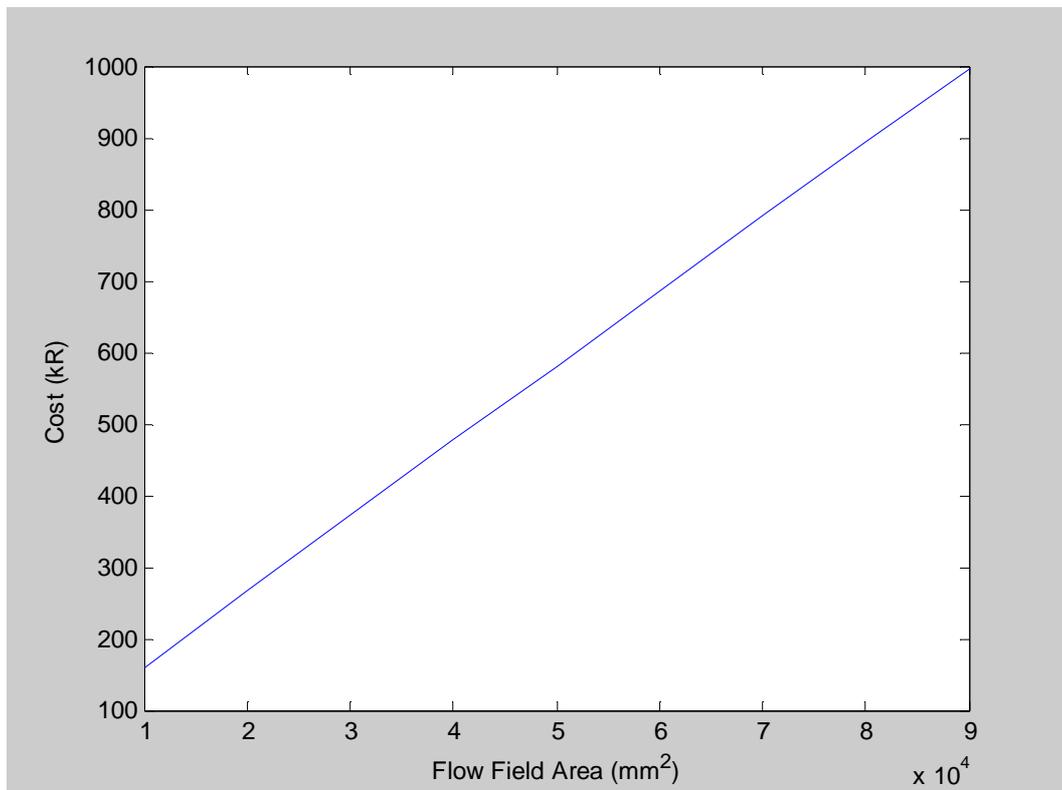
Figure 6.5: Graph of Mould Cost vs. Flow Field Area

From Figure 6.5 it can be seen that increasing the area of the end plate increases the cost significantly. Almost every cost driver increases with an increase in plate area. This includes material costs, channel machining time, polishing time, the number of ejector pins needed and the material hardening costs. The graph also shows that there is a linear relationship between cost and area.

The costs considered so far have been for the construction of a mould for a BP, with channels on both sides. The difference in cost to construct a mould for an end

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plate (channels on only one side) and a BP must now be estimated. The cost model was used with the same parameters used for the analysis above. The two costs are shown in Table 6.2 below. From the table it can be seen that there is a small increase in the material cost, due to the extra tools that are needed for the channel machining. There is a much larger jump in the labour cost, due to the increased time to machine the channels as well as the increased polishing time as the polishing of the channels takes much longer than polishing the flat surface of the end plate mould.

Table 6.2: Mould Cost Comparison for an End Plate vs. a BP

	End Plate	**Bipolar Plate**
Material Cost	R 30 100	R 35 700
Labour Cost	R 85 520	R 123 850
Total	R 115 620	R 159 550

Now that the effect of the BP parameters has been investigated, the total cost of moulding BPs can be estimated. As with the analysis of the mould making model, the effect of channel size and size of the plate will be considered. Changing the channel size will only affect the cost of making the mould while changing the size of the plate will affect the material costs as well. The costs estimated below are for BPs and not end plates, and so there are channels on both sides. This is because there will be higher production rates for the BPs as each fuel cell has multiple BPs but only one end plate on each end.

The first aspect to consider is the estimated cost for the design specified by HySA Systems. The cost estimated here will be used to determine if the manufacture of BPs in South Africa is economical. For this the change in cost with production volume needs to be considered. Thus it can be determined at what point the manufacture becomes economical, if at all. Figure 6.6 shows the cost per plate of BPs over various production volumes. From the graph it can be seen that the cost decreases asymptotically towards a value of R140. This is where the value of the mould begins to become insignificant and the material and labour for the moulding become dominant. The cost for a batch of 1000 plates, which should easily be reached, is about R295.

The first design change to consider is the change in channel width. As mentioned above this only affects the cost of the mould making, but it is useful to see how this change in design changes the overall cost of the BP. The graph below shows the cost vs. channel size. A production volume of 1000 is used for the graph, and the other design parameters are kept the same as for the mould making analysis done earlier in this section.
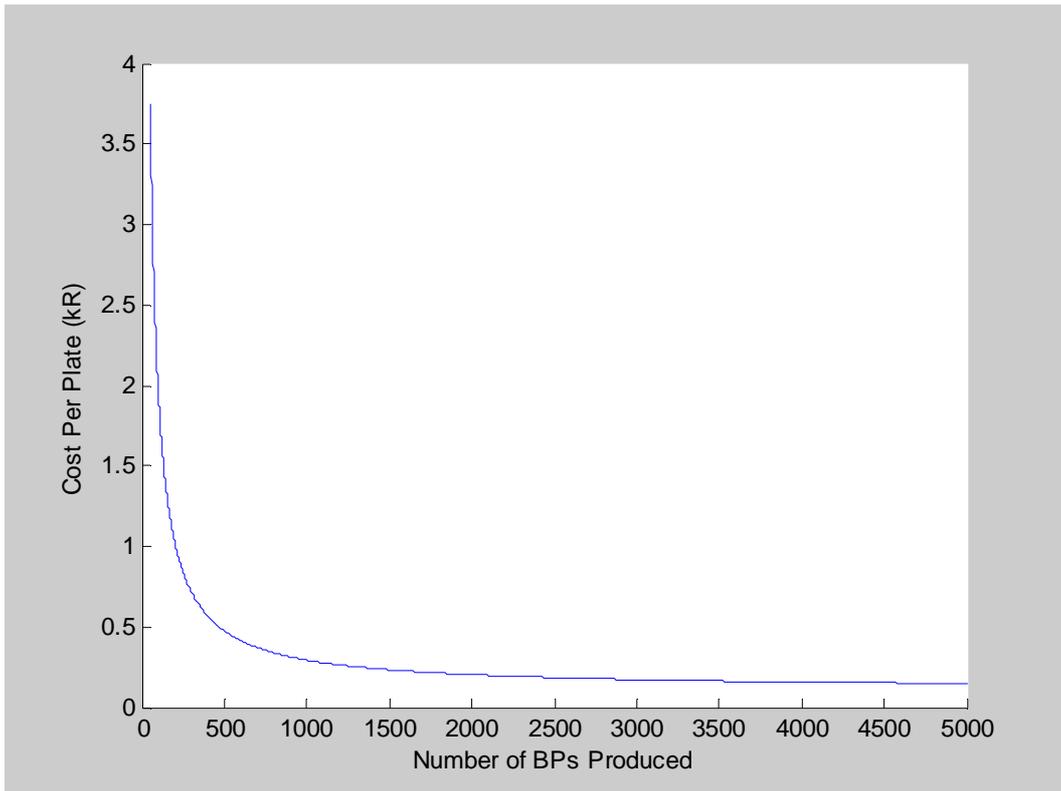
**Figure 6.6: Graph of Cost vs. Production Volume**
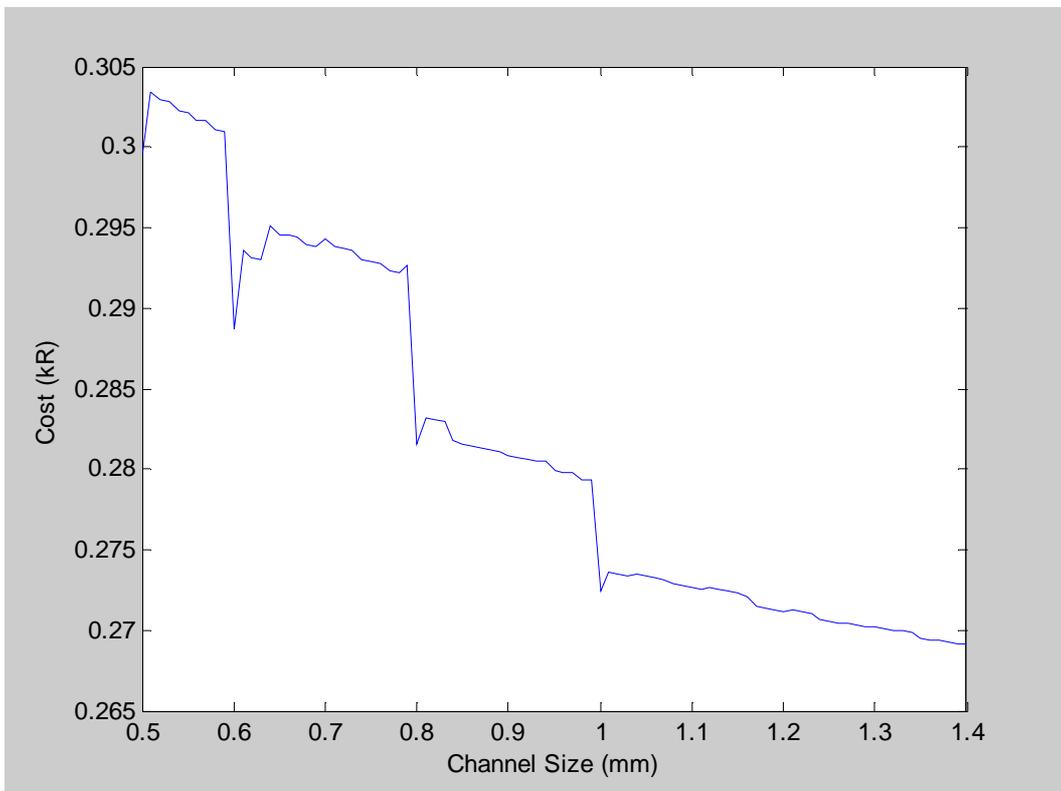
Figure 6.7: Graph of Cost vs. Channel Size for Compression Moulded BPs

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From Figure 6.7 it can be seen that the cost of BPs is relatively insensitive to the channel size for larger production volumes. This is because the mould cost is only a small part of the total cost for large production volumes. The cost is only reduced by less than R30 per plate for an increase in channel size of 0.8 mm. Although the reduction in cost is not large, if a cell were to have 20 BPs in it, the cost of the cell would be reduced by R600 which is a significant difference in cost. Therefore channel size is an important consideration.

The next consideration is the change in cost with size of the BP. This increases the cost of the mould as well as the cost of the material used in the moulding. Figure 6.8 below shows how the cost increases with an increase in BP area. The analysis was done for a production volume of 1000, and the other parameters were kept the same as for the mould making analysis done earlier in this section.
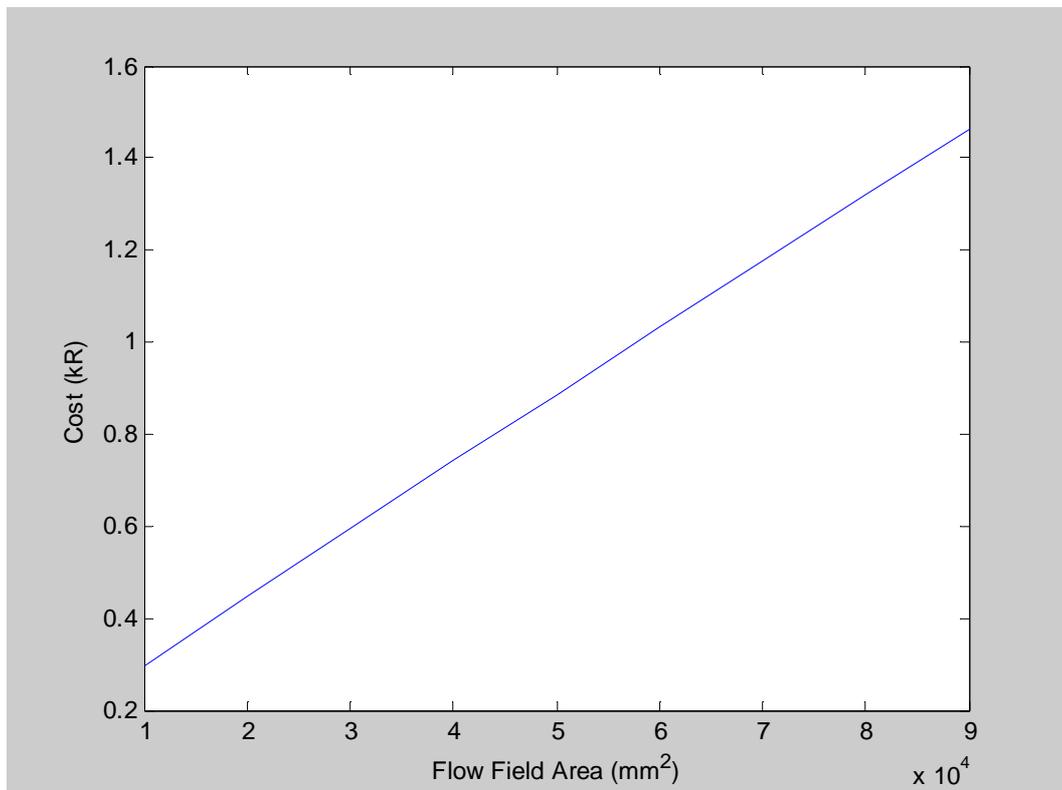
Figure 6.8: Graph of Cost vs. Flow Field Area for Compression Moulded BPs

From Figure 6.8 it can be seen that the cost increases linearly with area similarly to the mould making cost. Due to the fact that all aspects of the cost are increased, the increase in cost is significant. It goes from R295 for a BP of 100x100 mm to about R1460 for a BP of 300x300 mm. This increase in cost will be more prominent for lower production volumes since, although all the cost drivers increase, the mould making cost increases most significantly. This can be seen in Figure 6.9 which shows cost vs. production volume. The different lines are the different flow field sizes. From the graph it can be seen that the difference in cost

is huge for the low production volume of 100 plates, but is much less at 5000 plates. The difference in cost at a production of 5000 plates is still significant with an increase of R160 between the blue and red lines and about R240 between red and green.
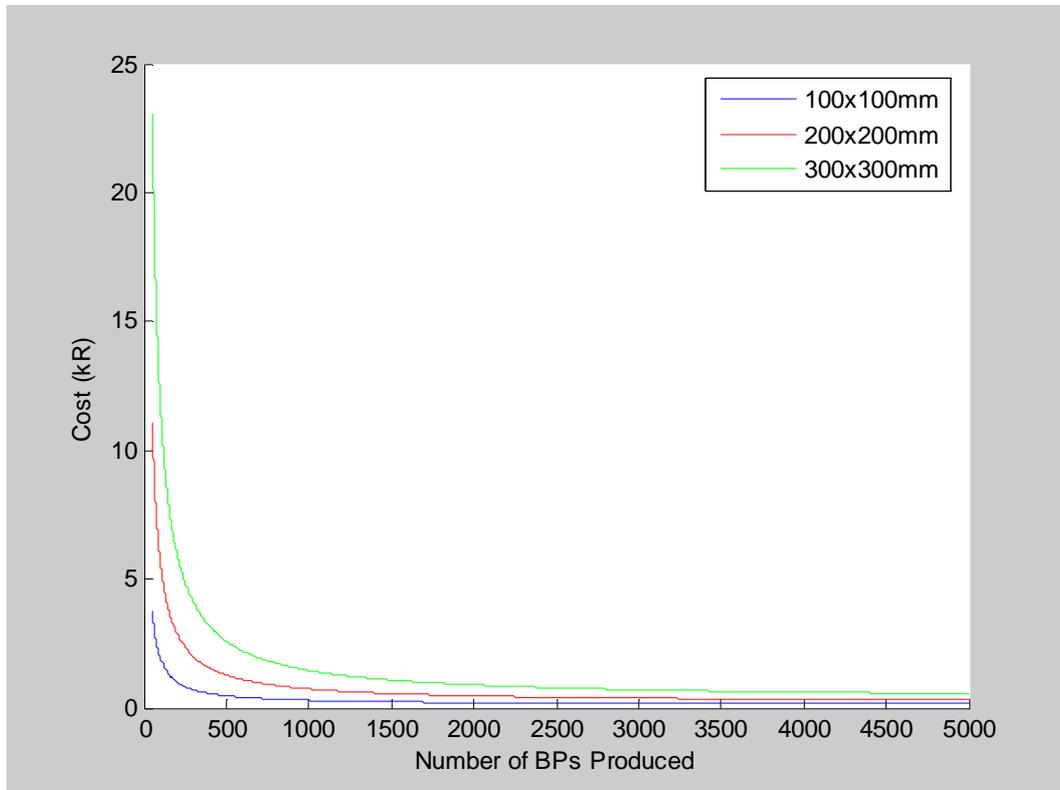
Figure 6.9: Graph of Cost vs. Production Volume for Various Flow Field Areas

6.4. Manufacturing Method Comparison

Now that the two manufacturing methods have been discussed on their own, and the effects of the design and production volumes on the cost have been analysed, a comparison between machining and compression moulding can be made. One of the objectives of this thesis was to determine the best method for the production of BPs, and so the costs of both methods will be compared here to establish which is better.

The manufacture methods will be compared against production volume as it is expected that machining will be cheaper for lower volumes as it has a low initial cost, and compression moulding will be better for higher volumes as it has the high initial cost of the mould, but produces BPs at a faster rate with lower material costs. Using this analysis the production volume at which one method becomes cheaper than the other can be estimated and a decision can be made on what method to use.

For the comparison the same design for the BP had to be the same for both manufacture methods. It was decided that a BP would be used instead of an end plate as far more of these would be produced, seeing as there are many in one cell. An active flow field area of 100 x 100 mm would be used and a channel size of about 0.71 mm. This is close to a typical design for a BP. Figure 6.10 below shows the cost vs. batch size for the two methods. From the graph it can be seen that compression moulding becomes cheaper at a batch size of 324 plates. This corresponds to a cost per plate of R675. After the crossover point the cost of compression moulding continues to drop and will eventually go as low as about R140 per plate. The cost of machining on the other hand stays constant. With the number of BPs in a single stack easily reaching 20, after the sale of only 17 stacks the compression moulding method becomes preferable with large savings to be made at sales of stacks in the hundreds.
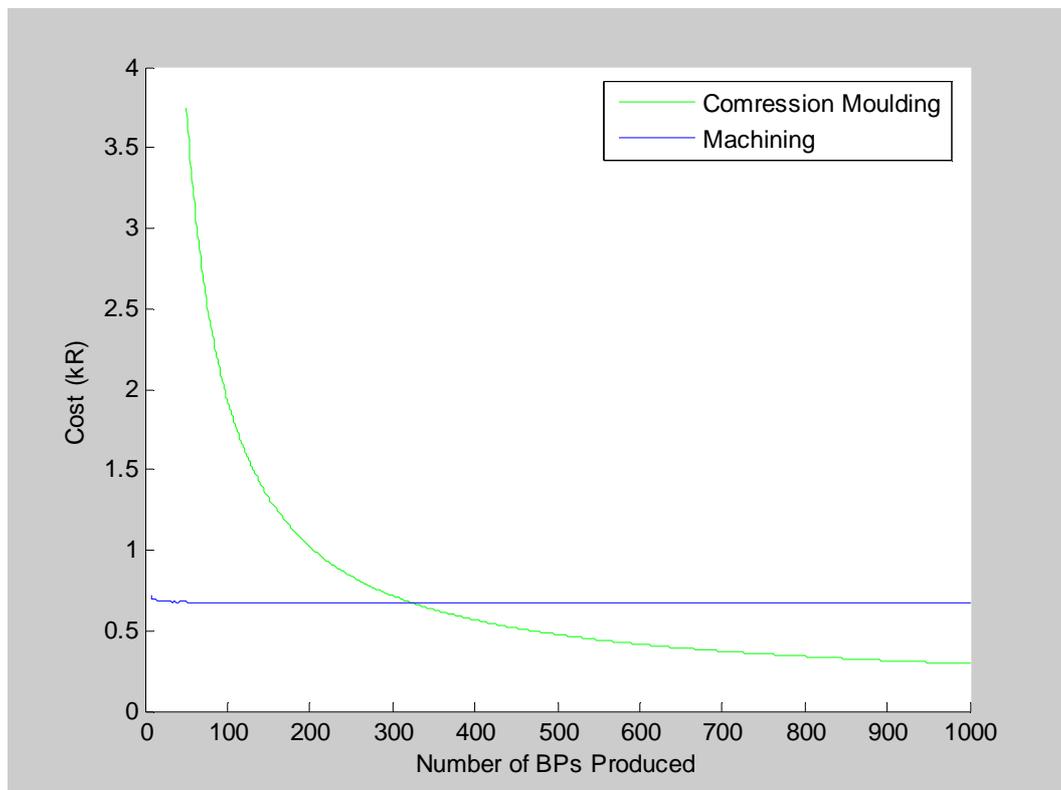
Figure 6.10: Comparison of Costs for Machining and Compression Moulding

A possible issue with the comparison is that if the machining method were to be used, the composite material may not be the best choice. There are several advantages to this material, but the main one is that it is mouldable. If machining where to be used, the designer may decide to make the BPs out of graphite to save on cost. To account for this situation, the material cost for the machining process was reduced to R208 from R408, and the analysis has been done again. With this lower material cost, the crossover point is at about 500 plates. This is still a relatively low production volume.

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The analysis done above is for the production of BPs, however each fuel cell stack would still need end plates at each end of the cell. The production volumes for these end plates would be significantly less, especially since the cathode and anode end plate are slightly different. At first glance it would seem that another mould would be needed for the moulding of the end plates, but this is not necessarily the case. Only the top or bottom mould plate would need to be changed with one that did not have channels and thus a whole new mould is not needed. The added cost of the extra mould plates for the production of end plates does need to be considered however.

From the analysis done here it can be seen that machining is only preferable for very low production volumes. So, if South Africa wished to become a role player in the fuel cell industry, compression moulding would be the manufacture method to employ.

Another factor that should be considered is the use of multi cavity moulds. If a multi cavity mould where to be used, multiple BPs would be produced at the same time, reducing the cycle time per plate. The cost of the mould, however, would be more. For high enough production volumes, the increased mould cost is offset by the reduced cycle time and even greater saving can be made than those for a single cavity mould. More research would need to be done to find the production volume at which the use of a multi cavity mould was justified.

It should also be noted that in the analysis above, the mould cost has been split over the number of BPs made. If it was assumed instead the mould cost where to be split over the number of plates it could make in its life, the mould cost would be reduced. The cost to produce 1000 BPs, with the cost of the mould split over its whole life of 10 000 plates, comes to less than R140.

7. Recommendations and Conclusion

The purpose of this thesis was to establish whether the manufacture of bipolar plates (BPs) for PEM fuel cells would be economical, the methods that could be used, as well as the cost to produce the plates using the different methods. This information could then be used to determine whether it is worth manufacturing the BPs in South Africa and will help establish whether SA can be competitive in the fuel cell industry. The effect of changes in the design on the cost was also considered, so that the cost could still be estimated for future design changes. It also allows designers to optimise the design of the BP and strike a balance between performance and cost. The BPs considered were for use in a high temperature PEM fuel cell.

The two methods that where considered in the thesis were machining and compression moulding. The research on machining was done by Essmann (2011), and his cost model was adapted for use in this thesis. The focus of this thesis was the development of a cost model for compression moulding, which included the cost for the mould construction as well as the actual moulding. The methods used to develop the cost models have been discussed in detail and their validity has been argued.

Using the two models, the cost of machining and compression moulding BPs was compared for different production volumes. This gave a clear idea of which method was more economical depending on the estimated production volume that would be obtained. The comparison showed that machining would be cheaper for small production volumes while compression moulding takes over, and offers a large cost saving, for larger production volumes. This is expected as the moulding process has a high initial cost for tooling, but shorter cycle times, while machining has no high initial cost, but longer cycle times and material cost. The crossover point for a typical design was determined to be 324 BPs.

The cost models were also used to determine the effect of design changes on the cost. Changes in the channel size and size of the BP were considered. As expected a reduction in channel size increased the cost due to the slower feed rates used with the smaller tools, meaning longer machining times, as well as the reduced tool life. Also, the cost increased linearly with an increase in BP flow field area, which is also intuitive. These effects are more pronounced with the machining process as the profile is machined into each plate instead of just once for the moulding process.

Through the use of the cost models developed in this thesis, it was determined that it would be possible to produce BPs in SA using either machining or compression moulding. However, if machining is used, the cost may be too high to be economically feasible. Compression moulding reaches low enough costs to be competitive for the production volumes projected. A moulding of a prototype end plate was attempted to establish that the process does work, but more work needs to be done on the material development. The model estimates a cost of R294 for a

production volume of 1000 BPs, which should be obtainable with HySA planning on producing fuel cell stacks in the low 100s.

As is typical with cost estimation, there are always areas which can use refinement. More experimentation in the micro-milling of BPs, using different channel designs, will give a more accurate machining model. More importantly, there is also work that can be done to refine the compression moulding model. Further trial mouldings are needed to get the material to an optimum for moulding. Research into the use of cheaper aluminium moulds, for manufacturing smaller numbers of BPs would also be useful. Further work should also focus on the other components of the fuel cell, so a cost model can be developed for the production of a complete cell, rather than just one component of the cell.

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Appendix A: Sample Calculations

A.1. Machining Model

Below the calculations for the machining of a typical BP will be performed. It is assumed that there is one operator on one machine for these calculations. All estimated are per plate, unless otherwise stated.

The first step is to give the design of the BP:

$\text{chan\_width} := 0.7\text{mm}$

$\text{BP\_area} := 10000\text{mm}^2$

$\text{sides} := 2$ This is a multiplier that shows whether an end plate or BP is being machined

The first cost considered is the material cost (Section 3.4.1 and 3.4.3):

$\text{C\_plate} := 398 \cdot \left(\dfrac{\text{BP\_area}}{10000\text{mm}^2} \right) \text{ZAR}$ $\text{C\_delivery} := 10\text{ZAR}$

$\text{C\_min\_tool} := 100\text{ZAR}$ $\text{C\_maj\_tool} := 90\text{ZAR}$ $\text{C\_per\_tool} := 80\text{ZAR}$

$\text{C\_material} := \text{C\_plate} + \text{C\_delivery} = 408\text{ZAR}$

The next calculations are for determining the labour costs (Section 3.6.1).

$\text{HR} := 310\dfrac{\text{ZAR}}{\text{hr}}$ This is the hourly rate charged by the workshop

$\text{B} := 100$ B is the batch size (the number of plates made)

The setup time must be determined.

The times for the various steps of the process are as follows (Section 3.3.1):

$\text{T\_ref\_xyz} := 135\text{s}$ $\text{T\_ref\_z} := 46\text{s}$ $\text{T\_set\_par} := 24\text{s}$

$\text{T\_fix} := 17\text{s}$ $\text{T\_flip} := 19\text{s}$ $\text{T\_remove} := 17\text{s}$

$\text{T\_insp} := 30\text{s}$ $\text{T\_tool\_change} := 34\text{s}$

The time spent setting up and inspecting the plates is calculated as follows:

$\text{T\_si} := \text{T\_ref\_xyz} = 2.25 \cdot \text{min}$ Set up time per batch

$\text{T\_si} := \text{T\_ref\_xyz} = 2.25 \cdot \text{min}$ Set up time per batch

$\text{T\_tool} := (2 \cdot \text{sides} + 1)(\text{T\_tool\_change} + \text{T\_set\_par} + \text{T\_ref\_z}) = 8.667 \cdot \text{min}$

$\text{T\_spp} := \text{T\_tool} + \text{T\_fix} + \text{T\_flip} + \text{T\_remove} + \text{T\_insp} = 10.05 \cdot \text{min}$ Set up time per plate

$\text{T\_setup} := \dfrac{\text{T\_si}}{\text{B}} + \text{T\_spp} = 10.072 \cdot \text{min}$

Next the machining time is calculated, as well as the number of tools used.

First the channel length is calculated. This is done in the same way as for the mould making and so is not repeated here. Below is the channel length for one side only.

$$\text{ch\_maj} := 6.9\,\text{m} \qquad\qquad \text{ch\_length\_maj} := \text{ch\_maj} \cdot \text{sides} = 13.8\,\text{m}$$

The machining parameters must be specified (From manufacturer's guidelines and BP design):

$\text{v\_maj} := 70\,\dfrac{\text{m}}{\text{min}}$	$\text{v\_min} := 70\,\dfrac{\text{m}}{\text{min}}$	$\text{v\_per} := 90.32\,\dfrac{\text{m}}{\text{min}}$	Cutting speeds
$\text{ft\_maj} := 15\,\mu\text{m}$	$\text{ft\_min} := 15\,\mu\text{m}$	$\text{ft\_per} := 50\,\mu\text{m}$	Feed per tooth
$\text{D\_maj} := 0.7\,\text{mm}$	$\text{D\_min} := 0.5\,\text{mm}$	$\text{D\_per} := 2.5\,\text{mm}$	Tool diameters
$\text{d\_maj} := 0.735\,\text{mm}$	$\text{d\_min} := 0.5\,\text{mm}$		Channel depths

Due to the slowing down of the machine while turning corners and time wasted moving between points, the max feed rate is not achieved. Therefore an adjusted feed is used:

$$\text{feed} := 950\,\frac{\text{mm}}{\text{min}}$$

Now the machining time must be calculated for the major, minor and peripheral machining:

Major Channels:

Tool life is calculated using the formula derived by Essmann (Equation 3.9).

$$\text{p1\_maj} := 5.84236367 + 5.27526596\,\frac{\text{d\_maj}}{\text{mm}} - 0.00034793\left(\frac{\text{v\_maj} \cdot \text{min}}{\text{m}}\right)^2 - 0.00505855\left(\frac{\text{ft\_maj}}{\mu\text{m}}\right)^2$$

$$\text{p2\_maj} := -1.72381224\left(\frac{\text{d\_maj}}{\text{mm}}\right)^2 + 0.00270405\left(\frac{\text{v\_maj} \cdot \text{min}}{\text{m}}\right)\cdot\left(\frac{\text{ft\_maj}}{\mu\text{m}}\right)$$

$$\text{TL\_maj} := e^{(\text{p1\_maj}+\text{p2\_maj})}\cdot\text{mm}^3 = 6.533\times 10^3 \cdot \text{mm}^3$$

$$\text{z\_maj\_total} := \text{ceil}\left(\frac{\text{ch\_length\_maj}\cdot\text{D\_maj}\cdot\text{d\_maj}\cdot\text{B}}{\text{TL\_maj}}\right) = 109 \qquad\qquad \text{Equation 3.15.}$$

$$\text{z\_maj} := \frac{\text{z\_maj\_total}}{\text{B}} = 1.09$$

$$\text{T\_mach\_maj} := \frac{\text{ch\_length\_maj}}{\text{feed}} + (\text{T\_tool\_change} + \text{T\_ref\_z})\cdot\text{z\_maj} = 15.98 \cdot \text{min}$$

Minor Channels (Equation 3.9): $\qquad\qquad \text{ch\_length\_min} := 0.21\,\text{m}$

$$\text{p1\_min} := 5.84236367 + 5.27526596\left(\frac{\text{d\_min}}{\text{mm}}\right) - 0.00034793\left(\frac{\text{v\_min} \cdot \text{min}}{\text{m}}\right)^2 - 0.00505855\left(\frac{\text{ft\_min}}{\mu\text{m}}\right)^2$$

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$$p2\_min := -1.72381224 \left(\frac{d\_min}{mm} \right)^2 + 0.00270405 \left(\frac{v\_min \cdot min}{m} \right) \cdot \left(\frac{ft\_min}{\mu m} \right)$$

$$TL\_min := e^{(p1\_min + p2\_min)} \cdot \left(\frac{0.5}{0.7} \right) \cdot mm^3 = 2.228 \times 10^3 \cdot mm^3 \qquad \text{Tool life corrected for tool size}$$

$$z\_min\_total := ceil \left(\frac{ch\_length\_min \cdot d\_min \cdot D\_min \cdot B}{TL\_min} \right) = 3$$

$$z\_min := \frac{z\_min\_total}{B} = 0.03$$

$$T\_mach\_min := \frac{ch\_length\_min}{feed} + (T\_tool\_change + T\_ref\_z) \cdot z\_min = 0.261 \cdot min$$

Peripheral Machining:
$$ch\_length\_per := 4.97 \, m$$

$$n := 0.14 \qquad C\_t := 170 \qquad \text{Constants used for this type of material and machining} \\ \text{(Essmann, 2011)}$$

$$TL\_per := \left(\frac{C\_t}{v\_per} \cdot \frac{m}{min} \right)^{\frac{1}{n}} \cdot min = 91.599 \cdot min \qquad \text{Equation 3.16}$$

$$z\_per := ceil \left(\frac{ch\_length\_per \cdot B}{feed \cdot TL\_per} \right) \cdot \frac{1}{B} = 0.06 \qquad \text{Equation 3.18}$$

$$T\_mach\_per := \frac{ch\_length\_per}{feed} + (T\_tool\_change + T\_ref\_z) \cdot z\_per = 5.312 \cdot min \qquad \text{Equation 3.17}$$

Total Machining Time:

$$T\_m := T\_mach\_maj + T\_mach\_min + T\_mach\_per = 21.552 \cdot min$$

Costs:

$$C\_labour := HR \cdot (T\_setup + T\_m) = 163.395 \, ZAR$$

$$C\_material = 408 \, ZAR$$

$$C\_maj\_tooling := C\_maj\_tool \cdot \left(\frac{ceil(z\_maj \cdot B)}{B} \right) = 99 \, ZAR$$

$$C\_min\_tooling := C\_min\_tool \cdot \left(\frac{ceil(z\_min \cdot B)}{B} \right) = 3 \, ZAR$$

$$C\_per\_tooling := C\_per\_tool \cdot \left(\frac{ceil(z\_per \cdot B)}{B} \right) = 4.8 \, ZAR$$

$$C\_tooling\_tot := (C\_maj\_tooling + C\_min\_tooling + C\_per\_tooling) = 106.8 \, ZAR$$

$$C\_mach := C\_material + C\_labour + C\_tooling\_tot = 678.195 \, ZAR$$

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A.2. Mould Making Model

Below are the calculations to determine the cost of manufacturing bipolar plates by compression moulding. This calculation is for the manufacture of an end plate (channels on one side).

First the parameters of the end plate are given:

Inputs:

$\text{BP\_active\_area} := 10000\text{mm}^2$ Area of active flow field

$\text{Channel\_width} := 0.7\text{mm}$ $\text{Channel\_fillet} := 0.3\text{mm}$ Channel dimensions

$\text{Channel\_depth} := \text{Channel\_width} \cdot 1.05 = 0.735 \cdot \text{mm}$

$\text{length\_BP} := \sqrt{\text{BP\_active\_area}} + 60\text{mm} = 160 \cdot \text{mm}$

$\text{width\_BP} := \sqrt{\text{BP\_active\_area}} + 36\text{mm} = 136 \cdot \text{mm}$

$\text{sides} := 1$ $\text{w\_gap} := 1.7\text{mm}$ Other BP parameters

Constants:

$\text{HR} := 450\dfrac{\text{ZAR}}{\text{hr}}$ Hourly rate for workshop

$\text{C\_tool} := 700\text{ZAR}$ Cost per tool for channel machining (Table 4.2)

$\text{C\_mat} := 80\dfrac{\text{ZAR}}{\text{kg}}$ Cost per kg for cavity and core material (Table 4.2)

$\text{rho} := 7.85 \cdot 10^3 \dfrac{\text{kg}}{\text{m}^3}$ Density of Bohler M201 Steel

Next the cost of the mould base is calculated, including material and machining (Section 5.1.1.):

$\text{Ac} := (\text{length\_BP} + 160\text{mm}) \cdot (\text{width\_BP} + 160\text{mm}) = 0.095\text{m}^2$ $\text{h\_p} := 7.2\,\text{cm}$

$\text{C\_mb\_material} := 9689.7\text{ZAR} + 5.462 \cdot \text{Ac} \cdot \text{h\_p}^{0.4} \left(\dfrac{\text{cm}^{-\frac{12}{5}}}{}\right)\text{ZAR} = 2.109 \times 10^4 \, \text{ZAR}$ Material cost for the mould base (Equation 5.2.)

$\text{C\_mb\_labour} := \text{C\_mb\_material}$ Labour cost for custom work on the mould base

Next the material and manufacture costs for the cavity and core are calculated:

Material Cost, including material hardening:

$$m\_cav := (length\_BP + 58mm)(width\_BP + 58mm) \cdot 36mm \cdot rho = 11.952kg$$

Mass of cavity and core inserts (Equation 5.3. & 5.4.)

$$m\_core := (length\_BP + 58mm)(width\_BP + 58mm) \cdot 48mm \cdot rho = 15.936kg$$

$$C\_insert\_material := C\_mat \cdot (m\_cav + m\_core) = 2.231 \times 10^3 \ ZAR$$

$$C\_hard := (m\_cav + m\_core) \cdot 42.5 \frac{ZAR}{kg} = 1.185 \times 10^3 \ ZAR$$

Cost of hardening

Channel Machining Time (Section 5.1.2.):

First the length of the major channels is determined (Equations 5.9 to 5.12)

$$No\_channels := floor\left(\frac{\sqrt{BP\_active\_area} - 2w\_gap}{6Channel\_width}\right) = 23$$

$$Channel\_proportion := \frac{3No\_channels \cdot Channel\_width}{\sqrt{BP\_active\_area}} = 0.483$$

$$Channel\_area := Channel\_proportion \cdot BP\_active\_area = 4.83 \times 10^{-3} \ m^2$$

$$Channel\_length := \frac{Channel\_area}{Channel\_width} = 6.9m$$

An algorithm is used to find the three tool sizes used for the channel machining, and is shown in Section 5.1.2. The tool sizes are given below:

$$Tool\_1 := 2mm$$

$$Tool\_2 := 1mm$$

$$Tool\_3 := 0.6mm$$

The depth that each tool will cut must then be found (Equation 5.7. & 5.8.):

$$p\_1 := \sqrt{(0.5 \cdot Tool\_1 + Channel\_fillet)^2 - (0.5 \cdot Channel\_width + Channel\_fillet)^2} = 1.126 \cdot mm$$

$$Depth\_1 := 0.5 \cdot Tool\_1 - p\_1 + Channel\_fillet = 0.174 \cdot mm$$

$$p\_2 := \sqrt{(0.5 \cdot Tool\_2 + Channel\_fillet)^2 - (0.5 \cdot Channel\_width + Channel\_fillet)^2} = 0.466 \cdot mm$$

$$Depth\_2 := 0.5 \cdot Tool\_2 - p\_2 + Channel\_fillet - Depth\_1 = 0.159 \cdot mm$$

$$Depth\_3 := Channel\_depth - (Depth\_1 + Depth\_2) = 0.401 \cdot mm$$

Now the cutting time for each tool size can be found:

First the manufacturer's recommendations are assigned: (Table 5.2)

$$\text{Max\_depth\_1} := 0.11\,\text{mm} \qquad \text{Max\_depth\_2} := 0.05\,\text{mm} \qquad \text{Max\_depth\_3} := 0.025\,\text{mm}$$

$$\text{Spind\_speed\_1} := 31000\,\text{rpm} \qquad \text{Spind\_speed\_2} := 40000\,\text{rpm} \qquad \text{Spind\_speed\_3} := 40000\,\text{rpm}$$

$$\text{Feed\_rec\_1} := 3500\,\frac{\text{mm}}{\text{min}} \qquad \text{Feed\_rec\_2} := 3000\,\frac{\text{mm}}{\text{min}} \qquad \text{Feed\_rec\_3} := 1300\,\frac{\text{mm}}{\text{min}}$$

The machine's maxima must also be defined:

$$\text{Spind\_speed\_max} := 20000\,\text{rpm}$$

Now the time for the cutting can be calculated using the number of passes needed and the time for each pass:

The CNC machine slows down considerably while moving along the z-axis. Therefore the feed for the lace machining will be assumed to be:

$$\text{F\_lace} := 300\,\frac{\text{mm}}{\text{min}}$$

First tool: (2mm)

$$\text{No\_cuts\_1} := \text{ceil}\left(\frac{\text{Depth\_1}}{\text{Max\_depth\_1}}\right) = 2$$

$$\text{Feed\_1} := \left(\frac{\text{Spind\_speed\_max}}{\text{Spind\_speed\_1}}\right)\text{Feed\_rec\_1} = 2.258\times 10^3\cdot\frac{\text{mm}}{\text{min}}$$

$$\text{Prof\_mach\_1} := \frac{\text{Channel\_length}\cdot\text{No\_cuts\_1}}{\text{Feed\_1}} = 6.111\cdot\text{min} \qquad\qquad \text{Equation 5.9.}$$

$$\text{Lace\_mach\_1} := \text{ceil}\left(\frac{\sqrt{\text{BP\_active\_area}}}{\text{Tool\_1}\cdot 0.1}\right)\cdot\frac{\sqrt{\text{BP\_active\_area}}}{\text{F\_lace}} = 166.667\,\text{min} \qquad \text{Equation 5.10.}$$

Second tool: (1mm)

$$\text{No\_cuts\_2} := \text{ceil}\left(\frac{\text{Depth\_2}}{\text{Max\_depth\_2}}\right) = 4$$

$$\text{Feed\_2} := \left(\frac{\text{Spind\_speed\_max}}{\text{Spind\_speed\_2}}\right)\text{Feed\_rec\_2} = 1.5\times 10^3\cdot\frac{\text{mm}}{\text{min}}$$

$$Prof\_mach\_2 := \frac{Channel\_length \cdot No\_cuts\_2}{Feed\_2} = 18.4 \, min \qquad \text{Equation 5.9.}$$

$$Lace\_mach\_2 := ceil\left(\frac{\sqrt{BP\_active\_area}}{Tool\_2 \cdot 0.1}\right) \cdot \frac{\sqrt{BP\_active\_area}}{F\_lace} = 333.333 \, min \qquad \text{Equation 5.10.}$$

Third tool: (0.6mm)

$$No\_cuts\_3 := ceil\left(\frac{Depth\_3}{Max\_depth\_3}\right) \cdot 2 = 34$$

$$Feed\_3 := \left(\frac{Spind\_speed\_max}{Spind\_speed\_3}\right) Feed\_rec\_3 = 650 \, \frac{mm}{min}$$

$$Prof\_mach\_3 := \frac{Channel\_length \cdot No\_cuts\_3}{Feed\_3} = 360.923 \, min \qquad \text{Equation 5.9.}$$

$$Lace\_mach\_3 := ceil\left(\frac{\sqrt{BP\_active\_area}}{Tool\_3 \cdot 0.1}\right) \cdot \frac{\sqrt{BP\_active\_area}}{F\_lace} = 555.667 \, min \qquad \text{Equation 5.10.}$$

$$Mach\_1 := Prof\_mach\_1 + Lace\_mach\_1 = 172.778 \, min$$

$$Mach\_2 := Prof\_mach\_2 + Lace\_mach\_2 = 351.733 \, min$$

$$Mach\_3 := Prof\_mach\_3 + Lace\_mach\_3 = 916.59 \, min$$

The total time for machining the channels is then calculated. The machining time for the smallest tool is increased as time is wasted every time a tool breaks.

$$T\_ch\_mach\_tot := (Mach\_1 + Mach\_2 + Mach\_3 \cdot 1.6) \cdot sides = 33.184 \, hr$$

The number of tools used is then calculated.

It is assumed that only one each of the larger tools are used and that a new tool is used for every six steps down with the smallest tool.

$$N\_tools := ceil\left(\frac{No\_cuts\_3}{6}\right) \frac{BP\_active\_area}{10000mm^2} \cdot sides + 2 = 8$$

$$C\_tools := N\_tools \cdot C\_tool = 5.6 \times 10^3 \, ZAR$$

Next the time for machining the ejector pins and peripherals, the polishing and the assembly is calculated:

$$N\_ep := ceil\left(\frac{BP\_active\_area}{850mm^2}\right) = 12 \qquad \text{There is one pin for every 850mm^2 of area. Equation 5.6.}$$

$$T\_ep := 2.5hr \cdot N\_ep = 30 \cdot hr \qquad \text{Equation 5.5.}$$

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$$T\_per\_mach := (20hr + 12hr \cdot sides) \cdot \left(\frac{BP\_active\_area}{10000mm^2} \right) = 32 \cdot hr \qquad \text{Equation 5.17}$$

$$T\_polish := 40hr \cdot \left(\frac{BP\_active\_area}{10000mm^2} \right) \cdot sides = 40 \cdot hr \qquad \text{Equation 5.11.}$$

$$T\_assemble := 8hr \qquad \text{Section 5.1.3.}$$

The final step is to calculate the costs:

$$C\_material := C\_mb\_material + C\_insert\_material + C\_hard + C\_tools = 3.01 \times 10^4 \, ZAR$$

$$T\_tot := T\_ep + T\_ch\_mach\_tot + T\_per\_mach + T\_polish + T\_assemble = 143.184hr$$

$$C\_labour := C\_mb\_labour + T\_tot \cdot HR = 8.552 \times 10^4 \, ZAR$$

The total cost for the mould is then:

$$C\_total := C\_material + C\_labour = 1.156 \times 10^5 \, ZAR$$

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A.3. Compression Moulding Model

Below is the sample calculation for the cost of compression moulding bipolar plates. This calculation is for the cost of an end plate (channels on only one side).

The parameters of the mould are as follows:

$$\text{BP\_area} := 10000\,\text{mm}^2 \qquad \text{ch\_width} := 0.7\,\text{mm} \qquad \text{ch\_depth} := \text{ch\_width} \cdot 1.05 = 0.735 \cdot \text{mm}$$

Other Constants:

$$n\_s := 1$$

$$C\_mg := 262\,\frac{\text{ZAR}}{\text{kg}} \qquad C\_mr := 152\,\frac{\text{ZAR}}{\text{kg}} \qquad C\_ms := 50\,\frac{\text{ZAR}}{\text{kg}}$$

Cost of the resin, graphite and solvent. Table 5.3.

$$\text{rho\_mat} := 1.9\,\frac{\text{gm}}{\text{cm}^3}$$

Density of the final mixture.

$$\text{m\_batch} := 25\,\text{kg}$$

Mass of material that can be made in one batch.

First the cost of the mould is needed. The calculations for the mould cost can be seen in a separate sample calculation. The cost for this example is given below:

$$C\_mould := 115620\,\text{ZAR}$$

$$\text{HR} := 300\,\frac{\text{ZAR}}{\text{hr}}$$

Workshops hourly rate

$$B := 1000$$

Batch size, or the number of BPs that will be produced

The cost of the moulding material must be determined (Section 5.2.1.):

Mould volume:
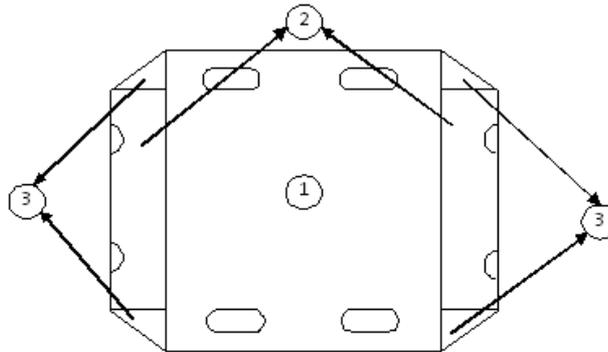
In one:

$$\text{w\_1} := \sqrt{\text{BP\_area}} + 10\,\text{mm} = 110 \cdot \text{mm} \qquad \text{t\_1} := 3\,\text{mm}$$

$$\text{l\_1} := \sqrt{\text{BP\_area}} + 36\,\text{mm} = 136 \cdot \text{mm} \qquad \text{r\_slot} := 4\,\text{mm} \qquad \text{l\_slot} := 17\,\text{mm}$$

In two:

$w\_2 := 23.5\,mm$ $\qquad$ $l\_2 := \sqrt{BP\_area} - 42mm = 58\cdot mm$ $\qquad$ $t\_2 := 1.5\,mm$ $\qquad$ $r\_h2 := 8mm$

In three:

$w\_3 := 23\,mm$ $\qquad$ $l\_3 := 30\,mm$ $\qquad$ $t\_3 := t\_2$

Channels:

$$de := \frac{ch\_depth \cdot BP\_area \cdot n\_s}{2} = 3.675 \times 10^3 \cdot mm^3$$

$$A\_1 := (w\_1 \cdot l\_1) - 4\left(l\_slot \cdot 2r\_slot + \pi\, r\_slot^2\right) = 1.421 \times 10^4 \cdot mm^2$$

$$A\_2 := 2 \cdot w\_2 \cdot l\_2 - 2 \cdot \pi\, r\_h2^2 = 2.324 \times 10^3 \cdot mm^2$$

$$A\_3 := 4 \cdot 0.5 l\_3 \cdot w\_3 = 1.38 \times 10^3 \cdot mm^2$$

$$V\_part := (A\_1) \cdot t\_1 + (A\_2 + A\_3) t\_2 - de = 44.526\,cm^3$$

Now the cost of the material can be determined:

$$m\_mat := V\_part \cdot rho\_mat = 84.599 \cdot gm$$

$$m\_graph := 0.88 \cdot m\_mat = 74.447 \cdot gm$$

Section 5.2.1.

$$m\_res := 0.12 \cdot m\_mat = 10.152 \cdot gm$$

$$m\_solv := 30 m\_res = 304.555 \cdot gm$$

$$C\_material := C\_mg \cdot m\_graph + C\_mr \cdot m\_res + C\_ms \cdot m\_solv = 36.276\,ZAR$$

Material Mixing

The material is mixed in batches of 25kg at a time. Thus the time spent mixing depends on the number of plates made and in turn the number of batches needed. A breakdown of the mixing time can be seen in Table 5.5.

$$N\_batch := ceil\left(\frac{m\_mat \cdot B}{m\_batch}\right) = 4$$

$$T\_mixing := 40\,min$$

$$T\_mix\_pp := \frac{T\_mixing \cdot N\_batch}{B} = 9.6\,s$$

Now the time for the actual moulding can be estimated (Section 5.2.2):

The times for each step are (Table 4.5):

$T\_place := 10s$ $\qquad$ $T\_close := 5s$ $\qquad$ $T\_comp := 5s$ $\qquad$ $T\_open := 5s$

$T\_cure := 12\,min$ $\qquad$ $T\_remove := 10s$

$T\_mould := T\_place + T\_close + T\_comp + T\_cure + T\_open + T\_remove = 12.583 \cdot min$

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Once the plate is moulded the flash needs to be removed.

$$T\_flash := 2min$$

The labour costs can now be calculated:

$$C\_labour := (T\_mix\_pp + T\_mould + T\_flash) \cdot HR = 73.717\, ZAR \qquad \text{Equation 5.13.}$$

The total cost per plate using the moulding process is then estimated:

The mould cost is divided by the number of plates in the batch. This may inflate the cost, as the batch size is much smaller than the total number of plates the mould could make in its life.

$$C\_moulding := \frac{C\_mould}{B} + C\_material + C\_labour = 225.613\, ZAR$$

Appendix B: Quotes

B.1: Mould Shop Quote

MOULD SHOP (PTY) LTD.

INJECTION, BLOW AND COMPRESSION MOULDS, COMPONENT & MOULD DESIGN
CNC MACHINING, SPARK ERODING & WIRE CUTTING

Established 1988, Registration number 960867807
Vat number 4170159083

No 20 4th STREET
MONTAGUE GARDENS
MILNERTON
CAPE TOWN
SOUTH AFRICA

TEL: (021) 5551698
FAX: (021) 5551687
EMAIL: mouldshop@mweb.co.za

Quotation No: 110811-001   11th AUGUST 2011

TO: Department of Mechanical and Mechatronic Engineering
    Stellenbosch University

ATT: Juan Atkinson

BIPOLAR PLATE MOULD					
DESCRIPTION	CAV	MLD DESIGN	MATERIAL	LABOUR	TOTAL
COMPRESSION MLD	1	CUSTOMER	R 34,000.00	R 86,800.00	R 120,800.00

EXCL VAT

PAYMENT TERMS: 40% DEPOSIT
               40% ON DELIVERY
               20% ON APPROVED SAMPLE

LEAD TIME NEW MOULD: +/- 6 - 8 WORKING WEEKS AFTER APPROVAL OF MOULD
DRAWINGS

DELIVERY: TO BE DISCUSSED WHEN WE RECEIVE THE ORDER NUMBER, DEPOSIT AND
FINAL COMPONENT DRAWINGS.

WE THANK YOU FOR YOUR VALUED SUPPORT.

LUCIO

---

* ALL MOULD REMAINS THE PROPERTY OF MOULDSHOP UNTIL FULLY PAID.

MANAGING DIRECTOR LUCIO PORCHIAZZO, DIRECTOR DAVID OPPEL, DIRECTOR ASHLEY WASSUNG

B.2: The Tool Room Quote

Good morning Juan

We are pleased to submit the following cost-estimate for your consideration.

To manufacture 1 x compression mould to produce bipolar plate as per design supplied :

R 132 500-00 (exc.)

The above mould will comply with all the specifications required. We also suggest that material for cavity and force be changed to a hot working steel such as W305 / 2344.
Cavity and force hardened and tempered.
Cavity highly polished.
Lead time : 6-7 weeks from date of order.
Terms : 50% deposit on order ; 40 % on delivery ; 10% on approval/30 days.

We would like to thank you for the opportunity to quote on the above and hope it meet your requirements.

Kind regards
Andre Robertson
The Toolroom Manufacturing
Tel: 021 851 8578/9
Fax: 021 851 8580
Cell: 083 225 7674
E-mail: andre@thetoolroom.co.za
Website: www.thetoolroom.co.za

B.3. Plascom Consultants Material Development

27-MAY-2001 00:42 FROM DENEL   TO 00866155206   P.01

QUOTATION.

Plascomp Consultants

For all your plastics,
elastomer, composite
material and processing advice

To: Stellenbosch University,
    Dept. of Mechanical and Mechatronic Engineering,
    Private Bag X1,
    Matieland.
    7602.
For attention: Prof. Anton Basson.
Copy to: Juan Atkinson.
Telephone number: 021-808 4250.
Fax number: 086 615 5206.
Telephone number: 021-808 4250.
Reference number: PC 5??? 2011

Date: 21 October, 2011.

Re: Quotation to Develop and Manufacture a suitable Moulding Compound in order to Compression Mould the Bi-Polar Plate as required for the Fuel Cell project.

This quotation serves to confirm the man-hour and material costs required to develop and manufacture a phenol formaldehyde resole resin/graphite flake moulding compound in order to compression mould the Bi-Polar Plate as per supplied drawings: S-100-15-02-abpa and " Channel and Seal Detail ". To complete the above, the following actions need to be completed:

1. Actions to be completed:

  1.1 Identify the commercial, constituent, material designation and overseas suppliers

  1.1 Identify the commercial, constituent, material designation and overseas suppliers from suppliers.
  1.3 Place orders for all Direct and Indirect Raw Materials.
  1.4 Determine a range of formulations and mixes.
  1.5 Laboratory level mixing, drying and granulating trials.
  1.6 Trial moulding of test samples.
  1.7 Completion of all Mechanical, Physical and Chemical tests.
  1.8 Manufacture first prototype in the Bi-Polar Plate Compression Mould.

2. Cost Analysis: R   c.

  2.1 Development and Manufacture of a suitable Moulding Compound
     Required to compression mould the Bi-Polar Plate........................ – 48400 .. oo.
                  Total Cost............... =R48400 __ oo.

- page 2

- **Note!! Plascomp Consultants do not qualify for VAT payment!!**

3. Delivery:

3.1 Delivery of all the above, mentioned actions, will be completed within 6 to 8 weeks (or sooner if progress allows.) of receipt of a typed and approved order with a valid order number.

4. Full and Final Advance Payment:

4.1 **A Full and Final Advance Payment amounting to R48400,oo** will be required on placing the order on Plascomp Consultants to cover all C.O.D. Direct and Indire4ct Material purchases plus C.O.D. Moulded Material testing.

5. General Conditions:

5.1 Should the above quotation be acceptable, please confirm your acceptance by means of an order number with written acceptance. The above quotation remains valid for 30 days from the date of this quotation and thereafter will be subject to an escalation percentage, mutually agreed to by both parties. Payment will be within 7 days of receipt of a delivery note and a" bona fide " invoice quotation and thereafter will be subject to an escalation percentage, mutually agreed to by both parties. Payment will be within 7 days of receipt of a delivery note and a" bona fide " invoice ~~number. Yours ... ~~ **Consultants.** Please be assured of my constant and positive in achieving a satisfactory conclusion to your above, mentioned requirements. Should you have any queries regarding the above quotation, schedule or technical inputs, please do not hesitate to contact me via my telephone numbers: 021-850 2772 (office) or 021-850 2803 (lab.) or cellphone: 082 494 5977. My fax number at work is: 021-850 2755 and E-mail address: lawrence.vanniekerk@rheinmetall-denelmunition.com

Lawrence C van Niekerk.
Director/Consultant.

B.3. Hestico Quote

3035 - 3636 - rises 86 fully loc DME

Plate Name	Plate size L X W X H	Price DME	LOCAL
N01 - Back Plate Blank	346 x 346 x 26	3771.8	2332
N05 - Back plate	346 x 346 x 26	3771.8	2332
N10 - Cavity Plate	296 x 346 x 36	3310.07	3340
N10 - Cavity Plate	296 x 346 x 36	3310.07	3340
N20 - Support Plate	296 x 346 x 46	3771.77	2959
N30 - Rises	46 X 346 X 86	1438.82	1188
N40 - Ejector Plate	202 x 346 x 16	1434.01	1122
N50 - Support Ejector Plate	202 x 346 x 26	1749.82	1375
location Sleeve	TD 32 x 140 (4pcs)	636	686.4
Pillar Sizes	FSC 24 - 36 - 36 (4 pcs)	852	739.2
Bush Sizes	FBC 24 - 36 (4 pcs)	832	902
Set Screws Complete for Die.		218	218
SB-3 Washer + screw	(4 pcs)	179	179
IS 610	M8 x 30 allen cap(4 pcs)	16 n/a	
bushes	FBC 16-26	286	310.2
IS 610	M12 x 30 allen cap(4 pcs)	24 n/a	
IS 610	M12 x 170 allen cap(4 pcs)	228 n/a	
Piller	FSN 16-26-86(2 off)	390	376.2
WZ8031 TB 10076	4pcs	81.3 n/a	
EJ PIN 6 X 125 AH	12pcs	408 n/a	
Total		**26708.46**	**21399**

4045 - 3636 - rises 106 fully loc DME

Plate Name	Plate size L X W X H	Price DME	LOCAL
N01 - Back Plate Blank	446 x 446 x 36	4865.52	3817
N05 - Back plate	446 x 446 x 36	4865.52	3817
N10 - Cavity Plate	396 x 446 x 36	4603.22	4906
N10 - Cavity Plate	396 x 446 x 36	4603.22	4906
N20 - Support Plate	396 x 446 x 56	5857.05	4585
N30 - Rises	56 X 446 X 106	2960.2	2321
N40 - Ejector Plate	280 x 446 x 20	2245.6	1760
N50 - Support Ejector Plate	280 x 446 x 26	2658.8	2079
location Sleeve	TD 42 x 130 (4pcs)	752	818.4
Pillar Sizes	FSC 34 - 36 - 46 (4 pcs)	1072	932.8
Bush Sizes	FBC 34 - 46 (4 pcs)	1024	941.6
Set Screws Complete for Die.		280	280
SB-3 Washer + screw	(4 pcs)	179	179
IS 610	M8 x 30 allen cap(4 pcs)	16 n/a	
bushes	FBC 16-26	286	310.2
IS 610	M16 x 30 allen cap(4 pcs)	64.8 n/a	
IS 610	M16 x 170 allen cap(4 pcs)	334.6 n/a	
Piller	FSN 16-26-86(2 off)	390	376.2
WZ8031 TB 10076	4pcs	81.3 n/a	
EJ PIN 6 X 125 AH	12pcs	408 n/a	
Total		**37546.83**	**32029.2**

5055 - 3636 - rises 106 fully loc DME

Plate Name	Plate size L X W X H	Price DME	LOCAL
N01 - Back Plate Blank	546 x 546 x 36	6766.03	5302
N05 - Back plate	546 x 546 x 36	6766.03	5302
N10 - Cavity Plate	496 x 546 x 36	6051.65	6303
N10 - Cavity Plate	496 x 546 x 36	6051.65	6303
N20 - Support Plate	496 x 546 x 56	7859.8	6160
N30 - Rises	56 X 546 X 106	3295.66	2585
N40 - Ejector Plate	380 x 546 x 20	3572.6	2794
N50 - Support Ejector Plate	380 x 546 x 26	4389.18	3130
location Sleeve	TD 42 x 130 (4pcs)	752	818.4
Pillar Sizes	FSC 34 - 36 - 46 (4 pcs)	1072	932.8
Bush Sizes	FBC 34 - 46 (4 pcs)	1024	941.6
Set Screws Complete for Die.		350	350
SB-3 Washer + screw	(4 pcs)	179	179
IS 610	M8 x 30 allen cap(4 pcs)	16 n/a	
bushes	FBC 16-26	286	310.2
IS 610	M16 x 30 allen cap(4 pcs)	64.8 n/a	
IS 610	M16 x 170 allen cap(4 pcs)	334.6 n/a	
Piller	FSN 16-26-86(2 off)	390	376.2
WZ8031 TB 10076	4pcs	81.3 n/a	
EJ PIN 6 X 125 AH	12pcs	408 n/a	

Total   **49710.3**   41787.2

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