Investigating the effect of process parameters on dimensional accuracy and ultimate tensile strength of micro injection moulded micro parts

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To my parents Mahmoud and Mahnaz and my brother Hossein,
without whom this work would not have been possible

Abstract

This thesis presents two models for optimizing and guiding the micro injection moulding process. The models are generated by the use of a mathematical procedure, an understanding of the process, and empirical data obtained from several sets of experiments.

Micro injection moulding is a well-known process that is heavily used in the mass production of micro polymer parts. It is a very reliable process and apart from the initial investment required for manufacturing a mould, the process is very low cost. Furthermore, polymer developments have led to the process being suitable for the production of micro parts in equipment used in several industries such as medical, automotive, aerospace and sensing. Due to these important industrial applications, several quality criteria have been the subject of research in recent years. One of the main challenges in micro moulding is the modelling of the process in terms of polymer flow and accuracy. This is because current available models use PVT data (pressure, volume, temperature) that is used for modelling of conventional injection moulding. Furthermore, these models ignore several factors in micro moulding such as the high shear rates and 3D flow of the polymer melt. Moreover, modelling of the mechanical properties of the micro parts based on mathematical systems used for macro parts leads to large errors.

This study proposes a new method for modelling the effect of process parameters on the dimensional accuracy and UTS (Ultimate tensile strength) of micro walls. This results in reduction of risk and cost, and optimization of the process. The “accuracy model” relates the dimensional error to four process parameters (polymer melt and mould temperature, and injection velocity and pressure), polymer characteristics (density, specific heat capacity and thermal conductivity) and a characteristic of the machine (plunger diameter). The “mechanical model” relates the part’s UTS to the same parameters as in the accuracy model.

In order to develop the “accuracy model” an understanding of the effect of process parameters on dimensional accuracy and the polymers needs to be obtained. Several sets of experiments were conducted to investigate and establish this effect. Two

polymers, Polyoxymethylene (POM) and Polypropylene (PP), were used to conduct the study. The results showed that the polymer melt temperature had the highest effect, followed by injection pressure, injection velocity and mould temperature. Amongst these, injection velocity had an adverse effect on dimensional accuracy. Further analysis was done to investigate whether the effect was consistent for several sets of the parameters. Results of the experiments showed that while the effect was not linear, the trends obtained earlier were correct.

The same procedure was applied to investigate the effect of process parameters on the UTS of the micro walls. Polymer melt temperature had the highest level of influence, followed by injection velocity, injection pressure and mould temperature. Increase in all parameters resulted in reduction of the UTS, except for the mould temperature.

Next, the two models were developed through a method called dimensional analysis. Several dimensionless expressions were developed to form a general relationship between the parameters and the quality criteria. Then, the obtained results and data were used to find the constants and the specific form of the functions. The overall models were validated by a fresh set of selected experiments using an original brass insert.

The achieved trends and models were validated experimentally, using a different mould insert with a micro channel with a different dimension. While the values for the dimensional error and UTS were different, the trends obtained before were correct for the new insert. The same trend was observed with the models. Again, predictions for PP parts had better agreement with experimental data compared to those of POM. In addition, the amount of error for the steel insert was higher, due to different thermal conductivity of the insert material and surface roughness of the micro channels.

List of publications

M.R. Mani, R. Surace, J. Segal, I. Fassi, S. Ratchev (2011) *Effect of Process Parameters on the Quality of Micro Injection Moulded Parts.* In *8th International Conference on Multi Material Micro Manufacture (4M 2011)* Stuttgart, Germany: Research Publishing

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List of Abbreviations

ABS	Acrylonitrile Butadiene Styrene
ANOVA	Analysis of Variance
AR	Aspect Ratio
CD	Compact Disc
CM	Compression Moulding
CNC	Computer Numerical Controls
CNF	Carbon Nano Fillers
COC	Cyclo-olefine copolymer
DNA	Deoxyribonucleic Acid
DOE	Design of Experiments
DVD	Digital Versatile Disc
FIB	Focused Ion Beam
HDPE	High Density
IM	Injection Moulding
IR	Infrared
LCP	Liquid Crystalline Polymer
LIGA	Lithographie, Galvanoformung, Abformung (Lithography, Electroplating, and Moulding)
MEMS	Micro Electro Mechanical Systems
µEDM	Micro Electro Discharge Machining
µIM	Micro Injection Moulding
µm	Micro Meter
MST	Micro Systems Technology
mm	Millimeter
PA	Polyamide
PBT	Polybutylene terephthalate
PC	Polycarbonate
PEEK	Polyetheretherketone
PET	Polyethylene terephthalate
PFA	Perfluoralkoxy copolymer
PMMA	Polymethylmethacrylate
POM	Polyoxymethylene

PP	Polypropylene
PS	Polystyrene
PSU	Polysulfone
PVC	Polyvinlchloride
PVDF	Polyvinylidenefluoride
PVT	Pressure, Volume, Temperature
TiO_2	Titanium Dioxide
TS	Tensile Strength
UTS	Ultimate Tensile Strength
UV	Ultraviolet
ZrO_2	Zirconium Dioxide

List of Symbols

a_{inj}	Injection acceleration
A	Area
C_p	Specific heat capacity
d	Change
D_c	Dimension of the width of the channel
D_p	Plunger diameter
E	Young's Modulus
E_0	Activation Energy
f	Friction factor
k	Thermal conductivity
L	Length
L_m	Width of the micro channel on the mould
L_p	Width of the micro wall on the polymer part
M	Mass
P	Pressure
P_h	Holding pressure
P_{inj}	Injection pressure
q	Heat transfer
Q	Melt throughput
r	Radius
R	Ideal gas constant
t_c	Cooling time
t_h	Holding time
T	Temperature/Time (Dimensional analysis)
T_{ejc}	Ejection Temperature
T_m	Mould temperature
T_p	Polymer melt temperature
U	Coefficient of heat transfer
V	Velocity
V_{inj}	Injection velocity
V_p	Packing velocity
x	Distance

β	Pressure constant
γ	Shear rate
ΔL	Difference in length/ Dimensional error
ΔP	Change in pressure
ΔT	Change in temperature
θ	Temperature (Dimensional analysis)
μ	Viscosity
μ_0	Viscosity at ambient temperature
$\mu(T)$	Zero shear rate viscosity at temperature T
ρ	Density
σ_m	Tensile strength of the polymer matrix
σ_w	Weld line strength
σ_{UTS}	Ultimate tensile strength of weld line
φ	Nano filler concentration

Chapter 1

Chapter 1 Introduction

In 2007, Germany's Federal Ministry of Education and Research [1] stated that micro injection molding's global market is growing at the rate of 15% annually and it will continue to grow in the near future. According to other studies there was an increase in the micro manufacturing market from $12 billion in 2005 to $24 billion in 2009 [2]. In agreement with these estimates, in 2012 µIM's market was valued at $308 million, and is still expected to have an annual growth at a rate of 14.2% to reach $763.6 million in 2019 [3, 4]. This growth is expected in the manufacturing of polymer and thermoplastic parts for applications in several industries such as medical and health care, telecom and fiber optics, automotive and micro drive systems and control [4]. µIM is becoming increasingly important amongst the available processes for production of micro electro mechanical systems (MEMS) and microsystems (MST). This is due to advantages such as optimisation and integration of functions in less space, and elimination of interface requirement, which increases the reliability of the system [5]. In addition, most other micro production processes such as micro machining, hot embossing and reaction injection molding are costly and time consuming, or have long cycle times [5-7]. Other advantages of µIM include high repeatability and reliability, versatility in polymer selection and cost effectiveness. Furthermore, µIM has a low cycle time which makes it an attractive choice for mass production [8, 9].

µIM has growing applications in medical, automotive, aerospace, electronics and optics industries. Medical applications of micro injection moulding include micro fluidic devices such as pumps, valves, nebulizers, capillary analysis systems, devices for investigating living cells, pressure and flow sensors. Other medical applications include drug delivery and body monitoring systems, and DNA sequencing devices [6, 10].

Applications of µIM in aerospace include the manufacturing of pressure sensors in flight control systems, cabin pressure monitoring and hydraulic systems. Automotive applications include airbags, vehicle dynamic control and navigation systems, engine air intake and tyre pressure sensors [2].

The most well known micro moulding products in electronics are CD, DVD and credit card holograms. Another range of micro moulded products are optical components such as spectrometers, lenses, optical switches, optical fiber connectors, waveguides, anti-reflective surfaces, optical gratings and photonic structures [6, 10, 11]. Today, micro electronics are a prospective application of thermoplastics μIM. An example is the production of electronic circuits with critical dimensions as small as 10 μm [6].

1.1 Motivation

Considering the vast number of applications micro injection moulding has in several important industries, it is crucial that parts are manufactured with the highest quality possible. In fact, these products are pushing the boundaries of sizes of manufactured parts whilst requiring tight tolerances and high quality. The best example of this is the medical sector where products need to pass vigorous testing to be approved before use. The parts used in these products need to be made with great precision, and if they are not made to the required quality they cannot be used as they can cause failure of the device. Another industrial example is when parts are used in the aerospace industry as pressure sensors in cabin monitoring and hydraulic systems. If one of these parts fails the outcome could be catastrophic. These are only two of the many examples where achieving a high quality part is crucial to the successful approval of the product.

Considering the importance of the quality of the parts in combination with increasingly higher production demand, there is a need for better understanding of the micro injection moulding process, and the effect it has on the quality of the parts. This study therefore focuses on establishing an understanding of the process and its effects on the quality of the replicated parts, and to model these effects in order to achieve high quality products in large volumes in a reliable and repeatable manner.

To replicate a part, a mould has to be designed based on the customer's specification and expectations. This is often a very expensive and time consuming task as many factors such as the runners and their size, gates and their locations and heating and cooling channels must be considered. After the design is complete, the mould has to

be manufactured. This is also very costly and there are many limitations and challenges in manufacturing the very small features. Once a mould is successfully made, several tests and experiments have to be carried out to investigate if a part or a specific feature can be replicated according to the customer's needs. This often depends on the experience of the users. If the final results are not satisfactory several adjustments are required during this process. This iterative process has to be repeated until the satisfactory results are achieved; resulting in a costly and time consuming process to successfully replicate a micro part or a part with micro features.

1.2 Aim and Objectives

The aim of this project is to contribute to knowledge by developing a method to optimise the process of µIM in terms of dimensional error and ultimate tensile strength (UTS).

This is done by developing two models which can be used to guide the optimisation and application of the µIM process, to achieve high quality parts with micro features in an efficient, reliable and repeatable manner. These models enable the estimation of the dimensional accuracy and the ultimate tensile strength of the micro moulded parts. In order to form these models, one must understand the effect of process parameters on these quality aspects. From this understanding, empirical models can be developed. These models will take several aspects into consideration:

- Characteristics of the product in order to measure the quality of the parts (dimensional accuracy and UTS)
- Characteristics of the polymer (density, thermal conductivity and specific heat capacity)
- Characteristics of the process (polymer melt and mould temperature, and injection velocity and pressure)
- Characteristics of the µIM machine (plunger diameter)

To achieve the overall aim, the following objectives are required:

A. Understanding the effect of process parameters on the dimensional accuracy of micro moulded parts
    - Selection of mould, inserts and features
    - Selection of a polymer
    - Conducting experiments with different combinations of process parameters in a systematic and logical manner
    - Measurement of the parts
    - Statistical analysis to understand the effect of process parameters on dimensional accuracy

B. Understanding the effects of process parameters on UTS of the micro moulded parts
    - Selection of mould, inserts and features
    - Selection of a polymer
    - Conducting experiments with different combinations of process parameters
    - Tensile testing of the polymer parts
    - Statistical analysis to understand the effect of process parameters on dimensional accuracy

C. Construction of mathematical models
    - Selection of the variables
    - Generation of a general mathematical model through dimensional analysis
    - Generation of the empirical data based on the results obtained from the previous two objectives
    - Generation of further empirical data and their implementation to form the final models

1.3 Thesis Structure

The thesis is divided into eight chapters which are outlined below.

Chapter 1 provides a brief introduction into µIM's market and its importance. It also provides the motivation behind the work conducted in this study. The overall aim of the study and detailed objectives to achieve the aim are explained.

Chapter 2 explains the general working principles of µIM, and its major differences with conventional IM. It also provides a detailed description of the most recent developments in the field of µIM. Finally the knowledge gaps related to this study are identified and listed.

Chapter 3 provides a summary of the entire thesis and the work conducted in this study. The knowledge gaps are reviewed and the motivation and problem definition are explained. Next, the tackling of the knowledge gaps and contributions to the field are stated. Finally, the link between the contributions and the overall aim of this study are described.

Chapter 4 begins by providing the motivation for the investigation of the effect of process parameters on the dimensional accuracy of the parts. Selection of different characteristics of the process are explained and examined. Additionally, the experiments and the method selected for conducting them are explained. Furthermore, the results of the experiments are presented. Finally, the results are analysed and discussed.

Chapter 5 starts by providing an explanation for the importance of the investigation of the mechanical behavior of the parts, and the effect of the process parameters on them. Selection criteria for the process, features, and the experimental approach and methods are explained. This is followed by the presentation of the experimental results, and analysis and discussion.

Chapter 6 begins with the selection and introduction of the method used for construction of the models. Selection of the variables and the reasons behind these

selections are then explained. The method is then applied to µIM and, more specifically, the defined problem in this study. At this point the general mathematical equations are formed. The results of the two previous chapters are then used to generate the required empirical data. This data is then used to complete the mathematical equations and form the final models.

The experimental results and the final models are validated in **Chapter 7**. A case is introduced for manufacturing a product. The results obtained in chapters 4 and 5 are validated through further experiments. The constructed models in chapter 6 are also used to predict the dimensional accuracy and UTS of the product. A discussion of the models and their limitations is also provided in this chapter.

Chapter 8 reviews the motivation behind this work, with a brief revision of the knowledge gaps and contributions. Conclusions are made on each of the contributions addressed in this study. Overall concluding remarks are made to link the three contributions and the overall impact on the µIM domain. Finally, areas for further research and future work are identified.

Chapter 2

Chapter 2 Literature review

The intention of this chapter is to provide a review of the state of the art and recent developments in the field of micro injection moulding. Firstly, a background into µIM and its development are provided. Then the development of µIM machines and the general working principle are explained. Differences between the types of machines are explained and specific operations of the one used in this study are described. This is followed by a summary of the mould making technologies. Effects of mould design and manufacture on part quality are explained and the polymers suitable for µIM are listed with their characteristics. Then the recent development in optimisation of the process and the effect of the process on the quality of micro moulded parts are provided. The research into modelling of the process and its effectiveness are presented and discussed. Finally, a summary of the knowledge gaps that are most relevant to the aim of this project are provided.

2.1 Development of micro injection moulding

The concept of miniaturisation has been around for many years. The importance of micro manufacturing and miniaturisation were introduced by Richard Feynman in 1959 [12, 13]. Initially, he saw the need for production of units that can store information at a much higher rate and using less space; and also the need for technologies and machinery that could produce such devices. However, the concept of miniaturisation and making smaller products had already started in 1929 when Jaeger-Le Coultre produced the record for the smallest watch. Around the same time a new level of complexity had been reached for production of astronomical watches. L. Oechslin produced one such a device with 213 parts, which showed the movement of 6 planets [14]. This trend continued and miniaturisation developed until A. Beyner produced the thinnest watch in 1981. This watch had a thickness of 0.98 mm, which had a coil made of 7000 turns of a 10 microns diameter wire. Pinion axis was machined down to 70 microns and the gear had a pitch of 120 microns [14]. This was the time when the production of parts with smaller sizes had become increasingly important. However, most of these products were made by hand and the production depended heavily on the experience of the workers.

At the same time, silicon had become a very important material in the manufacturing of semiconductors; and as a result many technologies for processing silicon were developed. This development resulted in the production of micro electro mechanical systems (MEMS) and microsystem technology (MST) [15]. At this time, injection moulding (IM) was already developed and was used as an industrial process. This process became very attractive, especially after the development of polymers. Polymers are considerably less costly compared to silicon and do not need the expensive equipment that is required for the processing of silicon parts [16]. In addition, IM proved to be a very reliable technology for the mass production of polymer parts at low cost. Furthermore, unlike silicon, most cases the final product does not require any finishing operation [17].

In the late 1980s as the need for miniaturisation increased, companies started to modify commercial IM machines to produce micro products. These machines were hydraulically driven and often had clamping forces of 25 to 50 t [18]. However, this technique had several problems such as the massive amount of wasted polymer compared to the part, and accurate control of the movement of the injection screw. In the mid- 1990s the first efforts were made by mechanical engineering companies and research institutes to develop machines that were specifically suitable for µIM [18]. This was the start of the development of µIM machines, which were developed to focus on manufacturing of real micro parts.

2.2 Micro replication technologies

Several technologies exist for manufacturing of micro products. The list includes direct methods such as laser ablation, laser cutting and stereolithography, photolithography, which have mostly been used for low scale production and prototyping [19]. However, much effort and resources in the commercial and research domain have been focused on mass replication technologies. Some studies [6, 19, 20] have compared micro replication technologies and the general agreement is that IM and µIM are the most suitable processes for mass production of micro polymeric parts.

2.2.1 Injection moulding

IM is one of the most important and most commonly used technologies for production of polymer products [17]. The process involves heating of the polymer until it melts. The melt is then injected into a cavity which holds the features. The polymer melt in the cavity is then cooled until it solidifies and is finally ejected from the mould. In this process, each polymer requires a specific set of conditions to produce the optimal part. *Figure 2-1* shows the schematics of the IM process.

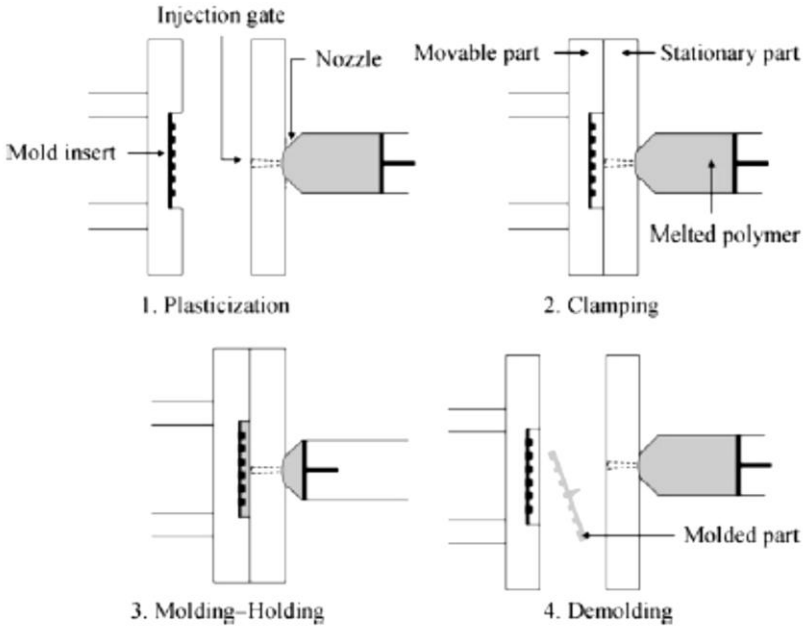


Figure 2-1- Schematics of the injection moulding process [21]

The main reason for the attractiveness of this process is that it can produce polymer parts in a relatively short amount of time and is therefore cost effective. However, for manufacturing a specific part, a specific mould must be designed and manufactured. Each mould in turn requires a design based on its own characteristics. Depending on the cavities, heating and cooling channels have to be designed. Also, depending on the product and its characteristics, a demoulding system may be required. These steps result in a high initial investment cost. Therefore, this technique is only suitable for the mass production of micro parts. A comparison [6] of hot embossing and IM showed that hot embossing is less costly and more accurate for the manufacture of low to medium quantity of products. However, IM has clear benefits in mass manufacture of products due to its shorter cycle time. Therefore, different variations

of the IM process are used for manufacturing 32% (by weight) of all polymeric parts [22].

2.2.2 Micro injection moulding process

Several characteristics have been given in the literature [23-30] to define what a micro moulded part is. A general definition is given as polymer parts that have structures with dimensions in micro or nano range. Yao and Kim [23] suggested parts with overall dimensions of less than 1 mm, or a part with larger dimensions with tolerances in the range of 200 µm. Another suggestion [24] is parts that are manufactured by µIM with a weight of a few milligrams and tolerances of a few µm. A summary of these characteristics has been provided [31] and are accepted as:

- "A part that weighs less than a milligram or it is a fraction of a polymer pellet, where a pellet can be approximated to be spherical in shape with an average diameter of approximately 3mm.
- It is a part with micro structured regions, or more specifically, with wall thickness less than 100 microns.
- It is a micro precision part, which is a part that can have any dimensions, but has tolerances in the micrometer range, or more specifically, between 2 to 5 microns."

The general working principle in µIM is the same as IM. The polymer needs to be heated into a melt, the melt then has to be injected into a mould cavity and cooled. Then the final part is ejected from the mould. However, µIM cannot be described as the scaling down of IM [21]. While there is a large amount of information and know-how in polymer processing, several differences and characteristics of the µIM process makes it different and more complicated than IM. For example, mould manufacturing techniques that can be used for production of cavities in µIM are different to those used for IM. These processes need to deliver features and cavities in much smaller ranges than in IM, which results in higher stresses applied to the mould surface. This is also reinforced by the effect of high temperatures generated as a result of material removal [32].

When dealing with micro parts, part quality and filling are very important. Because of the small dimensions, structures such as square shaped corners become especially difficult to fill [18].

The other difference is in the injection of the polymer melt; because of the small dimensions of the runners and cavities shear stress increases as the injection velocity increases. This is especially important at the gates because of the small dimensions of the gates and the area that the material can go through. These factors increase the shear rates by a large factor; 10×10^4 to 5×10^6 /s in µIM compared to 10000 /s in conventional IM [33]; and also lead to increases in the stresses which could cause degradation of the material, which will adversely affect the mechanical properties of the polymer and the parts.

A list of technological differences between µIM and conventional IM can be drawn from conducted studies. Martyn et al [34] provided a summary of these differences, which have since been extended by other studies [35, 36]:

- Mold construction technology
- Application engineering
- Raw material variation
- Precision technology
- Nano-rheology
- Process measurement
- Product properties
- Modelling of the molding process.
- Different process parameters for high quality parts
- Different control systems

2.2.3 Micro injection moulding machines

As explained in section **2.1**, in the 1980s companies used IM machines to produce micro parts. Some development happened at the time to modify these machines so that they become more suitable for the production of micro parts. However, use of these machines led to large amounts of polymer waste. The size of the runners

compared to the actual part was massive. This however, was a necessity of the process. Since these machines were developed for IM and large parts, they were only able to have large metering size. Therefore, to compromise for the difference between the part and the metered polymer, the runner had to be designed to be large. In addition, the hydraulic systems used in these machines to control the metering size were not accurate enough for production of micro parts. The control of the movement of the screw and the clamping unit, which require very small tolerances, was also difficult and inaccurate. The level of required accuracy in the movement and tolerances can only be achieved by servo electric machines [37]. Furthermore, the identification of the switch over point (i.e. the point where injection pressure switches to holding pressure) based on the injection pressure led to inaccurate control of the amount of injected polymer. This point is now identified by the position of the plunger in µIM machines [38]. This results in more accurate control over the injected volume. Finally, the size of the µIM machine has to be smaller than that of the IM ones. This results in smaller parts in the injection unit, such as screw, barrel and nozzle, and lower clamping force. This in turn reduces the volume of the polymer required and energy consumption [18].

To address these issues, and to produce real micro parts with the characteristics already mentioned, three concepts are developed. The first is a modification of a conventional IM machine, with a single step system. In this concept the sizes of the barrel and the screw are reduced to dimensions lower than 20 mm [18]. However, injection still happens through the movement of the screw. This creates several problems. First, the flow length is long and there is a large melt cushion. Thermal separation of the sprue and the melt cushion creates a cold material slug which becomes larger in every cycle. Also, control of the screw for very small shots is very difficult. For example for a 1 mg shot weight, a 14 mm screw has to move 5.6 µm. The schematic of this kind of machine is shown in *Figure 2-2*.

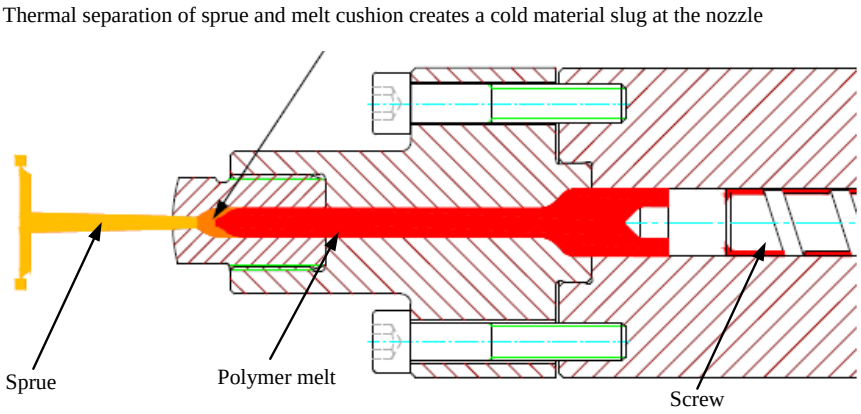


Figure 2-2- Machine with a single step system (Taken from [39] and modified)

The second concept is one where the plasticising and injection units are separate. This concept used a plunger and a hot cylinder. The third concept is similar to the second, in that it has separate plasticising and injection units, with the difference that its plasticising unit has a screw instead of a plunger. The screw heats up the polymer by means of both thermal and mechanical energy. Therefore, it is more efficient than the plunger and the polymer is thermally more homogenous [40]. The plunger then injects the polymer into the cavity. This provides a more precise control of the amount of injected polymer compared to a large rotating screw [18, 40]. These two concepts are shown in *Figure 2-3* and *Figure 2-4* respectively.

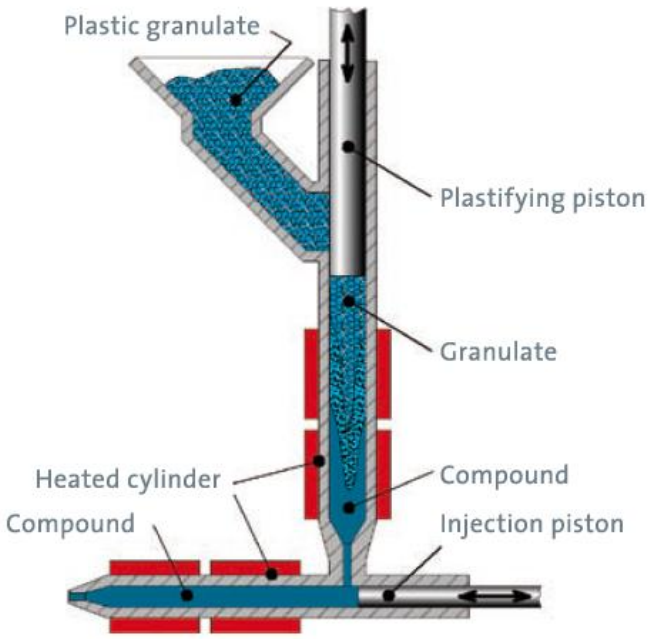


Figure 2-3- Plunger plasticising and injection system [41]

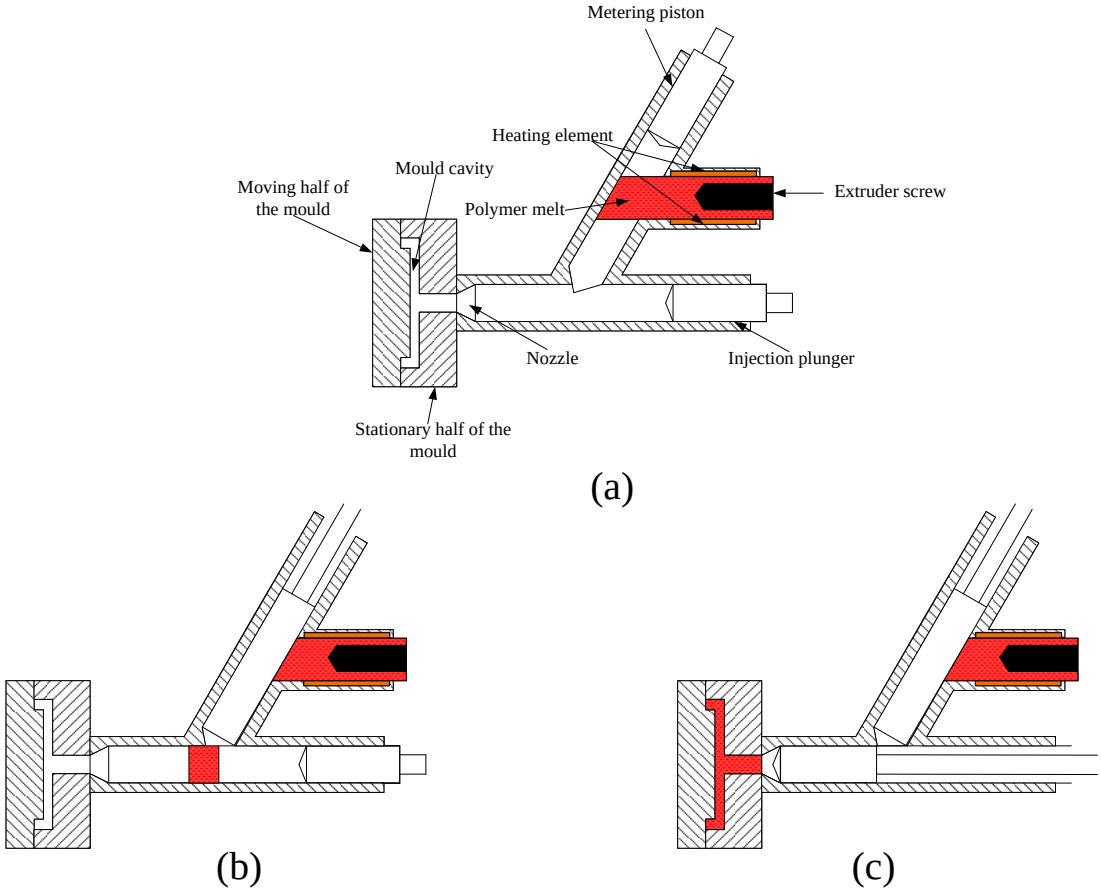


Figure 2-4- Screw plasticising and plunger injection system

The concept shown in *Figure 2-4* shows the one employed in Battenfeld Microsystem 50, which is used in this study. This machine addresses the issues and requirements that were discussed previously in this section. The operating procedure of the machine is:

- Polymer pellets are heated to their melting point and moved into the dosing chamber by the extruder screw (*Figure 2.4 a*).
- A shut off valve closes to ensure that the polymer melt cannot move back from the dosing chamber.
- The predefined volume of the polymer melt is measured in the dosing chamber and pushed into the injection chamber by the metering piston (*Figure 2.4 b*).
- The polymer melt is injected into the cavity by the injection plunger (*Figure 2.4 c*).
- Once the injection phase is finished, a holding pressure is applied through the movement of the plunger to compensate for the shrinkage.

The main characteristics of Battenfeld Microsystem 50 are shown in *Table 2-1*. A list of commercially available machines for µIM and their characteristics are provided in *Table 2-2*.

Table 2-1- Main characteristics of Battenfeld Microsystem 50

Clamping force	50 kN
Ejection force	1.2 kN
Extruder screw diameter	14 mm
Maximum screw speed	300 rpm
Maximum shot volume	1.1 cm^3
Injection plunger diameter	5 mm
Maximum injection pressure	1050 Bar

Table 2-2- List of commercially available machines for µIM [42]

Manufacturer	***Model***	***Clamp force (KN)***	***Injection capacity (cm^3)***	***Injection pressure (Bar)***	***Plasticization***	***Injection velocity (mm/s)***
Lawton	Sesame nanomolder	13.6	0.082	3500	10mm Plunger	1200
APM	SM-5EJ	50	1	2450	14mm Screw	800
Battenfeld	Microsystem 50	56	1.1	1050	14mm Screw	760
Nissei	AU3	30	3.1	-	14mm Screw	-
Babyplast	Babyplast 6/10	62.5	4	2650	10mm Plunger	-
Sodick	TR05EH	49	4.5	1970	14mm Screw	300
Rondol	High force 5	50	4.5	1600	20mm Screw	-
Boy	12/AM	129	4.5	2450	12mm Screw	-
Toshiba	EC5-01.A	50	6	2000	14mm Screw	150
Fanuc	Roboshot S2000-15A	50	6	2000	14mm Screw	300
Sumimoto	SE7M	69	6.2	1960	14mm Screw	300
Milacron	Si-B17 A	147	6.2	2452	14mm Screw	-
MCP	12/90 HSE	90	7	1728	16mm Screw	100
Nissei	EP5 Real Mini	49	8	1960	16mm Screw	250
Toshiba	NP7	69	10	2270	16mm Screw	180

2.2.4 Mould manufacture and material

µIM of a product requires a mould to be designed and manufactured. Characteristics of the mould such as the design of gates and runners and the material used for them plays an important role in the quality of the product. Studies have been conducted on the effect of different design characteristics on the replication of micro parts.

Zhang et al. [43] conducted a study on the effect of mould design on the replication of micro parts and concluded that quality of the replicated parts is very sensitive to the flow direction. Results showed that the features in the direction of the flow are replicated better. While the effect of the distance between the features was insignificant, the location and thickness of the substrate slightly influenced the filling of the cavities. However, Yang et. al [44] conducted a set of experiments on filling micro channels and results showed the opposite effect, with increased air trap in the features along the flow of polymer melt. This shows that the configuration of the features and their design are important factors in the filling of the cavities.

The material of the mould also has an effect on different quality criteria. Jungmeier et al. [45] conducted an experiment on the effect of the mould materials on the mechanical properties of the parts. Three moulds made out of ceramic (ZrO_2), steel and polymer (PEEK) were used. The conclusion was that the ceramic mould showed the best replications due to its low thermal conductivity. The polymer insert was deformed due to the high temperature.

Griffiths et al. [46] conducted an experiment to investigate the relationship between the filling of the cavities and the runner system design. Experimental results showed that filling of the micro cavities is sensitive to the size of the runners, due to changes in temperature and pressure as the polymer flows. This, however, is only true for certain polymers that are sensitive to a temperature decrease such as POM.

Yang et al. [47] and Griffiths et al. [48] also studied the effect of the tool surface roughness on the replication of micro parts. They showed that as the surface roughness of the mould inserts increased the flow length was reduced. Yang et al [47] also concluded that the effect of surface roughness could be reduced by using

higher melt temperature and injection velocity due to increased pressure of air trapped during the injection process. Experiments conducted by Griffiths et al [48] showed that at the same surface roughness higher settings of process parameters resulted in better filling of the cavities. This highlights the role that process parameters play in replication of micro parts. It shows that even under the same physical conditions, adjusting to the process parameters to optimised values can make a difference in the quality of the micro parts.

Once the design is finished, a mould has to be manufactured. Several manufacturing technologies exist for the production of micro moulds. Selection of the technology depends on the required features and their sizes. This is because each particular technology can produce a range of sizes successfully. A list of common technologies is presented in *Table 2-3*.

Laser machining is a very competitive process amongst the material removal techniques. It allows the fabrication of structures of about 10 μm with aspect ratios of 10. The main drawback of this technology is that tight tolerances are difficult to make due to the size of the laser spot [21]. The smallest achievable spot is half the wavelength of the light [19, 49].

Micro electro discharge machining (µEDM) can achieve structures with the width of 15 μm and it ensures the manufacturing of very complex geometries. A high voltage current applied between an anodic electrode and a cathode tool causes the removal of the metal. Cylindrical electrodes are used for drilling holes and tungsten wires are used for manufacture of complex geometries [50, 51]. The main drawback of this technology is that accuracy of the dimensions and surface roughness depends heavily on the vibration of the electrode. µEDM is suitable for the production of features bigger than 50 µm with tolerances in the range of 10 µm [21].

Table 2-3- Examples of mould manufacturing technologies (taken from [21] and modified)

Technology	*Typical structure size*	*Feature tolerance*	*Aspect ratio [52]*	*Wall roughness [53]*	*Materials*
Ion Beam LIGA/2D	0.1-0.5 µm	0.02-0.5 µm	1	-	
Focused Ion beam/2D&3D	0.2 µm	0.02 µm	-	-	Any
X-ray LIGA/2D	0.5 µm-1 mm	0.02-0.5 µm	10-100	< 20 nm	Electroformable materials
Electron Beam LIGA	0.1-0.5 µm	-	1-2	-	
UV LIGA/2D	2-500 µm	-	1-10	-	
Femto-second Laser 2D/3D	1 µm	< 1 µm	1-10	-	Any
Excimer Laser 2D/3D	6 µm	< 1 µm	1-10	1 µm – 100 nm	Polymer, ceramics and metals
Ultra short pulses ECM 2D/3D	Few micrometers	< 1 µm	8	-	
µEDM 2D/3D	10-25 µm	3 µm	10-100	0.3-1 µm	Conductive materials
Micromilling 2D/3D	25 µm	2 µm	10-50	Few micrometers	PMMA, Aluminium, Brass, Steel
Deep UV resists	-	2-3 µm	22	1 µm	-
Deep Reactive ion etching	-	< 1 µm	10-25	2 µm	Silicon

LIGA (Lithography, Electroplating, and Moulding) is another common process for manufacturing micro moulds. In this process layers of conductive materials are first coated onto a substrate, usually silicon wafer, for the electroplating step. X-Ray of UV sensitive polymer such as PMMA is then deposited on the layers. After placing the mask containing the geometry on the layer, the irradiation step starts. The part is obtained by dissolution of chemically modified material [21]. *Figure 2-5* shows the schematics of the process.

The performance of this method greatly depends on the type of radiation. UV and X-ray lithography are the most common radiations used in the manufacture of mould inserts [54, 55]. However, since UV is less costly, it is the preferred method in production of MEMS [54]. Nowadays, LIGA and LIGA like techniques are used for production of mould inserts with high aspect ratios [55]. Two main drawbacks exist with this technique. Firstly, LIGA cannot be used on conventional tooling materials such as steel [21]. Secondly, draft angles, which reduce the chance of damage during demoulding, are very difficult to produce [56].

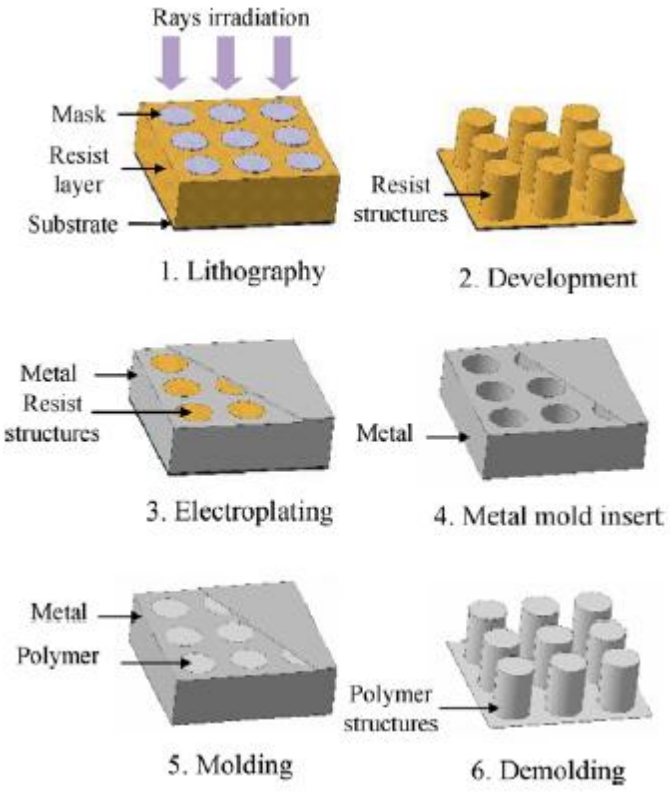


Figure 2-5- Schematics of LIGA process [21]

Micro milling is a process often used for production of micro channels. Development of precise computer numerical controls (CNC), high speed spindles and hard material for cutting have made the manufacturing of micro features by the milling process possible. In this process the cutting tool moves in a predefined path and removes the unwanted material. The minimum achievable feature size depends on the size of the cutting tool used. At present the minimum cutting tool has a diameter of 30 µm. Similar to µEDM, this process is suitable for production of features larger than 50 µm and tolerances of 10 µm. The main drawback of this process is that due to the

high spindle speed a large amount of heat is generated, which can melt the edges of the features. The generated heat can also cause expansion of the cutting tool and the work piece, which can result in removal of too much material or breaking of the cutting tool [57]. Therefore, an integrated cooling method is required.

Focused Ion Beam (FIB) is a process that is sometimes used in mould manufacture. This process enables the production of sub-micron features. FIB involves bombardment of the work piece by ions with very high velocity and energy. When surface atoms receive high energy from the ions they are removed from the specimen. By scanning the ion beam in different directions and adjusting its parameters, the process can be used for milling. However, material removal by firing ions alone is often slow and results in inaccuracies and undesired topography [58]. Therefore, in most cases, gases such as Cl_2, Br_2, I_2 and XeF_2 are used to assist the process. The gas is injected toward the surface and under ion bombardment reacts with the substrate to produce volatile products which have higher or lower sputtering rate than the sample material [59].

While theoretically any material can be processed by FIB, best results are achieved when conductive amorphous materials are used. Multi crystalline materials are not suitable due to different orientation of their grains. Inserts with few micron sized features for µIM were fabricated by Zhange et. al. [60]. These were made on a bulk metallic glass composition of $Zr_{47}Cu_{45}A_{18}$ and have depth of 2.24 µm, with height of 1.91 µm and a range of width of 0.3 to 4 µm. Vladov et. al. [61] also produced features with dimensions of 7µm on Brass.

2.3 Polymer materials for µIM

Polymers are classified depending on several criteria. However, an initial classification can be made depending on their chemical structure. *Figure 2-6* shows this classification.

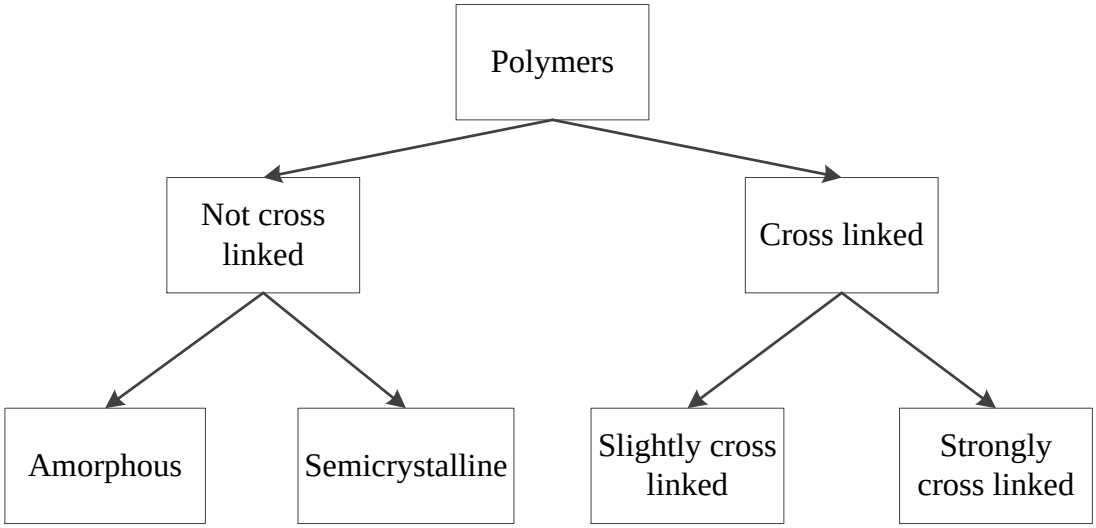


Figure 2-6- Polymer classification [17]

Polymers are made out of linear or branched molecules. This is shown in *Figure 2-7* with the characteristics of each type of polymer.

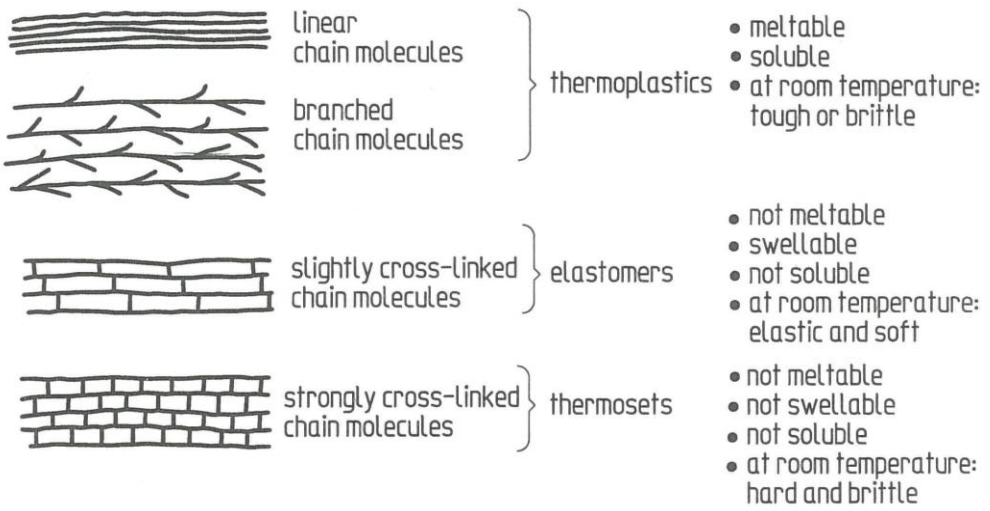


Figure 2-7- Depiction of the arrangement of long chain molecules in different polymers [17]

There is no chemical connection between the individual macromolecules. Therefore, they can be remelted and reused several times [17]. Thermoplastics can be further differentiated to amorphous and semicrystalline polymers. Amorphous polymers are those in which the molecules are arranged at random. They can be easily identified by their transparency. Semicrystalline polymers are those with some areas arranged in a regular manner [17]. Schematics of these are shown in *Figure 2-8*.

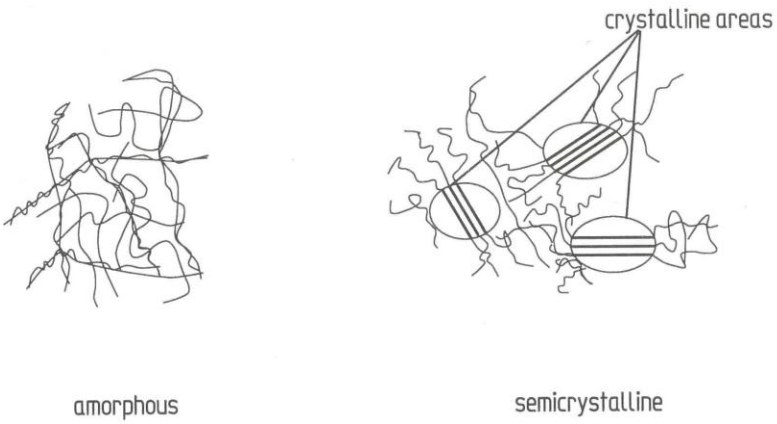


Figure 2-8- Schematics of the arrangement of molecules in amorphous and semicrystalline polymers[17]

Because the macromolecules are entangled, complete crystallisation is not possible and there are always amorphous regions between the crystalline areas. The proportion of crystalline regions to in relation to complete crystallisation is defined as the degree of crystallinity. The simpler the chain structure in a polymer, the higher the degree of crystallinity [17, 62].

2.3.1 Polymer processing

Polymers and polymer processing are very important in the field of micro injection moulding because they have relatively low cost, and offer good mechanical and thermal strength, electrical insulation, optical transparency, chemical stability and biocompatibility. This is particularly important in the replication of micro fluidic and medical devices [5, 31]. Furthermore, polymers can be tailored to specific applications due to their specific properties as can be seen in a variety of publications [11, 21, 31, 33, 45, 63]. Polymers are good electrical insulators compared to similar materials such as silicon. They also offer good mechanical properties [31]. This is important because polymeric parts need to have high enough mechanical strength to not only withstand the ejection force, but also be able to function under mechanical load in certain applications such as gear teeth.

In addition to the applications stated above, polymer processability is another important consideration. The flow process in IM mainly involves shear of the melt. Shear flow occurs when the polymer melt adheres to the adjacent surfaces. When one surface moves, the layers in between slide correspondingly and the melt is sheared.

Shear rate is calculated from the difference in velocity between the upper and lower surfaces. Shear flow of the polymer melt results in the application of shear stresses to the polymer melt. Shear stress is the necessary force to deform the material divided by the area. The proportionality factor between the shear rate and shear stress is the viscosity [17, 62].

Polymer melts are considered non Newtonian fluids and experience what is referred to as shear thinning i.e. decrease in viscosity as shear rate increases. An explanation for shear thinning is that the distance between the molecules becomes higher, and they become less entangled and more oriented (higher degree of crystallinity). This allows them to be displaced more easily while forces are acting [17, 62]. Polymers go through severe operating conditions in µIM such as high temperatures and pressures. Therefore, flow properties radically change due to high shear rates [31]. Due to the small dimensions of the features in µIM, polymer viscosity has to be low enough for the melt to be able to fill the cavities. Therefore, depending on the size of the crucial features or tolerances in a product, the choice of polymer becomes a very important factor.

Generally, polymers used in conventional IM can be used in µIM [64], however, Pakkanen et. al. [65] and Liou and Chen [66] found not all polymers present the same flow behaviours. In fact, different polymers showed different responses in flow direction and filling of the cavities. In addition, Yao et. al. [23] concluded that these polymers have to be researched again due to different flow properties and complexity of the melt flow behaviour in micro cavities. In particular the behaviour of semi crystalline polymers such as POM is of great interest and needs to be investigated [9]. A list of commonly used polymers in µIM is presented in *Table 2-4*.

Table 2-4- List of commonly used polymers in µIM (Taken from [6] and modified)

Acronym	*Full name*	*Temperature stability (°C)*	*Properties*	*Structure*
COC	Cyclo-olefine copolymer	140	High transparency	Amorphous
PMMA	Polymethylmethacrylate	80	High transparency	Amorphous
PC	Polycarbonate	130	High transparency	Amorphous
PS	Polystyrene	80	Transparent	Amorphous
POM	Polyoxymethylene	90	Low friction	Semi crystalline
PBT [67]	Polybutylene terephthalate	225	High dimensional stability & mechanical properties	Semi crystalline
PFA	Perfluoralkoxy copolymer	260	High chemical resistivity	Semi crystalline
LCP [68, 69]	Liquid crystalline polymers	325	Good mechanical properties & Dimensional stability	Semi crystalline
PVC	Polyvinlchloride	60	Low cost	Amorphous
PP	Polypropylene	110	Mechanical properties	Semi crystalline
PET	Polyethylene terephthalate	110	Transparent, low friction	Amorphous / Semi crystalline
PEEK	Polyetheretherketone	250	High temperature resistivity	Semi crystalline
PA	Polyamide	80-120	Good mechanical properties	Semi crystalline
PSU	Polysulfone	150	Chemical and temperature resistivity	Amorphous
PVDF	Polyvinylidenefluoride	150	Chemically inert, Piezo electric	Semi crystalline

2.3.2 Solidification of polymers

As heat is removed from polymer melt, the molecules lose their ability to move freely, which makes the melt more viscous. In semicrystalline polymers, at a temperature close to the melting temperature, the molecules start arranging themselves in crystalline and amorphous regions. At the start of crystallization, the material becomes soft and rubbery, yet not brittle. This is because the amorphous regions are still at a temperature higher than glass transition temperature. For

common semicrystalline polymers the degree of crystallinity is between 30 and 70%. [62]

In injection moulding of thermoplastics, due to the heat needed for crystallisation more heat needs to be removed from the melt to solidify the part. Slow cooling rates result in high packing time and more pressure needs to be applied to reduce the shrinkage of the final part. This increases the cycle time. At high cooling rate, degree of crystallisation is reduced. This results in formation of larger amorphous regions, which after the process become more crystalline. This results in further shrinkage of the part and variation in dimensions of the final part. [62]

Shrinkage of injection moulded thermoplastic parts is affected by volumetric shrinkage, flow induced residual stresses and orientation, flow induced crystallisation, and heat transfer [70]. Other factors include the polymer itself, processing parameter and the geometry of the mould [71]. Geometry can affect shrinkage in two ways. First, it can change the direction of flow which causes an orientation effect (amorphous or crystalline), resulting in shrinkage anisotropy [72]. Secondly, it can cause geometrical constraints such as ribs and walls[72]. Several studies have been conducted on the effect of processing parameters for several polymers in conventional injection moulding [70-73]. However, there does not seem to be many studies conducted on the effect of process parameters on the µIM micro parts, and a comparison of the results with CIM [74]. Due to the different degree of orientation and crystallisation in µIM and CIM, the results obtained from macro studies cannot be applied to micro parts [74]. Annicchiarico et. al [74] conducted a study to investigate the effect of five process parameters, P_{inj}, P_h, T_p, T_m and t_h on the shrinkage of micro moulded rectangular plates, both in the direction of the flow and perpendicular to it. Results showed that T_m had a significant effect on reducing shrinkage in the direction of the flow, while it caused increased shrinkage in direction perpendicular to the flow.

2.3.3 Yield in polymers

If a polymer is subject to high strain deformation, it deforms permanently (plastic deformation) and finally fails. *Figure 2-9* shows the process of failure for a typical

polymer on a stress-strain curve. At low stress and strain the polymer behaves as a linear elastic solid. The point at which the linear behavior becomes non-linear is called the proportional limit. The local maximum at this point is the yield point. This point is the start of plastic i.e. permanent deformation. The stress at this point is the yield strength. Beyond the yield point the material stretches further which forms the plastic region. Further elongation of the polymer leads to rupture of the polymer. The stress at this point is strength at break [75].

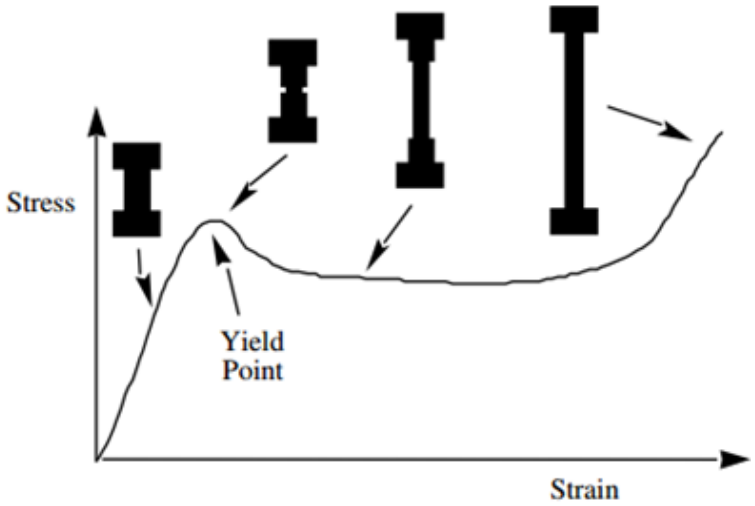


Figure 2-9- Failure in polymers [75]

Some polymers such as PS fracture before or immediately after yield. Others such as PE can reach much higher strain. Unlike metals it is difficult to distinguish between the elastic (recoverable) and plastic (permanent deformation) strain. This is because the recovery of a polymer and its return to the original dimensions depends on the temperature and the recovery time. In general, the stress-strain behavior of a polymer depends on several factors such as processing parameters and micro structures of the polymer [75]. These are discussed further in **Chapter 5**.

2.4 Effect of process parameters on the replication of micro moulded parts

Several studies have been conducted to understand the effect of process parameters on the replication quality of the micro moulded parts. Each study has defined quality as specific criteria. In most cases these are flow length and filling of the cavity. Studies have also looked at the effect of process parameters on the mechanical

stability and strength of the micro parts. While the general agreement is that higher settings for the process parameters result in better replications, experiments have shown that there are limitations to this.

Several process parameters can be investigated on a μIM machine. Zhang et. al. [60] conducted a set of experiments where a number of ridges and channels were replicated by HDPE. Injection velocity (V_{inj}), holding time (T_h) and pressure (P_h), and melt and mould temperatures (T_p and T_m) were investigated. The study focused on the quality of the replications and sharpness of the parts and their height. The conclusion was that the main factor in the production of sharp edges was the direction of flow. The ridges aligned with polymer flow showed better edge definition. Regarding the height of the features, higher settings in P_h, T_m and V_{inj} showed significant positive effects. None of the other parameters showed significant effects apart from V_{inj}, which had a positive effect. All interactions also had no significant effect. In another study [76] Zhang et al investigated these factors to characterise the process during the filling stage. The quality criteria were cavity pressure and velocity. V_{inj} and P_h showed the highest positive effect on the velocity and the others were insignificant. Contradictory, V_{inj} showed a small effect on the cavity pressure and P_h and T_m had significant negative effect. The effects on the dimensions of the parts were not examined in this study.

Chu et. al. [77] also conducted a similar study where the effect of V_{inj}, T_p, T_m and packing velocity (V_p) on cavity injection pressure at different stages were examined for POM, HDPE and PC. Experimental results showed that V_{inj} had the highest influence on the investigated criteria for all three polymers. However, lower V_{inj} resulted in better repeatability for POM while the opposite was the case for HDPE and PC. The effects on the actual parts were not mentioned in the study.

Park et. al. [78] investigated the effect of mould heating on the replication of the parts. A special localised heating method was used by high frequency induction to investigate the heating effect and suitability of the method. Mould heating proved to be a very important factor with the method improving replications by 300% and 38% in comparison with water heating and normal induction, respectively. In fact, mould heating has been the subject of several studies. The general agreement is that the

mould temperature in µIM needs to be increased considerably compared to conventional IM. *Table 2-5* shows a comparison of the mould temperature used in µIM and IM for four semi-crystalline polymers.

Table 2-5- Comparison of Tm in µIM vs. conventional IM (taken from [21] and modified)

Polymer	***T_m in µIM (°C)***	***T_m in conventional IM (°C)***
HDPE	125, 140, 150	30-60
PBT	120	80
POM	90	70-90
PP	163	30-60

Studies have shown that mould temperature needs to be close to or above the softening temperature of the polymer. [66, 79-81]. Generally, a fixed temperature lower than the polymer's glass transition temperature can be used. However, the higher the aspect ratio, the more mould temperature has to increase [21, 82]. *Figure 2-10* shows a relationship between mould temperature and aspect ratio.

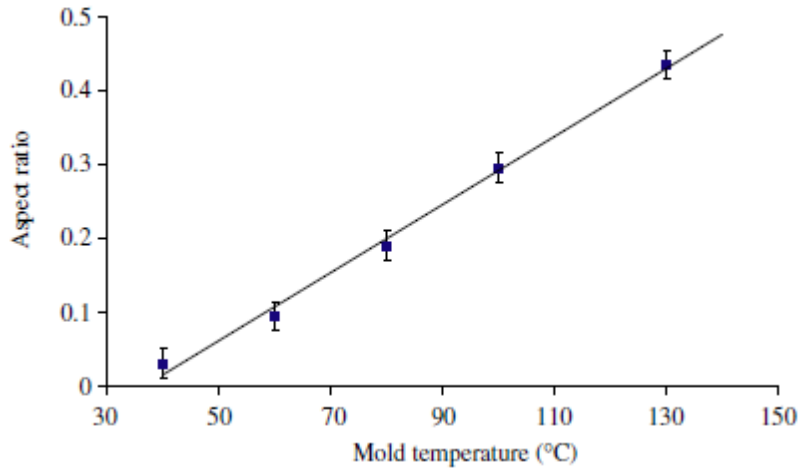


Figure 2-10- Achievable aspect ratios in microstructures as a function of mould temperature [21]

Fu et. al. [83] conducted a set of experiments with an amorphous polymer (COC) to manufacture a set of micro channels. Results showed that T_p had the highest influence on the width of the micro channels (68.36%) and all the other parameters (T_m, V_i, P_i, P_h, T_h and cooling time (T_c)) had minor effects, between 0.03-9.5%; with T_m and P_h showing the highest effects. Pre heating the polymer in the hopper showed

the smallest effect with 0.01%. Kirchberg et. al. [84] also conducted experiments with three amorphous polymers, PC, PMMA and PS, to produce an array of micro lenses. The quality criteria used were the surface roughness and diameter of the parts. PMMA produced the best results in terms of dimensional variation; however, it also showed the highest surface roughness. The study does not explain the optimisation method for process parameter values.

Yang et. al. [85] manufactured a set of micro ribs with aspect ratios of between 0.5 and 2 with PP and PMMA. The study investigated the effect of T_p, T_m, V_{inj}, P_h, T_h, aspect ratios (AR) and the choice of polymer. Results showed that T_p and V_{inj} had the highest effect on height and width for both materials. However, parts made with PP showed better height and width replication due to its higher melt flow index (300%) compared to PMMA. Replication quality deceased with increase in AR and distance from the gate. T_m also showed a significant effect for PMMA. However, T_m for PP did not have a significant influence. This is in agreement with a study by Griffiths et. al. [46] where mould temperature did not influence polymers with lower sensitivity to changes in temperature such as PP.

µIM of a micro fluidic device, made out of PMMA, by Attia et. al. [86-88] showed that amongst the investigated parameters (T_m, T_p, V_{inj}, P_h and T_c) P_h, T_m and V_{inj} had the highest influence on the mass of the parts. However, V_{inj} alone was responsible for reducing the variation in mass. Increasing V_{inj} showed a negative effect on the part mass, however, it proved to have a positive effect on its variation. Dimensional variation of the part and the influence of parameters on it were not examined. Nebo et. al. [89] investigated the effect of T_p, T_m, P_{inj} and t_h on the mass of the parts for PP and HDPE. The conclusion was that t_h and T_p were the most influential factors in achieving the optimum mass for PP. None of the factors were shown to have a high influence on the mass of the parts made by HDPE. Bellantone et. al. [90] also conducted a similar study with POM and LCP, investigating the same process parameters. Results showed that T_m had the highest influence in reduction of the variability. V_{inj} for LCP and T_h for POM had the highest effect on the mass of the parts. The other parameters also showed a relatively high effect. For POM, T_m had a negative effect on the mass, while for LCP T_h had a negative effect on the mass, although the effect was very small. Further analysis of P_h showed a linear

relationship between P_h and the mass of the part and the filling length between P_h of 500 and 1500 bar. This is shown in *Figure 2-1111*.

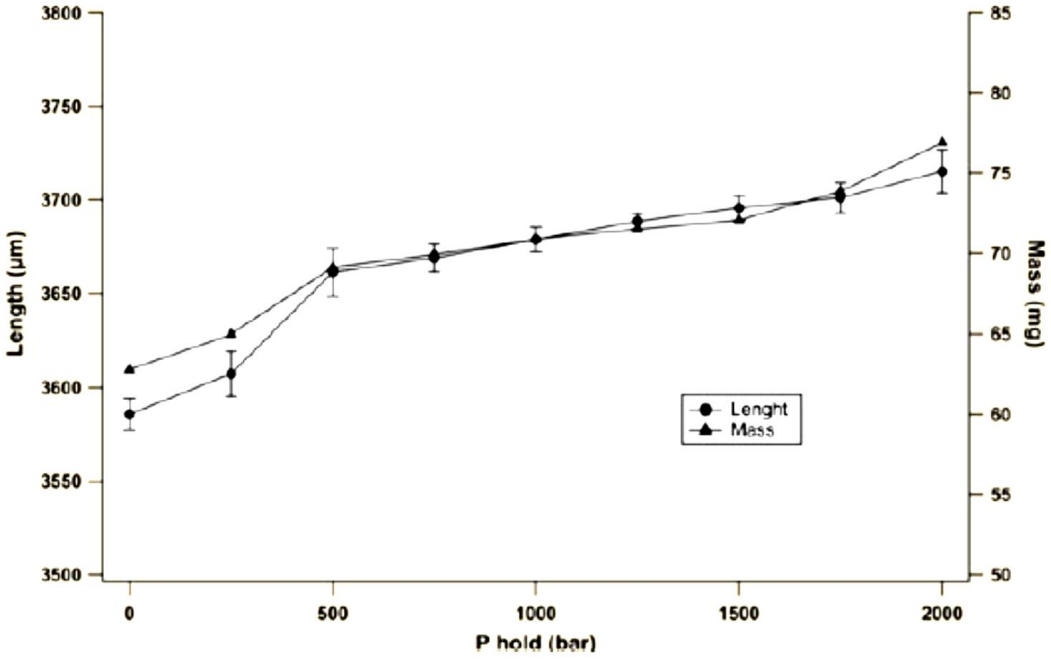


Figure 2-11- Effect of Ph on the filling length and mass of the parts [90]

Chen et. al. [91] investigated the effect of T_p, T_m, $V_{inj.}$ and packing pressure (P_p) on dimensional accuracy of micro moulded micro channels for four amorphous polymers, PMMA, PC, PS and COC. Results showed that at higher settings for all of these parameters, COC produced parts with very close dimensions to the mould. PC also showed good replications at specific combinations. However, PMMA and PS showed poor dimensional accuracy.

Sha et. al.'s [92] investigation of T_m, T_p, V_{inj}, P_h and air evacuation showed T_p and V_{inj} were the important factors in achieving higher aspect ratios for ABS and PP. For POM, T_m also showed high influence in addition to the other two parameters. Increase in T_m for PP and ABS did not result in better replication as they are not sensitive to changes in temperature. Air evacuation generally improved the replication quality. However, because it reduced the mould surface temperature it had a negative effect on parts made with POM. The same study by Packianather et. al. [93] with a different machine showed similar results. However, in this case the replicated AR was influenced by V_{inj} and T_p for PP. All parameters showed very high influence for ABS; and T_p, T_m and V_{inj} showed high influence for POM. This shows

that a change in the µIM machine results in different influences of the process parameters and their interactions. Yoon et. al. [94] also investigated the effect of T_m and V_{inj} on the AR of the replicated parts. T_m showed a significant effect in achieving higher AR, while V_{inj} had a positive influence, its effect was insignificant.

A study by Mani et. al. [95] investigated the effect of three process parameters (T_p, V_{inj} and P_{inj}) on dimensional accuracy of micro walls made out of POM and LCP. Results showed that P_{inj} and T_p had the highest level of influence respectively. V_{inj} had a minor negative effect on the filling of micro channels. Shrinkage of the polymer parts was one of the factors stated in this study as a reason for dimensional variation. This is confirmed in the study conducted by Annicchiarico et. al [74].

Yang et. al. [96] investigated the effect of T_m, P_p and t_p on the replication of micro channels with different dimensions made out of PMMA. Results indicated that T_m was the main factor affecting the replication quality. P_p and t_p resulted in different behaviours based on the dimension of the channels. While for the 40 µm channels shape of the replicated parts generally improved, for the 10 µm channels the behaviour was more unpredictable and the replication quality changed depending on the specific settings.

Tosello et. al. [9] also investigated the effect of T_p, T_m, V_{inj} and P_p on the filling of micro cavities made out of PS. The filling was investigated by using weld lines as flow markers. Experimental results showed that T_m and V_{inj} had the highest level of influence on the length of the filling.

As can be seen from the review of these studies, most of the studies have focused on the filling and weight of the moulded micro parts. There are only a few studies that investigated the effect of process parameters on the dimensional accuracy of the micro parts. In addition, apart from the process parameters several other factors influence the quality of the parts. Not only different types of polymers, with amorphous and crystalline polymers exhibiting different behaviors, within each group polymers show different responses to the process parameters. Also, different combinations of process parameters have resulted in different polymer and filling

behaviors. Furthermore, using different µIM machines have caused the process parameters have different effects on the quality criteria.

2.5 Effect of process parameters on the UTS of micro moulded parts

Another quality criterion in µIM that is still under investigation is the mechanical property of micro moulded parts, specifically, the ultimate tensile strength (UTS) of the parts. Several factors can influence the UTS of a micro part. Some of the studies in this area have been explained below. Although the general agreement is that higher settings for process parameters result in better replication, in the case of UTS that is not the case.

Xie et. al. [97] conducted a set of experiments with PP to investigate the effect of the parts' cross section (semi-circle, trapezium and triangular) and three process parameters (T_p, T_m and P_{inj}) on the UTS of micro bars. Results showed that no matter the cross section, higher injection pressure lead to lower UTS. However, for the trapezium cross section, melt and mould temperature did not show any effect on the UTS. Whereas, for the other two shapes, higher mould and melt temperatures resulted in stronger UTS. The strength changed considerably for the semi-circular cross section.

Pal et. al. [98] studied the effect of P_{inj}, T_p and t_h on the tensile properties of micro parts. Increase in injection pressure resulted in lower breaking strain due to more compactness of the structure which results in the formation of larger crystals. Increase in T_p and t_h resulted in higher breaking strain. However, increases in the mentioned parameters had the opposite effect on breaking stress. The effect on the Young's Modulus (E) was not conclusive and changed during the course of the experiments. For all the three quality criteria, P_{inj} was shown to have the highest effect.

Meister et. al. [99] investigated the effect of the size of micro tensile bars on their mechanical properties. A range of sizes were tested in this study for parts made out of PC, POM and PA by µIM. Results showed that slow-crystalising polymers such

as PA showed high dependency of the tensile strength to the size of the parts, whereas fast-crystalising polymers such as POM and PC showed very little dependency to the size of the micro parts. The micro tensile bars were also manufactured by milling to compare the effect of the manufacturing process on the tensile strength. The milled parts showed higher tensile strengths compared to those made by µIM.

In another study, Meister et. al. [100] investigated the effect of tensile test bars' sizes and different mould materials on the tensile strength of the parts. In this study three mould materials were used, steel, a ceramic (ZrO_2) and PEEK. Results showed that as the size of the parts was reduced, their strength was also reduced due to faster cooling and less favourable inner structure. However, by using mould material with low thermal conductivity, the reduction in TS was reduced.

Xie et. al. [101] investigated the effect of combining nano fillers with PP on the UTS. Two nano fillers were used in the study, carbon nano fillers (CNF) and titanium dioxide (TiO_2). Then each combination was used to manufacture the parts by µIM. The results of the UTS measurements were compared to those of pure PP. Results showed that at higher than 10wt% parts with CNF had lower UTS than pure PP, while the effect was reversed for TiO_2. Effect of the process parameters on each combination was not investigated in the study.

Barkoula et. al. [102] also investigated the effect of fibre fillers on the UTS of micro parts. In the study compression moulding (CM) and IM were also compared. Results showed that filling PP with fibre resulted in higher UTS. In regards to the manufacturing process, while IM resulted in lower fibre length, better and more efficient orientation of the fibres resulted in higher TS, compared to CM.

In another study, Xie et. al. [103] investigated the effect of gate size dimensions on the strength of weld lines. PP and HDPE were used at different process parameters. Results showed different behaviors for each of the polymers. Generally, replications with gates with higher depth resulted in higher TS for PP. In terms of the effect of the process parameters, there seems to be a level at which the best results are achieved. Lower pressure, medium V_{inj} and T_p and high T_m resulted in the highest TS

for PP. As for HDPE, highest $P_{inj,}$ lowest V_{inj} and medium T_m and T_p showed the best results with the gate with smallest depth.

Wu et. al. [104] investigated the effect of T_m, P_p, T_p, V_{inj}, t_p and injection acceleration (a_{inj}) on the UTS of micro tensile bars with five different cross section areas. The polymers used in this study were PP and HDPE. The study also investigated the effect of weld lines on the UTS of the parts; and the effect of process parameters on the width of the weld lines. Experimental results showed that for parts without weld lines, process parameters do not greatly influence the UTS. The main factor in this case is the cross section area of the part. Parts with a higher cross section area had higher UTS. However, for parts with weld lines, the effect of process parameters on the UTS was significant. T_p, T_m, V_{inj} and P_p were shown to have the highest influence. The effect of the size of the parts was still evident; those parts with a higher cross section area had higher UTS. However, the reduction in the size of the micro bars was not as significant, compared to those without weld lines. In addition, a comparison of the UTS obtained from the experiments and those obtained by calculations from material datasheet showed a significant difference.

Tosello et. al. [105] conducted a study on the effect of process parameters on the depth and width of the weld lines for PS. Four process parameters were investigated to measure the dimensions of the weld lines, T_p, T_m, V_{inj} and P_p. Experimental results showed that depth of the weld lines was highly dependent on T_m and V_{inj} while the width only had high dependency to T_m. Increasing the mentioned parameters resulted in reduction of the size of the weld lines by 50% in both directions. While the UTS of the parts were not measured, reduction of the size of the weld lines is highly likely to increase the UTS. This confirms the finding of Wu et. al. [104] that if weld lines exist, process parameters play a crucial role in improving the UTS of the parts.

Xie et. al. [8] conducted a similar study to investigate the effect of six processing parameters on the strength of weld lines for parts made out of PP. The six parameters were T_p, T_m, P_{inj}, P_p, V_{inj} and ejection temperature (T_{ejc}). Experimental results showed that P_{inj} and P_p rarely had any effect on the UTS. T_m and T_p had the highest influence respectively with 42.4% increase and 19.59% decrease in the UTS. V_{inj} and T_{ejc} showed the next highest level of influence.

Kuo et. al. [106] studied the effect of the process parameters and the size of micro parts on the UTS for ultra-high molecular weight PE. Two different parts were used, one with weld lines and one without. The findings were similar to those of Wu et. al.[104]. For those parts without a weld line the size of the micro tensile bar showed to have the highest effect on the UTS. The parts with higher cross section areas were shown to have higher TS. The introduction of weld lines caused a considerable reduction in the TS of the micro bars. In these cases, the process parameters were shown to have a high effect on the strength of the parts. The cross section of the parts still played an important role. Reducing the cross section of the part led to a reduction in the UTS. However, the UTS was reduced at a lower rate compared to those without weld lines. Three process parameters, T_p, T_m and V_{inj} were also investigated to optimise the process parameters. However, from the study it is not clear which parameter had the highest effect on the UTS for different part sizes. The study also indicated that decrease of the UTS due to the polymer flow is more related to cross section size of the parts than the viscosity of the polymer.

From the conducted literature review of the mechanical properties of micro parts, it can be observed that the effect of process parameters on the formation of weld lines, and more generally the UTS, is still an area under investigation. Different polymers have shown different behaviours under µIM. Different combinations of process parameters have resulted in different UTS achieved for the tensile bars. In addition, all the studies have been conducted for conventional dog bone geometries. The effects of different designs where micro bars are an integrated part of a product need to be investigated further. Furthermore, as several studies have confirmed, the UTS in micro products is dependent on the size of the features, and the results are considerably different to those estimated from polymer data sheets.

2.6 Modeling in µIM

This section of the chapter reviews the previous studies conducted in µIM; and consists of three sections. The first section explains the special requirements and considerations which need to be taken into account for modelling in µIM. The second section is a review of the modelling of the process in terms of the filling of

the cavities and polymer flow. The third section is concerned with the modelling of the mechanical properties of the micro moulded parts.

Successful modelling of the µIM process and its characteristics has several major benefits [18, 107, 108]. It allows for visualisation of the flow of polymer and the last filled sections. In this method a number of short shots are performed to see the flow length and identify the defects in areas where the polymer flows to last. These defects include incomplete filling, voids and weld lines. Modelling the process can also assist in mould manufacturing. Mould design and manufacture are often very expensive and time consuming tasks. Successful modelling allows for investigation of the filling of the features, sprues, gating arrangements and flow paths before a mould has to be made; allowing any adjustments to be made before production of the mould. In addition, modelling can eliminate the need for expensive and time consuming experiments to identify the most influential process parameters, and their effect on a particular quality criterion. Furthermore, simulation can result in investigation of the post process properties of the parts such as shrinkage and wrapage.

2.6.1 Requirements and considerations in modeling µIM

The previous sections of this chapter reviewed the studies conducted for replication of high quality parts. Many variables are involved in the IM process such as the process parameters, the polymers and different designs of moulds; and each of these can affect the quality of the manufactured parts. Therefore, modelling IM has been a challenge. The non-Newtonian nature of polymers is an addition to the list, which further complicates the task of modelling. µIM also adds further challenges and restrictions to this task. As explained in section **2.2.2**, µIM cannot be explained as the scaling down of the IM process. The reasons for this and the differences between the two processes were explained. Due to these differences, softwares developed for modelling IM cannot be used in µIM. Because of this several requirements have to be met and some factors have to be considered when developing models for µIM. A summary of these has been provided by [31]:

- In conventional IM, simulating the polymer melt flow as a 2D shape is common. This is done by using an approximation based on the Hele-Shaw approximation. However, this approximation is not suitable for modelling micro affects such as transverse pressure gradient. In addition, Hele-Shaw approximation simplifies the modelling of the flow in sharp corners and changes in the part thickness. Furthermore, it is not possible in µIM to simplify the shape of the flow to one between two walls [107].
- Certain effects that are often neglected in IM cannot be neglected in µIM due to the large surface to volume ratio. Some of the main factors are surface roughness, surface tension, heating of the melt due to friction, and cooling of the melt front due to heat transfer and heat loss. The heat transfer coefficient has been shown to have significant effect in µIM [109].
- The viscoelastic nature of the polymer melts has more significant effects in µIM. Flow of the polymer melt through very small areas such as gates increases the shear rate significantly. This increase results in the reduction of viscosity by a large factor, which may be different from those in data sheets. Some experiments have shown that a change in gate dimensions from 0.01625 to 0.00375 mm reduces some physical properties by 5-7 % [110].
- 2D meshing elements commonly used in IM softwares results in over prediction of cavity filling.
- Special processing conditions such as variotherm and air evacuation need to be considered.

2.6.2 Modeling the polymer flow and cavity filling in µIM

Since µIM gained popularity in development and manufacturing of micro products, modelling and simulation of the process has become an interesting research topic. Several institutes and research groups conducted studies on modelling of the µIM process or some of its aspects. In one of the early studies, Hill et. al. [111] attempted to simulate the µIM process to optimise the process and find the most important factors in filling the cavities and identify problems associated with wrapage and shrinkage. The Hele-Shaw approximation was used in this study. Results showed that the model over predicted the filling of micro cavities. The main reason for this is due

to over simplification of the geometry in which only surface effects on the top and bottom of the flow were calculated, and side and end effects were ignored.

Piotter et. al. [18] conducted a study where experimental results were compared with a simulation of the filling through MOLDFLOW. The software was developed for prediction of flow in IM. Results showed that while MOLDFLOW can be used to investigate some qualitative criteria such as weld lines, it cannot be used for measuring the quantitative aspects of the quality of the part. In this particular study the simulation results over predicted the flow length compared to the experimental results. The likely reason for this was that the commercial software did not account for the microscopic effects on the flow of polymer. The conclusion was that there is a need for models that are specifically developed for µIM.

In another study Yu et. al. [109] modelled the filling of micro channels by µIM through C-MOLD, which is a 2D simulation software. The conclusions were the same as the previous study. While the software simulated the direction of flow correctly, it over estimated the flow length and filling of the cavities. This was again due to the 2D nature of the commercial software and the fact that it did not account for the 3D flow, heat transfer and the change in the shape of the micro features.

Around the same time, Yao et. al. [112] investigated the simulation of filling micro channels by investigating three main factors:

- The change in viscosity as a result of change in the size of the features,
- The wall slip effect, where polymer flow slips over a solid wall in micro cavities when shear rate exceeds a critical value,
- The surface tension.

Results showed that, for micro features made by PS, the surface tension was not an important factor in accurate modelling, however calculations had to include the micro viscosity effect and the wall slip effect to predict the filling of micro cavities.

Further to these developments, a study by Hung et. al. [113] employed a 3D simulation of the polymer flow. The results were in agreement with experiments and showed that the teeth of the micro gear were the last place to fill. Therefore, 3D simulation became a popular research subject. However, 3D simulation also has

some limitations. One limitation is in the size of the features that these softwares could simulate. The other limitation is that these 3D packages ignore or simplify the heat transfer in μIM.

A study by Ilinca et. al. [107] proposed a model for the filling of the cavities based on heat transfer equations. The mathematical results showed good agreement with the experimental results in predicting the length of the flow of the polymer.

Since the success of 3D simulation methods were reported, finite element modelling became the focus of researchers in developing models and simulation methods. For example Shen et. al. [114] used a finite element method (control volume) to optimise the process parameters for several polymers. The Navier-Stokes equation was used for the formation of the model to predict the flow of PS, PC and PMMA. The conclusion was that mould temperature was the most important factor for these three polymers. Mathematical results were in agreement with the experimental data.

In another study, Shen et. al. [115] used a finite element method (control volume) to optimise the process parameters for PP, PC, PS and POM. Mass, momentum and energy conservation equations for non-isothermal fluids were used to form the model. The study combined MOLDFLOW and Grey relational analysis to optimise the process parameters to achieve minimum wrapage. The results showed agreement between the mathematical model and the MOLDFLOW analysis. However, Grey relational analysis was faster and more efficient. PS showed the best performance in this study.

Yu et. al. [109] developed a hybrid model to simulate the flow and heat transfer of polymer melt in a micro channel by using the Cross-WLF viscosity model [116]. The method solved the momentum equation for the flow field where the velocity is significant. The Hele-Shaw equation was used in all other locations. The study concluded that the wall slip effect was very important for accurate prediction of the filling. In addition, results revealed that the uncertainty in heat transfer in the micro channels contributed significantly to inaccuracies of the filling prediction.

Griffiths et. al. [35] used the same viscosity model as the aforementioned study and finite element to simulate the length of flow of polymer melt in a micro cavity. The generated model was validated by experiments using PP and ABS. Two approaches were used, a dual-domain flow analysis and a 3D analysis. Neither the 3D analysis nor dual-domain flow analysis agreed with the experimental results. The dual-domain flow analysis overestimated the flow for both polymers. Whereas the 3D analysis underestimated the flow for PP, and depending on the process parameters, overestimated or underestimated the flow length for ABS.

Kuhn et. al. [117] conducted a study to model the filling height of micro structures made out of PC, PMMA and PP. The same Cross-WLF viscosity model was used to form the model and the validation was done through experimentation. Results showed that the general flow of the polymer in the main cavity was negligible compared to the flow in the micro structures. In addition, surface tension, wall slip and capillary forces showed to have little influence over the filling due to high pressure and shear rates occurring during the process. Mould temperature showed the highest influence during the filling. Experimental and modelling results did not show good agreements, even though the model showed correct trends and the correct relationship between process parameters and surface structures.

Zhuang et. al. [118] also formed a model to investigate the filling of micro channels. The methods and equations used for IM were compared to those of 3D nature, with consideration of viscosity in micro channels and wall slip. Results confirmed that equations and models used in IM are not suitable for use in μIM. In addition, the viscosity profile obtained from the calculations shows that the viscosity in micro features is much smaller than those calculated by conventional viscosity models. Using the Navier slip equation, the coefficient of slip was calculated for each of the channels.

2.6.3 Modeling the UTS of parts manufactured by µIM

A number of studies have investigated modelling of the UTS of micro injection moulded parts. Xie et. al. [8] used the Chebyshev polynomial coefficient equation to model the effect of process parameters on the strength of weld lines. The four process parameters used in the model are T_p, T_m, T_{ejc} and V_{inj}. The following equation was obtained:

$$F_{weld\ line} = 50.403 - 0.0573T_p - 0.1038T_m - 0.0039T_{ejc} + 0.00828V_{inj} \qquad \textit{Equation 2.1}$$

The model was validated through experimentation and the results showed that at the worst case, the difference between the experimental and predicted results were 21%.

A similar study was done by Pal et. al. [98] in which the mechanical properties were modelled as a function of P_{inj}, T_p and t_h. Three models for breaking strain (ε_{break}), breaking stress (σ_{break}) and Young's modulus (E) were obtained:

$$\varepsilon_{break} = -2781.94 + 4.65P_{inj} + 9.96T_p + 106.89t_h + 0.03T_p^2 + 6.45t_h^2 - 0.02P_{inj}T_p - 0.77T_pt_h \qquad \textit{Equation 2.2}$$

$$\sigma_{break} = 117.209 - 0.002P_{inj} - 1.162T_p - 1.353t_h + 0.003T_p^2 - 0.04t_h^2 + 0.009T_pt_h \qquad \textit{Equation 2.3}$$

$$E = 56.433 + 5.44P_{inj} + 8.841T_p - 10.37t_h + 25.417P_{inj}^2 + 8.72T_p^2 + 11.225t_h^2 + 5.8P_{inj}T_p - 8.04P_{inj}T_h + 8.257T_pt_h \qquad \textit{Equation 2.4}$$

In a study by Xie et. al. [101] effect of nano fillers in PP composites on the strength of weld lines of micro tensile bars was investigated and modelled. The assumption is the nano filler content is higher than 10% wt. The following empirical model was obtained:

$$\delta_w = a\varphi^2 + b\varphi + \delta_m \qquad \textit{Equation 2.5}$$

Where δ_w is the weld line strength, φ is the nano filler concentration and δ_m is the tensile strength of the polymer matrix.

2.7 Chapter summary and identification of knowledge gaps

This chapter provides a detailed review of the studies and work done in the field of µIM. The chapter started with a brief history of miniaturisation and micro manufacturing. The process of IM was explained and the use of IM machines and techniques for production of micro parts was reviewed. The problems and difficulties with this method were mentioned and the development of new machines for µIM and their requirements were stated. A review of different types of machines and their components was presented in the next section. The method of optimisation of the machines and the need for them was reviewed and explained. Then mould manufacturing techniques and their capabilities were reviewed and some of these techniques were explained in more detail. Afterwards a list of polymers and their characteristics were presented. The next three sections, contained detailed information of the studies conducted in relation to the process of µIM and its effects on the quality of the parts, and modelling of these effects. Following the literature review, four main gaps were identified.

2.7.1 Modelling of the effect of process parameters on Dimensional accuracy of the parts

Different studies and authors have investigated a variety of quality criteria. However, most of the modeling studies have focused on the filling of micro cavities. Initially, many of these studies used simplified equations that were used for prediction of filling of cavities in IM. This resulted in overestimation of the filling compared to experimental results. Once this became clear, 3D finite element methods with a combination of wall slip effect, micro viscosity effect and surface tension were employed to model the process. While there have been many studies on modeling the polymer flow and filling of the cavities, there does not seem to be a report of a model that considers dimensional accuracy of the micro moulded parts. Such a model can

be used to assess whether a part can be made with the required accuracy, and eliminate the need for several expensive and time consuming experiments.

2.7.2 Modelling of the effect of process parameters on UTS of the parts

There have been very few studies on modelling the UTS of the parts in relation to the process. This area has recently become the subject of further research. A few studies have looked at the effect of some process parameters, however, often overlooked or ignored the polymers used in the experiments, and characteristics of the micro moulding machine. Therefore, there is a clear need for a model that considers the characteristics of the polymer and the machine been used in addition to the process parameters. The application of such a model is the same as that of the accuracy model described above. .

2.7.3 Effect of process parameters on dimensional accuracy of the parts

There have been many studies on the effect of process parameters on different quality criteria. Once more, most of these have been focused on the filling of the cavities or the general geometry of the parts compared to the mould insert. Some studies have also focused on the weight of the parts to investigate if a full shot has been achieved. However, very few studies have focused specifically on dimensional accuracy of the micro features. Furthermore, each of the studies has identified a different set of parameters as the most effective and influential. The variations are the result of different methods of investigation and experimentation, and also mould designs and polymers. Therefore, there does not seem to be an agreement on the most influential process parameters and how they affect the dimensional accuracy. The effect of the process parameters on dimensional accuracy must be identified to be able to construct a model.

2.7.4 Effect of process parameters on UTS of the parts

Effect of process parameters on the UTS of the micro tensile bars is an area that has been investigated extensively. However, these investigations have focused on parts that in most cases do not have weld lines or other defects. Since the elimination of weld lines is not always possible due to different designs, air gaps, etc., the effects of process parameters on the strength of weld lines, and subsequently on the UTS, have become a subject of ongoing research. However, all of these studies have

investigated conventional micro tensile bars (dog bones) and the effect of the overall shape of the part has not been considered. In addition, the studies have investigated different process parameters, and therefore have identified a different set of parameters for optimization of the UTS. Understanding these effects will be a crucial first step in construction and formation of a model that can predict the UTS of the parts in relation to the process parameters and characteristics of the polymers and machines.

These four gaps are the subject of these studies and are addressed in **Chapters 4, 5** and **6**. **Chapters 4** and **5** investigate the effect of the process parameters on dimensional accuracy and the UTS, respectively. These are requirements for the next two knowledge gaps, the models, which are addressed in **Chapter 6**. The next chapter provides an explanation of the approach and methods that are used to address these gaps.

Chapter 3

Chapter 3 Research approach

3.1 Introduction

µIM has become a very important process in the field of polymer processing and micro manufacturing, mainly due to its fast cycle time and its ability for mass production[5, 6]. Many polymer parts that are made today have applications in micro fluidic and medical devices, aerospace and automotive, and sensing and optical industries. These parts require very tight tolerances and have to be made with great accuracy and strength. For example, micro gears are widely used in medical devices. Since most of these devices require invasive surgeries to be implemented inside a human body, it is crucial that they function without any failure, so the accuracy of the gear tooth is very important. If the size of the gear teeth is not within the required tolerances or the teeth break due to the force applied on them, the device can fail and this will require the device to be taken out of the patient's body and a new device installed, requiring further surgeries. This is only one of many examples where part accuracy is vital to the functionality of a product.

Extensive research was conducted on the µIM domain, and was presented in the previous chapter. From the literature review conducted several knowledge gaps were identified. One of the main challenges is to predict whether a product can be manufactured with the required accuracy and properties specified by the customer. This highlights the need for a model which can predict the outcome of the µIM process for the production of a specific component. Models and simulation tools exist for conventional injection moulding, such as MoldFlow, C-MOLD and Fluent; which can predict the flow of polymer melt in the cavity. In the previous chapter it was identified that due to factors such as the consideration of flow as 2D, simplified PVT data, considerably higher shear rates and different viscosities in micro dimensions, these tools cannot be used for µIM [107, 109, 110]. Studies [18, 111] showed that using them results in over prediction of the filling length. There are only a few studies investigating modelling the process in regards to the mechanical properties of the parts. These studies are very limited to specific polymers and process parameters [8, 98]. As a result, the focus of this research is to generate models that will enable the prediction of the accuracy of the replicated parts and its UTS; based on the parameters used in the moulding machine, the polymer and the

machine itself. Such a model will be useful for the µIM industry. µIM technicians and product engineers could use this model to predict whether a part with certain dimensions and tolerances can be manufactured with the process; and what parameters and what levels are required to manufacture a part within the acceptable tolerances. Furthermore, once it is established if the part can be made, the UTS model can predict if the part will be able to withstand the force during its operational life cycle. This eliminates the uncertainties in production feasibility and removes the need for the expensive and tedious tasks of designing and manufacturing a mould to test the possibility of manufacturing a part.

3.2 Problem definition

The problem definition for this work is designed based on the literature review, the industrial application, and the current state of the art in µIM domain.

To produce a part by µIM, a mould has to be designed. A design engineer receives product specifications from the customer and designs the mould based on what the product is, its size and specifications. Mould design is an expensive and time consuming task which requires several considerations such as the design of runner systems in terms of geometry and size, location and size of the gates, cooling and heating systems, location of sensors and their connection to the electrical system for receiving feedback. The design is sent to a machining technician, usually as a CAD file, the mould is then manufactured, which is a very expensive task. There are many limitations in terms of technologies that can produce moulds with micro features with different dimensions [21]; and the processes available to do this are often time consuming and costly. If at any stage there is a problem with the mould or the available technologies to the technician, feedback has to be sent to the designer to make adjustments to the drawing files. Once the mould is manufactured, several sets of experiments have to be done to ensure that a part can be manufactured with the required accuracy, stability and specifications that the customer demands. This process is time consuming and could sometimes fail as the outcome is not known. If the parts are manufactured, a quality engineer needs to confirm that the parts are made in accordance with the customer demand. If they are not, depending on the specific problem, feedback goes to the designer for redesign of the mould, the mould

manufacturer for adjustments or re-making, or the moulding technician to make adjustments to the process. All this is an iterative process and needs to be repeated until the product with the required tolerances and mechanical specifications can be manufactured. If one of the engineers or technicians cannot deliver what is required, then the feedback means that the previous task has to be repeated and details adjusted. The most severe case is when complete set of adjustments need to be made from the design stage. The iterative nature of this process makes it very tedious and expensive. *Figure 3-1* below shows the schematics of the current process.

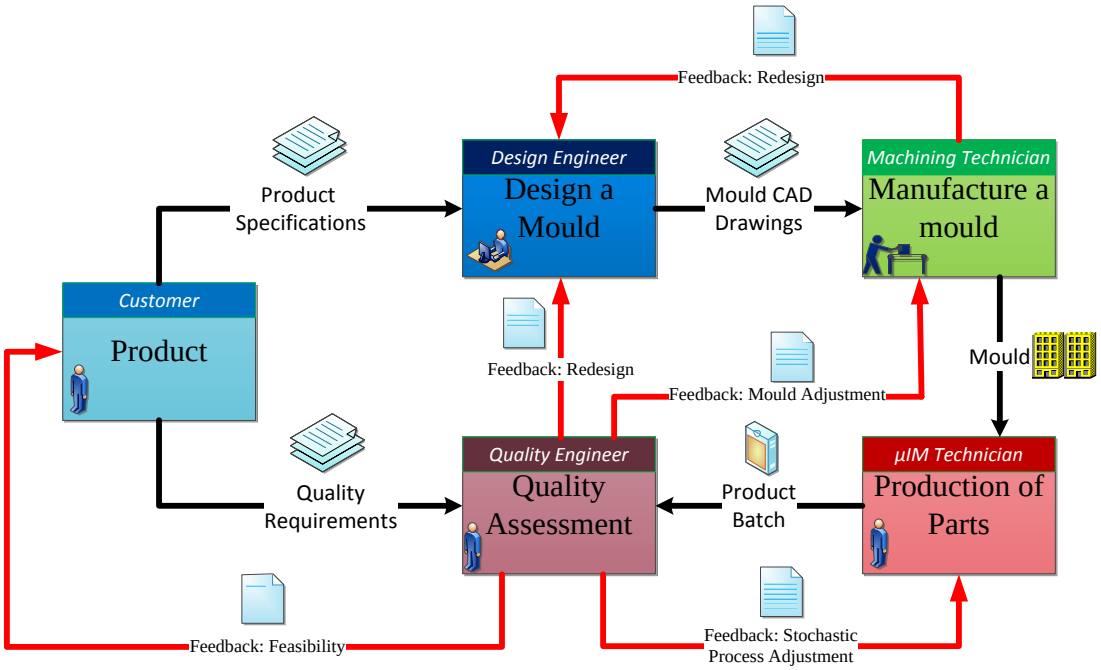


Figure 3-1- µIM Domain Overview

A model that can predict the accuracy of a replicated micro part and their mechanical properties is valuable to the µIM industry and the manufacturing domain. A model will reduce the need for experimentation with different combinations of process parameters and polymers. It also eliminates the need to rely on the level of expertise of the machine operators. This means that some of the risky, costly and time consuming iterative process can be eliminated. Therefore**, the aim of this work is to address this challenge by constructing a model that will predict the accuracy of replicated micro parts and a model that can predict a mechanical property of a micro part.** In these models the dependent variables are the dimensional accuracy and UTS of the parts. The independent variables are a set of characteristics from the process, the polymer and the machine used.

Several studies [18, 111-115] have been conducted, trying to model the µIM process. These do not consider factors such as the size of the cavities and runners, and the much higher shear rates that the flow goes through compared to conventional IM. Because these factors significantly change the viscosity of polymer and its physical properties, using these methods results in overestimation of the flow length [109, 110]. In order to understand the µIM process, it is important to distinguish between micro and macro injection moulding. The limitations of models used for conventional IM are mainly due to the fact that conventional fluid mechanics and PVT equations cannot be applied in micro scale. Although the general concept of reducing the viscosity to make the polymer flow easier is valid here, µIM cannot be described as scaling down of the IM process because of the differences between micro and macro IM (this was addressed in *Chapter 2*). There are also very few and limited models that can predict the mechanical properties of a product. Constructing a model based on the fluid mechanics equations which consider the effect of all the process parameters at once, and also the 3D flow of the polymer melt is a complicated task, which is not a reasonable objective for this work due to limitations of time and equipment. Therefore, a method is identified and used in this study which does not have the complexities and shortcomings discussed above.

This is done by investigating three main areas:

- Effect of process parameters on the dimensional accuracy of replicated features for the selected polymers
- Effect of process parameters on the mechanical characteristic of the features for the selected polymers
- Construction of the "Accuracy" and "Mechanical" models based on the characteristics of the process, polymers and the machine

3.2.1 Requirements and assumptions

The definition of the boundary conditions is a crucial task for establishing the scope of any model. The establishment of this boundary provides the guidelines for which sizes and features this model is valid.

Due to the large number of polymers that can be used for µIM and the time required to experiment with all of them, the number of polymers used in this study has to be restricted. Once this is done the polymers themselves need to be selected. Polymer selection is an important decision in micro injection moulding. This is because different polymers have different mechanical, chemical and flow characteristics and their use depends on the application of the component. For example, some polymers cannot be used for medical and micro fluidic applications due to their chemical composition and the possibility of contamination.

In addition to the application of the product, other factors need to be considered. Generally, a polymer has to have certain characteristics to be suitable for µIM. One of the most important characteristics is the manufacturability of the polymer. Polymers go through severe operating conditions in micro injection moulding such as high temperature and pressure. Polymers must have low viscosity and thus good flowability. This is important because, where the type of polymer does not depend on the application of the product, polymers with lower viscosity are preferred. This is because lower viscosity leads to better flow, filling and higher accuracy in the final product. High mechanical strength is also important so that the part can withstand the ejection forces and stresses due to demoulding. Also high strength is crucial in mechanical applications such as in the use of micro gears and filters. Polymers must also be compatible with the mould material. Polymers containing aggressive chemicals can cause corrosion of the mould which leads to the mould having a rough surface. Generally, standard thermoplastic polymers used in IM can be used in µIM, provided some manufacturability criteria are met [64].

As mentioned before, it is not possible to consider the use of all polymers in this study. While the aim is to generate models that can be applied to all polymers, perhaps with specific constants for each polymer, this study focuses on formation of the models based on two polymers that are commonly used in the field of µIM. These polymers are PP and POM. PP is widely used in manufacturing of polymeric parts. Its low melt viscosity makes it very attractive in manufacturing of micro parts by µIM. It has high tensile strength and elasticity module. Applications include manufacture of micro electrical and electronic components, optics and automotive industries. Its medical applications include manufacture of drug delivery systems and

micro centrifuge tubes used in the fields of medical research and diagnostics. POM has high melt flow index, high toughness, hardness and stiffness, and is a good electrical insulator. It has good chemical resistance and does not crack easily under stress. POM has applications in the automotive, electrical appliances and electronics industries. It is also used in the medical industry with parts of inhalers and insulin pens been made from POM.

The other aspect in the construction of the models is the selection of process parameters and the values used for them. The boundary values for the process parameters are selected primarily based on polymer manufacturers' recommendations. However, other studies and initial experiments prove that in certain cases values above or below the recommendations have to be used. This is because lower values result in premature freezing of the polymer melt and short shots. Higher values result in an increase of shear rates and burning of the polymer which causes deformation of the mechanical properties of the polymer and the end product. Therefore, the values for process parameters are selected based on screening of the process and its results, in addition to the manufacturers' recommendations. An important note must be made in regards to the process parameters. The assumption here is that the values set on the machine, are those that the polymer experiences during the filling process.

Also, in order to generate the models the features for the experiments have to be defined. Unfortunately, it is not possible to conduct experiments on all possible shapes and features as this study has a limited amount of time and resources available. Therefore, a feature has to be selected for this study. The selected feature is a micro wall. These are made by filling the cavities which have the shape of a micro channel. This feature is selected for two main reasons. First of all, micro walls have a wide range of industrial applications. For example, micro walls are used in micro fluidic and medical devices, micro filters and micro heat exchangers. Secondly, the micro walls used in this study are formed in a very similar shape to what is known as a dog-bone shape. There is a thin micro wall in the middle and large solid sections at either ends of the wall. This is useful in that it allows the same parts that will be used for dimensional accuracy analysis to also be used for mechanical testing. This is very important because the results of both accuracy and

mechanical experiments need to be compared so that the effect of a process parameter on each can be identified clearly. A different feature, or one with a different shape, results in a different flow of polymer and therefore the results would not be comparable. It is also important to use the same mould design as different mould designs lead to differences in polymer flow; resulting in incomparable flows and molecular formation.

In order to fully understand the effect of process parameters on the accuracy of micro parts and their mechanical properties, a range of dimensions need to be considered. This is also crucial in the formation of any model for either dimensional accuracy or mechanical stability. A model has to be valid and applicable to a range of polymers and a range of feature sizes. The size of the features in this study are selected based on what has been studied in the literature, the industrial applications of different sizes and the capability of the micro milling machine available to this project. Micro walls used in this study have a height of 100 micro meters and their width varies between 60 and 212 micro meters.

3.2.2 Definition of project objectives

The main aim of this work is to generate two models which will predict the quality of micro moulded parts. Quality here is defined in two terms, dimensional accuracy and UTS. To do this it is crucial **to establish a relationship between the quality criteria, the polymer and the process.** In this study a relationship is developed mathematically, which will enable the formalisation of a model. The general relationships are then expanded through experiments, to complete the objective of this study. The result is a mathematical function that relates the specific quality criteria to characteristics of the polymer, the process and the product.

There are three main knowledge gaps related to these models and µIM in general. The first is to understand the effect of process parameters on the polymer and its viscosity, **and subsequently the effect of process parameters on the dimensional accuracy of the replicated parts.** This area is still under investigation by many researchers. This will lead to the formalisation of the effect of process parameters on

dimensional accuracy for the selected design and features. The results are then used to construct the accuracy model.

The second is **to understand the effect of process parameters on a mechanical property of the parts, specifically UTS.** The result is the formalisation of the effect of process parameters on the strength of the features. These results are used in formation of the mechanical model.

The third gap is the models themselves. Forming the models through experimental results alone will result in very limited models which can only be used for the specific conditions used in this study. These models cannot be used for other sizes, polymers and processing conditions. This is due to the fact that change in features and their size, polymers and processing conditions result in different flow characteristics, and therefore, different dimensional accuracy and UTS. However, forming the models through theoretical equations is a complex task that is beyond the scope of this study. Therefore, this work will propose a method in which experimental results are used in a set of equations which are formed by using the "*law of dimensional homogeneity*". The results are **two mathematical functions which can be used to predict the dimensional error and UTS of the parts as functions of polymer properties and the process parameters.**

In summary there are three main objectives, which are also shown in *Figure 3-2*:

- Identification of the effect of process parameters on the dimensional accuracy of the micro moulded parts;
- Identification of the effect of process parameters on the UTS of the micro moulded parts;
- Construction and formation of empirical models to predict the dimensional error and UTS of the micro moulded parts.

The first two are used as inputs to the final models. The results of the first section are used in analysis of the accuracy and how the process can affect it, and how the process parameters are used in the model. The results from the second section are

used in the analysis of the UTS of the parts and how the process parameters are applied in the mechanical model.

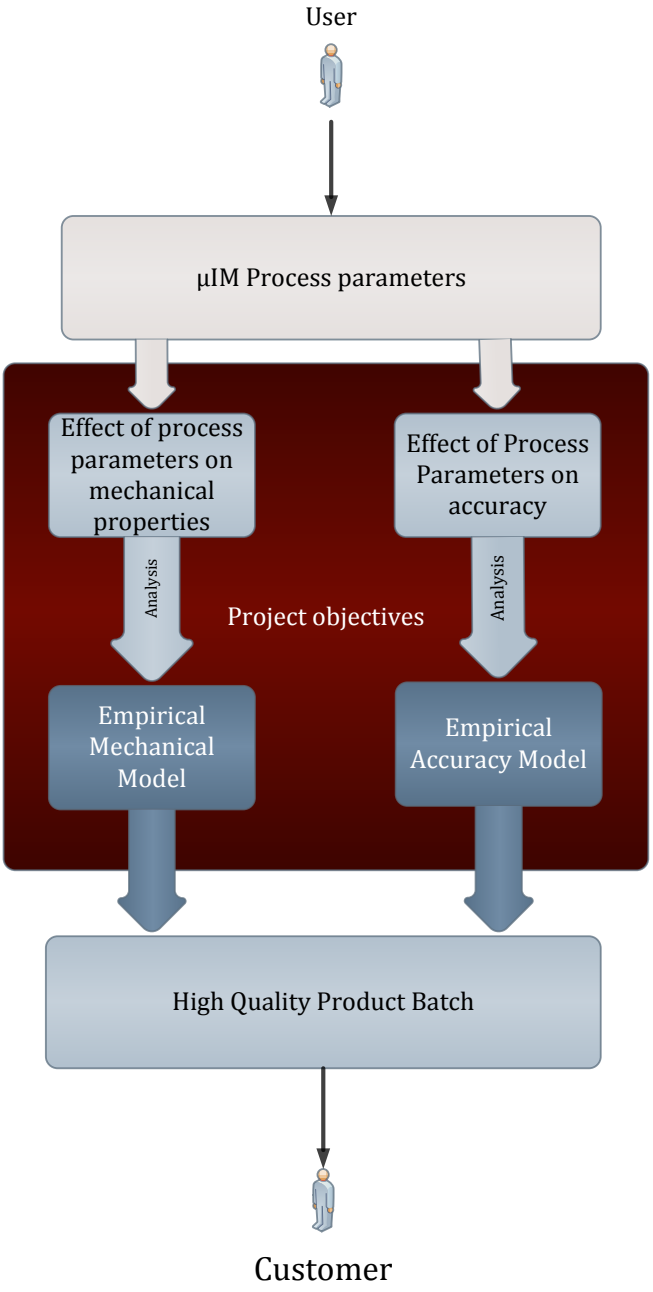


Figure 3-2- Project objectives

3.2.3 Definition of the research hypothesis

The definition of the hypothesis is the main focus of this chapter and sets the scene for this thesis. The main aim of this research is to generate models that can predict the quality of a replicated part in terms of dimensional accuracy and mechanical property. The relationship between the quality of the replicated parts and the process

parameters is an area which is still under investigation by researchers. The main premise of the hypothesis is that **conducting several sets of experiments will provide empirical data, which in conjunction with dimensional analysis, can be used to formalize a model which provides the relationship between the process parameters, polymer properties and the accuracy of a replicated part and its UTS.**

In the scenario that the empirical models can be used for generating the models, one must consider the variables and their importance in each of these models. To generate the accuracy model, the first step is to understand which parameters need to be included in the model. To do this **the effect of process parameters on the dimensional accuracy of the parts must be clearly understood.** In addition, the level of influence and interactions between the process parameters needs to be identified. Since there are several variables included in the model from the process, the polymer and the product, this step is crucial. The hypothesis is that **by conducting a controlled set of experiments and using statistical analysis on the dimensional accuracy of each polymer and process parameter combination, the level of influence of each parameter and its interactions with the other parameters or variables can be identified.** This understanding is then used and applied in the construction of the accuracy model.

To generate the mechanical model again the parameters need to be carefully selected, so that the results can be compared with those of accuracy. If the effect reinforces those of the accuracy analysis, it can be said that the same changes in the parameters will improve or worsen the quality of the part. However, if the effects of process parameters on the accuracy and UTS are contradictory, a compromise between accuracy and mechanical quality needs to be made when manufacturing a part. In this context, the application of the part is likely to be the deciding factor. If the part undergoes sever operating conditions (in the context of micro manufacturing) then mechanical properties are likely to be more important. However, if great accuracy and very tight tolerances are required dimensional accuracy will be more dominant factors. Therefore, the analysis in this section needs to include the process parameters that are used in the previous section. The next step is to identify the effect of process parameters on the UTS. Similarly, the hypothesis is that **by conducting a**

controlled set of experiments and using statistical analysis on the UTS of each polymer and process parameter combination, the level of influence of each parameter and its interactions with the other parameters or variables can be identified. This understanding is valuable and is used when constructing the mechanical model.

Once the effect of process parameters are understood and clearly identified, the construction of the models becomes possible. This is the main aim of this work. The first step in this process is to construct a general mathematical function for each of the quality criteria. This function needs to be applicable to all shapes, features and designs in the domain of µIM. Then the effect of process parameters and their level of influence and interactions will be included to form the predictive models. The hypothesis here is divided into two parts. First, is that **by using a technique called "*dimensional analysis*" the general mathematical function can be formed.** In this function dimensional error and UTS are the outputs of the equations. The inputs are the characteristics of the process and polymers. The second part of the hypothesis is that **by using the results of the previous two sections the function can be simplified and completed with its constants.** The combination of the general function with consideration of the influence of the parameters, and empirical data obtained from experiments, results in the formation of the final predictive model.

In summary, the research hypothesis requires three main elements which will contribute knowledge to the field of µIM. These are

- **To identify the effect of process parameters on dimensional accuracy of micro parts**;
- **To identify the effect of process parameters on UTS of micro parts;**
- **Empirical models which can predict the dimensional accuracy and UTS of a replicated part.**

3.2.4 Research methodology

The work presented in this thesis is a result of a systematic methodology presented in *Figure 3-3*.

The first step toward completing this work was to conduct an extensive literature review of the µIM domain. This literature review resulted in establishing the current state of the art in the field. The other part of researching the field was to identify the applications of µIM and the challenges that the industry faces. The industrial challenges in conjunction with the academic work presented in the literature review provided a starting point to establish a problem definition.

The problem definition provides a clear view of the domain which enables the identification of a clear set of research requirements. This provides a set of conditions for which the hypothesis is valid for. The other outcome of the problem definition was the identification of the research objectives which were extrapolated from the knowledge gaps in the literature. The combination of these provides the basis for the definition of the hypothesis.

The hypothesis for this work was broken down into three main sections which are the contributions of this research work to the knowledge in the µIM domain. The first was to identify the effect of process parameters on dimensional accuracy of micro moulded parts. This forms the basis for the selection of the variables used in the accuracy model and their level of importance. The second gap is to identify the effect of process parameters on the UTS of the replicated parts; which forms the basis for understanding and selecting the variables used in the mechanical model. The final contribution, which is the main aim of the work, is to construct the models which enable the prediction of dimensional accuracy and the UTS of a replicated part.

Identification of the effect of process parameters is done through conducting a set of controlled experiments. In these experiments the process parameters are varied methodically and systematically, to investigate their effect on the dimensional accuracy and the UTS of the moulded parts. For each combination dimensional accuracy is measured and compared with results from other combinations. The

overall results are then analysed through statistical analysis to investigate the effect of each process parameter in the dimension of the parts, the level of influence and the interactions of each parameter with the other parameters.

The two predictive models are formed in two stages. The first is to generate a mathematical function that shows a general relationship between the output (dimensional accuracy or UTS) and the inputs (process parameters and polymer properties). This general relationship will be true for parts of any feature or size. The limitation is that the constants of the equation and the form of the relationship for each of the variables in the equation will be unknown, and are likely to vary if the shape and sizes, or mould designs change drastically. Once the general mathematical function is constructed, the constants of the equations can be developed through use of empirical data generated based on the experiments. The combination of the mathematical equations and the incorporation of the empirical data presents the final predictive models.

Once the three knowledge gaps are addressed and the predictive models are completed, they need to be validated. A set of controlled experiments will be conducted with a different mould insert and a different polymer to those used in the study. For the first two contributions, the aim is to show that the same trend in the effect of process parameters is present. It is important to note that the aim is not to prove the same values for accuracy and UTS will be obtained, but to show that the trend will be the same. The third contribution is validated by inputting the values for the process parameters and polymer properties in the model and showing that the general equations are correct. For this contribution, the same polymers in the study are used on a different mould insert to show that the constants and the equations are accurate.

The final stage of this work is making concluding remarks on the results of the experiments, the predictive models and their applications, and the relevance of each of the contributions when considering mass production of a part in an industrial environment.

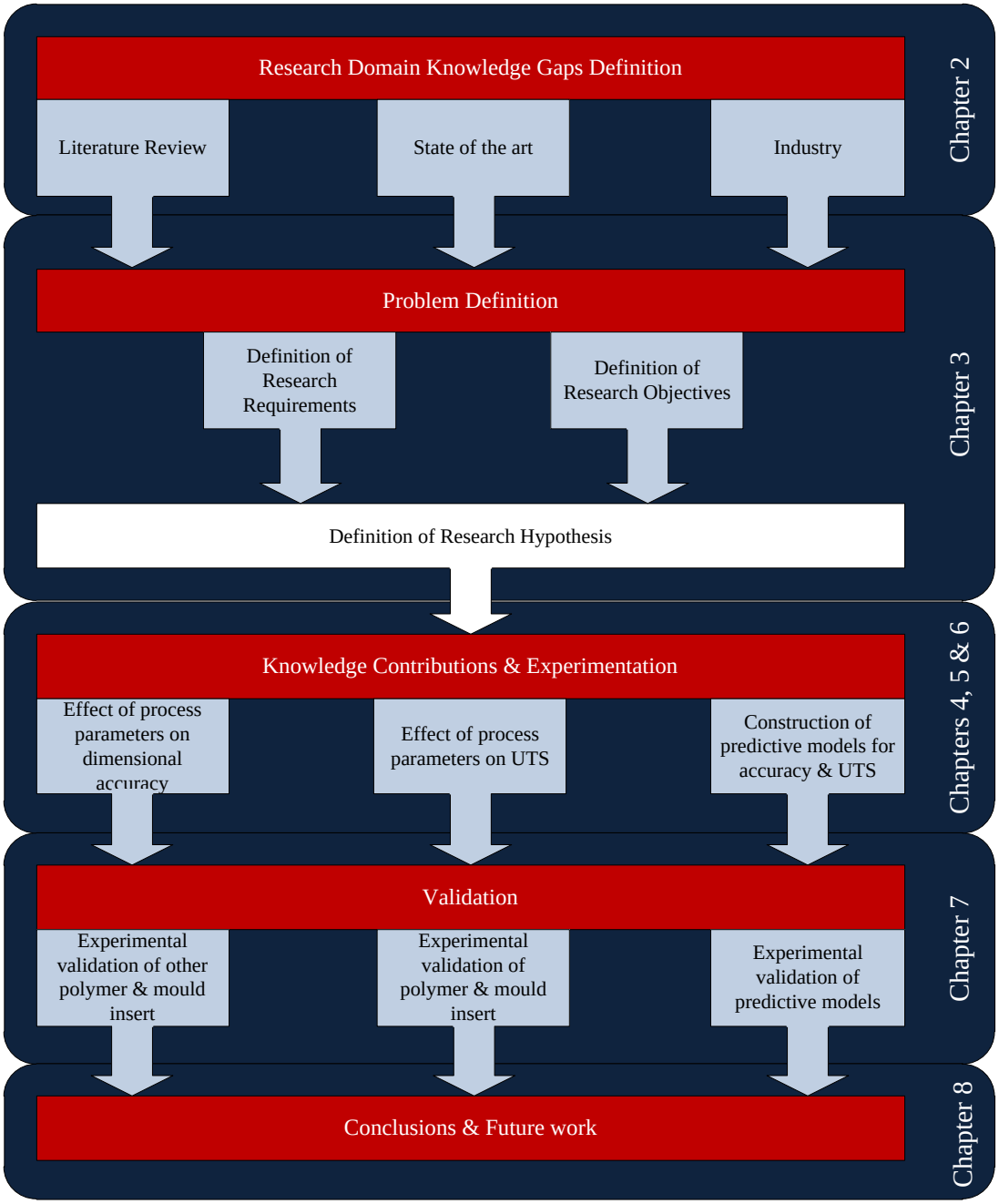


Figure 3-3- Research Methodology Overview

3.2.5 Identification of the effect of process parameters on dimensional accuracy of micro moulded parts

To identify the effect of process parameters on the accuracy of micro moulded parts, a set of controlled experiments are conducted. This is the first step in formation of the accuracy model. For the model to be comprehensive, features with a range of dimensions must be investigated.

Micro walls have a variety of applications in the field of micro manufacturing. They are extensively used in the production of micro fluidic devices for drug delivery systems, DNA sequencing and blood separation devices, micro filters and micro heat exchangers. Therefore, they have been chosen the main focus of this study.

To produce micro walls formed from polymers a mould insert is required with micro channels. The inserts for these experiments are made out of brass and the process used for manufacturing them is micro milling. Brass is widely used for manufacturing mould inserts. This is because it has a good thermal conductivity and has low cost compared to other metals. It is also easy to machine, reducing the chance of damaging the micro milling machine. In addition, since the metal can be machined easily, less stress is applied to the mould during the process and less heat is generated (compared to other metals such as steel). This reduces the chances of the mould insert being damaged during mould manufacturing.

In this study, the width of the channels varies from 155 to 211 µm. This enables the effect of different dimensions of the features on the behaviour of the polymer melt and the filling of the cavities to be investigated. The length of the channels is 2 mm and their depth is 300 µm.

Two level full factorial Design of Experiment is used to conduct these experiments. *Table 3-1* shows the inputs and outputs for micro injection moulding experiments.

Table 3-1- Input and output parameters for the Micro injection moulding experiments

Inputs: machine parameters	***Output***
Injection velocity, Injection pressure, Melt temperature, Mould temperature	Dimensional accuracy of the width of the micro walls

The outputs are measured by an SEM microscope. The accuracy is measured by calculating the error (ΔL).This value is calculated by first measuring the mould dimensions (L_m). Then the polymer parts are measured to investigate the width of the micro walls (L_p). The difference between these two dimensions is the error (ΔL).

This value is used in the accuracy model as the dependent variable (output of the model).

Once the values are obtained the process is investigated by statistical analysis. The method used for statistical analysis is ANOVA (Analysis Of Variance) which is widely used in experimental analysis. This analysis uses main effect and Pareto plots. The main effect plot shows the effect each variable (process parameter) has on the response, which in this case is dimensional accuracy. Pareto analysis is used to investigate which process parameter, or interaction, has the highest effect on dimensional accuracy. For this purpose computer software called Minitab is used. This software is widely used in designing experiments and analysing their results. One of its main functions is to enable the user to investigate the effect of several factors on a response and show this in a graphical form which is easy to understand. The results of these experiments are used to construct the predictive accuracy model.

3.2.6 Identification of the effect of process parameters on the ultimate tensile strength of micro moulded parts

To identify the effect of process parameters on the UTS of micro moulded parts, a set of controlled experiments are conducted. This is the first step in formation of the mechanical model. For the model to be comprehensive, features with a range of dimensions must be investigated.

Any results obtained in this section must be comparable to the results in the previous section. While accuracy and UTS are two different quality criteria, they both have to be considered when manufacturing a product by µIM. This is why the trends obtained from both sets of experiments need to be compared. Process parameters could have a different effect on the accuracy and mechanical properties of the parts. If the analysis shows different trends then the deciding factor is likely to be the application of the product, and whether accuracy or mechanical stability is more important. With this in mind, the experiments for this chapter have been designed to use the same variables as those in the previous one. The mould and the insert are the same. This is to ensure that the flow of polymer is the same for both of these experiments. Differences in polymer flow can result in different filling properties

both in terms of accuracy and the solidification and arrangement of the polymer molecules. UTS of a part depends heavily on its cross sectional dimensions. If the channels have bigger or smaller dimensions UTS will change. Therefore, the mould insert used for these experiments is the same as that in the previous chapter. The process parameters are also the same as before for the reasons mentioned above.

Two level full factorial design of experiment is used to conduct these experiments. *Table 3-2* shows the inputs and outputs for UTS experiments.

Table 3-2- Input and output parameters for the UTS experiments

Inputs: machine parameters	***Output***
Injection velocity, Injection pressure, Melt temperature, Mould temperature	Ultimate tensile strength of the micro walls

In this section, the output is measured by a machine that is specifically designed to conduct pull tests for the purpose of calculating UTS of a part.

Once the values are obtained the process is investigated by statistical analysis. The method used for statistical analysis is ANOVA. Main Effect and interaction plots, and Pareto Charts will be produced by using Minitab to perform the analysis and visualise the effect and interactions of each parameter.

The results of the analysis will be the starting point for developing the predictive mechanical model.

3.2.7 Generation of the accuracy and mechanical models

The need for a model, the reasoning behind why the current models are not suitable for µIM and their limitations were discussed and explained in **Chapter 2**. Therefore, the focus of this study is to propose a method for developing two models for predicting the dimensional accuracy and UTS of micro moulded parts.

Forming the model based on conventional fluid mechanics and PVT data does not yield correct predictions. Developing a purely empirical model is a task which requires an enormous amount of experiments and is a massive undertaking. Even if this was done it is likely that the resulting model could only be used for the specific features, polymers and parameter values used in the experiments used to generate the empirical data. Therefore, this study employs a method called "dimensional analysis" to form a general mathematical model that can be used for any product made by µIM. This method is often used to develop a mathematical function between several variables where their relationship is unknown. The method is based on the "law of dimensional homogeneity" and states that in explaining a physical phenomenon, the dimensions of each expression in the function must be the same. Dimensional analysis uses this law by attempting to form a function where all of the expressions are dimensionless. This method is specifically useful in this study due to the complexity of modelling the flow of polymer in µIM; and also different flows due to different designs; which both result in different qualities of the parts.

To perform this method a set of variables have to be selected. The selection in this study is done so that characteristics from the process, the polymer and the product are all included. Process parameters that were used in the previous two chapters are used as characteristics of the process. Density, specific heat capacity and thermal conductivity are the selected characteristics of the polymer; and the selected characteristic of the parts for the accuracy model is the dimensional accuracy of the width of the micro walls, and for the mechanical model is their UTS.

Once dimensional analysis is performed, a general function can be obtained for accuracy and UTS. However, the constants and specific form of each expression (polynomial, 2^{nd} order, 3^{rd} order, etc.) will be unknown. The results from the previous two chapters are used to find these unknowns.

Due to limited time and resources, and the complexity of the investigated field, it would be outside the scope of this study to ensure that the models work for all features, sizes and designs. However, to ensure that the model is comprehensive for the quality of the micro walls the features are designed with a range of dimensions. The micro channels on the mould are designed to have three different dimensions

which provide three micro walls in one part. All these are produced in one shot so that the injection conditions are the same.

3.3 Definition of the validation method

The definition of validation methods in any research requires an analysis of the domain. The proposed models target a domain which is quite vast, complex and expensive to validate for all existing features, sizes and polymers. Complete validation of the model even with only one of these inputs requires several years of studies and several sets of experiments with different features, not to mention different mould designs and manufacturing techniques, polymers and moulding machines. Therefore, a simple validation method is proposed.

Each of the three contributions will be validated by experimental means. The first contribution will be validated by using a different mould insert which has the same features with a different dimension. The design of the mould remains the same so that the flow of the polymer remains the same. The two polymers used in **Chapter 4** will be employed here to validate the findings and the trends identified and discussed in those chapters. The process parameters and the values will be the same as used in the previous chapters so that the results can be comparable. Clearly, the values for the dimensional accuracy of the width of the micro walls will most likely be different from those achieved in the original studies. However, the trend and behaviour of the polymer under the same conditions, although the size of the channel is different, will be validated.

The second contribution is validated in the same fashion. The mould and its design remain the same so that the flow of polymer does not differ from the original experiments. The two polymers used in **Chapter 5** will be investigated here with a micro wall of different dimensions. The results will be compared with those obtained in the original experiments, to ensure that regardless of the size of the channels the polymers and the process behave in the same manner. A third semi-crystalline polymer is also used to show that polymers from the same family will present the same behaviour under mechanical load. The same process parameters and values used in the original study are used in this section of the validation. Again, the values

for UTS will surely be different due to the fact that the cross sectional dimensions of the micro walls are different. However, what is important is the validation of the trend that the changes in process parameters cause.

The third contribution, the two models, will also be validated by experimental means. A controlled set of experiments will be conducted to produce new parts with different dimensions. The mould insert in this section will have micro channels with different dimension from the original studies. However, it must be noted that this dimension is close to the range selected previously. If the dimensions are changed significantly, while the general model will still be valid, the constants and form of each expression may not remain the same. To validate the models the two polymers that were used previously will be employed. This is to ensure that the constants for the polymers remain the same. Firstly, the new micro walls are produced on the machine with a set of values for the process parameters. The parts are then measured and the pull tests conducted as before. Once the results are obtained, the values will be included in the model to obtain a number for the dimensional error and the UTS of the micro walls. These results are then compared to validate the two models.

3.4 Chapter summary

This chapter provides an overview of the research methodology and explains the motivation behind this work. It provides a summary and introduction into the field of µIM and the main challenges that this work addresses. The chapter presents the definition of the problem that this thesis addresses and formalises a research approach. The gaps in the knowledge are identified and objectives of the study are explained in detail. The hypothesis for addressing the problem is described, detailing the contributions to knowledge and how this work addresses them. Each knowledge gap is then defined clearly and a framework for addressing it is explained. Finally, a validation method is proposed for each of the contributions to show that they are valid, not only to this study, but to the wider field of µIM.

Chapter 4

Chapter 4 Effect of process parameters on the dimensional accuracy of micro injection moulded parts

4.1 Introduction

Micro injection moulding is becoming increasingly important in the production of polymer micro parts. This is due to its ability to mass produce micro parts with a very short cycle time [5-9]. Many polymer parts that are made by micro injection moulding have industrial applications in industries such as medical devices, automotive, aerospace and defense. This means the quality of the moulded parts and their dimensional accuracy is of utmost importance.

The importance of predicting dimensional accuracy of the micro moulded parts and how a model can help in reduction of the uncertainties in production of the parts was reviewed in **Chapter 1** and **Chapter 2**. To produce such a model, the effect of process parameters and the level of their influence must be examined. This chapter therefore focuses on investigating the effect of process parameters on the accuracy of micro moulded parts. This is done by conducting a controlled set of experiments on features with different sizes. The micro features are then examined by a microscope to measure their dimensional accuracy in relation to the original mould insert. Once this is identified, statistical analysis (ANOVA) is deployed to provide an insight into the effect the process parameters have on the specific features. The analysis shows the impact each parameter has on the accuracy of the parts, positive or negative. It also shows the interactions between the parameters and how combinations of them affect the parts and their accuracies. The results of the statistical analysis are then explained and their implications are discussed to make general recommendations on how parts with higher accuracies can be manufactured.

4.2 Design of experiments

To understand the effect of process parameters on the accuracy of the replicated part a set of experiments are designed and conducted. The intention of these experiments is to identify the role that process parameters play in the replication of the features

and their accuracy. These experiments are explained below. Firstly, the justification for the experiments and the reasoning behind the setup is explained. Then the experimental setup is described and results of the experiments are presented. Finally, the results are discussed and the main findings of the chapter are presented.

4.2.1 Selection of process parameters

To understand the role that process parameters play on the replication of a part the parameters affecting the accuracy of the part must be identified and investigated. The accuracy of a replicated part depends on the flow of the polymer melt in the runners and cavities. Flow of liquids is often characterized by the viscosity of the flow. Viscosity is the measure of a fluid's resistance to shearing flows, where adjacent layers flow parallel to each other at different velocities [119]. The higher the viscosity the more resistance there is against the flow of the liquid. This is shown in *Figure 4-1*.

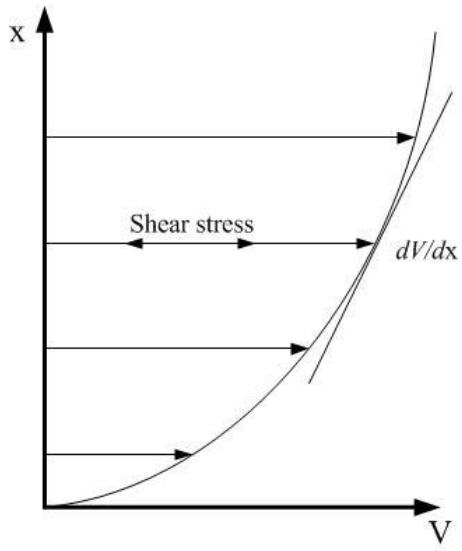


Figure 4-1- Fluid viscosity

Viscosity is defined as

$$\tau = \mu \frac{dV}{dx} \qquad \textit{Equation 4.1}$$

where τ is the shear stress (which is defined as F/A, μ is viscosity, *V* is velocity, *x* is distance, and dV/dx is the shear rate.

In this section four of the parameters that can be directly changed on the machine and have great influence on the viscosity of polymer melt flow are discussed. These are injection pressure, injection velocity, polymer melt temperature and mould temperature.

Several studies have been conducted to investigate the effect of pressure on the viscosity of a polymer melt. Studies have shown that at pressures under 500 bar the effect is negligible. However, at pressures of above 500 bar, such as those in μIM, the effect becomes significant [120] and as pressure increases, so does viscosity [17, 120]. This is supported by *Equation 4.*1. Considering $\tau = F/A$, at the same shear rate, increasing pressure leads to increase in viscosity. This can also be explained by the structure of the polymer and the effect of processing parameters on them. In the equilibrium state, flexible polymer chains take the shape of random coils, creating entanglements with each other. The motion of the coils is affected by the presence of groups of atoms attached to the backbone. The presence of these groups or their interactions leads to low flexibility of the polymer chains. This makes the structures highly susceptible to increased level of intermolecular interactions during the flow. Therefore, reduction of the volume between the molecules, due to increased pressure or decreased temperature, results in the rise of intermolecular friction, which is viscosity [121, 122]. In addition, the effect of pressure on viscosity of a polymer melt can be seen through the Barus equation [121, 123]:

$$\mu = \mu_0 \, exp(\beta P) \qquad \textit{Equation 4.2}$$

Where μ is the viscosity of the polymer melt, μ_0 represents viscosity at ambient pressure, P is pressure and β is the pressure constant. Based on this equation, as pressure increases so does the viscosity of a polymer melt.

Velocity is also an important factor in the calculation of the viscosity of a polymer. *Equation 4.3* [124] shows the relationship between shear rate and injection velocity.

$$\gamma = 8V\,{}^{D^2}/_{d^3} \qquad \textit{Equation 4.3}$$

Where *V* is injection velocity, *D* is the injection plunger diameter and *d* is the radius of the flow channel. Assuming *D* and *d* are constant, increase in injection velocity results in an increase in shear rate. In micro injection moulding, the polymer melt is a non-Newtonian fluid and undergoes shear thinning, meaning viscosity decreases as shear rate increases and vice versa. Since increase in velocity increases shear rate, it results in reduced viscosity. However, increase in injection velocity results in more difficult air evacuation [36, 125]. This demonstrates how injection velocity plays a role in the flow of the melt and the accuracy of the replicated part. Injection velocity also helps in faster movement of the polymer melt and may assist in faster filling of the cavities. Faster movement of the polymer melt also results in heating the polymer melt as a result of the increased shear rate. This is useful in that it does not allow premature freezing of the polymer.

Temperature also has an effect on viscosity. There is no generalized model that defines the relationship between temperature and viscosity for polymers. However, an empirical model has been developed which is shown in *Equation 4.4* [62]. This equation is especially suitable for the purpose of this study because it is commonly used for semi crystalline polymers.

$$\frac{\mu_0(T)}{\mu_0(T_0)} = exp\left(\frac{E_0}{R}\left(\frac{1}{T} - \frac{1}{T_0}\right)\right) \qquad \textit{Equation 4.4}$$

Where E_0 is the activation energy of the polymer, *R* is the ideal gas constant, *T* is the temperature, T_0 is a reference temperature, $\mu_0(T)$ and $\mu_0(T_0)$ are zero shear rate viscosities at temperatures *T* and T_0. Since E_0, *T0*, *R* and $\mu_0(T_0)$ are constant at the reference temperature, increases in temperature (*T*) cause a reduction in viscosity.

In µIM, the volume to surface ratio is very small, so the polymer starts to freeze as soon as it hits the surface of the mould and freezes very quickly after contact. This means the mould tool needs to be at a temperature at which it stops the polymer freezing prematurely and ensures complete filling of the cavity. Therefore, mould temperature becomes an important parameter in micro injection moulding. There is a general agreement that high mould temperature is one of the parameters that enhances the quality of the part. However, excessively high temperature will result in degradation of the polymer, which can adversely affect the mechanical and thermal properties of the part. It also causes gasification of the mould which will result in the formation of gas bubbles and bulges in the micro part. Excessively high temperature will also result in an unnecessary long cycle time and increase cost and lead time.

In µIM, it is crucial to reduce the viscosity of the polymer melt. Lower viscosity results in better flow of polymer melt in the runners and cavities, and reduced chance of premature freezing and incomplete filing of the mould cavity. Therefore, viscosity greatly affects the filling of the cavities, and hence, dimensional accuracy of the parts. Viscosity is affected by variation of the above parameters. Each of them has a different effect on viscosity and the accuracy of a part. Therefore, this study focuses on four process parameters: polymer melt temperature (T_p), mould temperature (T_m), injection velocity (V_{inj}) and injection pressure (P_{inj}). The focus of this chapter is to determine the influence of these four parameters on the accuracy of the part and the extent of it.

4.2.2 Experimental design

For the purpose of this study an approach is required to investigate the process parameters and their effect simultaneously. This is because in addition to investigating the effect of each parameter individually, their combined effect needs to be studied. This is due to the fact that variation in combinations of process parameters results in changes in accuracy [84, 95]. A design of experiment (DOE) approach was used to conduct this study. This approach was selected because it allows the investigation of all the selected parameters simultaneously and their main effect on the output, which in this study is the dimensional accuracy. Thus it is possible to systematically investigate the process variables and their effect on part

quality. In particular, process settings and characteristics that affect the part can be identified so that the process and product can be improved [126]. Factorial designs are widely used in the industry when several factors are involved and their effects need to be identified on a response. Full factorial designs are used when the combined effects of parameters are investigated; and fractional factorial designs are used to reduce the size of large DOE studies and for process monitoring and screening [127]. Full factorial designs are those where experiments are conducted based on all the possible combinations of variations in the factors. Fractional factorial designs are selected based on specific methods (e.g. Taguchi) to screen a process.

For the purpose of investigating the effect of process parameters on the accuracy of the parts two levels, 1 (lower) and 2 (higher), were selected for the four factors. Two levels are selected because the analysis is intended to show the effect of an increase or decrease of each parameter. Thus, Taguchi's L16 Orthogonal Array was used in this study; this is shown in *Table 4-1*. The table shows all the possible combinations of variations of process parameters by changing one or more of them in a given combination. For example in Run 1, all the factors are set at the lower level. Then one of them is changed to the higher factor in Run 2 (P_{inj}); two factors have changed in Run 4 (P_{inj} and V_{nj}) and so on until the last run (Run 16) were all the factors are set at the higher level. This ensures that the effect of process parameters and their combinations on the response (dimensional accuracy) is captured for all possible variations.

Table 4-1- Taguchi's Orthogonal Array for investigation of Tp, Tm, Vinj and Pinj

Run	***Factor***			
	T_p	T_m	V_{inj}	P_{inj}
1	1	1	1	1
2	1	1	1	2
3	1	1	2	1
4	1	1	2	2
5	1	2	1	1
6	1	2	1	2
7	1	2	2	1
8	1	2	2	2
9	2	1	1	1
10	2	1	1	2
11	2	1	2	1
12	2	1	2	2
13	2	2	1	1
14	2	2	1	2
15	2	2	2	1
$2^4=16$	2	2	2	2

4.2.3 Selection of features

Unfortunately, it is not possible to conduct experiments on all possible shapes and features as this study has a limited amount of time and resources available. Therefore, a feature had to be selected for this study. The selected feature is a micro wall. These are made by filling the cavities which have the shape of a micro channel. Micro walls have a wide range of industrial applications. They are used in applications such as micro fluidic and medical devices, micro filters, micro heat exchangers; with dimensions in the range of tens of microns to sub millimeters [83, 85, 91].

4.2.4 Mould design

Several factors need to be considered in the design of a mould. The importance of design and its effects on the replication of the parts was investigated and explained in

Chapter 2. The mould used in this study is designed to have short runner systems. Smaller runners mean that the polymer has to flow a shorter length. This means the conditions of the polymer melt are as close to the settings as possible. In addition, it reduces the frictional forces between the polymer melt and the surface of the runner; resulting in the polymer retaining more of its velocity. Higher velocity also creates more shear rate. This is shown in *Equation 4.5*, which is the definition of shear rate.

$$\gamma = \frac{dv}{dx} \qquad \textit{Equation 4.5}$$

Where γ is shear rate, *v* represents velocity and *x* represents the distance travelled by the melt. Due to the shear thinning effect, as shear rate increases viscosity decreases; this assists the filling of the cavities. High velocity also increases shear heating which could maintain the temperature of the melt. Shorter flow length also means that the polymer temperature remains close to the initial settings. This is because there is less heat transfer between the polymer melt and the surface of the mould, as explained by *Equation 4.6* [128].

$$q = UA\Delta T \qquad \textit{Equation 4.6}$$

Where q is the rate of heat transfer, U is the coefficient of heat transfer, A is the surface area between the polymer and mould wall and ΔT is the temperature difference between the polymer and the mould. The smaller the area (A), the smaller the heat transfer between the polymer (higher temperature) and the mould (lower temperature); which results in smaller overall heat loss. As explained previously by *Equation 4.4*, higher temperature results in reduction of viscosity which enhances the filling of the cavities and accuracy of the moulded micro parts.

A smaller runner system also ensures that pressure remains as close to the original setting as possible. Pressure drop occurs as a result of frictional forces between the polymer melt and the surface of the mould. Pressure drop in the channel can be expressed as *Equation 4.7* [128].

$$f = \frac{\Delta P \frac{\pi r^2}{2\pi r \Delta L}}{\frac{1}{2}\rho V^2}$$ *Equation 4.7*

Where V is the velocity of the fluid, ρ is the density of the fluid, r is the radius of the channel, ΔL is the length the polymer travels, ΔP is the pressure drop and f is the friction factor. Solving *Equation 4.7* for ΔP gives

$$\Delta P = \frac{f \rho V^2 \Delta L}{r}$$ *Equation 4.8*

From *Equation 4.8* reduction in the length of flow (ΔL) reduces pressure drop.

Short runner system also has the added bonus that most of the polymer is used for production of the part and less polymer is wasted.

4.3 Experimental set up

Experiments in this study are conducted on a Battenfeld Microsystem 50. This is a three stage commercial machine that is being widely used in the field of µIM. Advantages of three stage machines and the details of the operation of the particular machine used in this study were discussed in **Chapter 2**. The configuration of the machine has not changed so that the results of the experiments are valid for the commercial machine and can be used by any operator.

4.3.1 Mould and insert

The experiments conducted in this study focus on replication of polymeric micro walls. For production of these parts three micro channels were manufactured on a Brass pin, using the KERN Evo micro milling machine. Each channel is designed to have a specific width. This is to investigate the effect of process parameters on different sizes of channels. Heights of all channels are designed to be 100 microns and the width varies in the range of 151 to 212 microns.

Schematics of the pins and the dimensions of the channels are shown in *Figure 4-2* and *Table 4-2*.

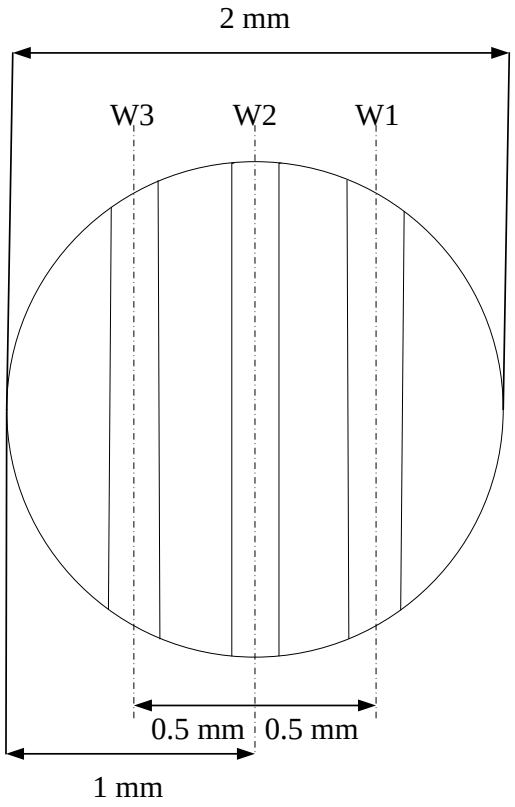
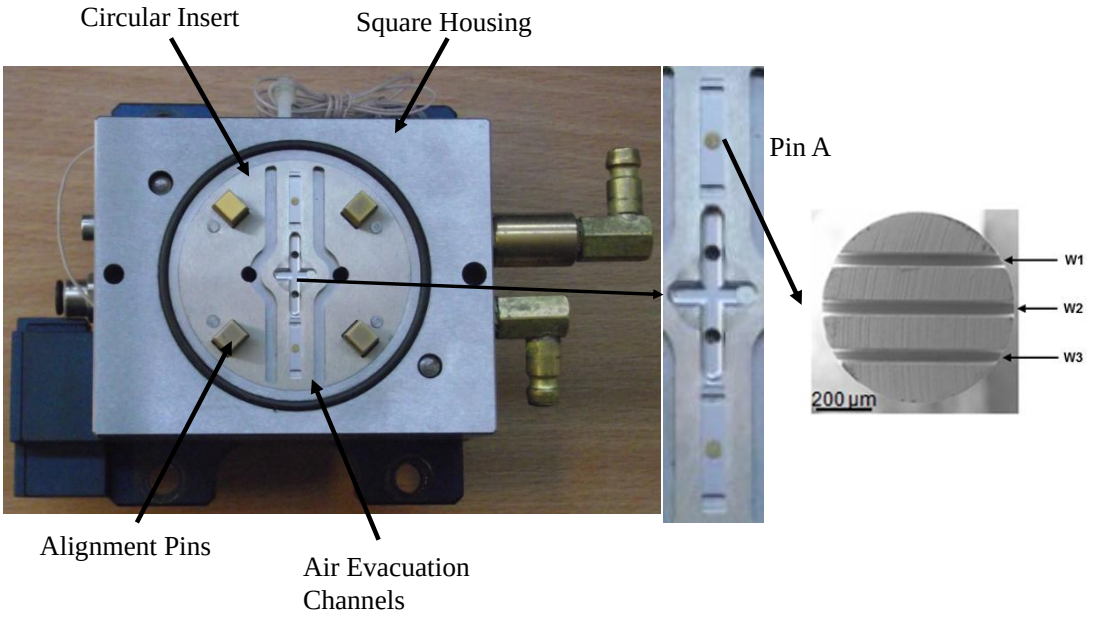


Figure 4-2- Schematics of the Brass pins

Table 4-2- Width of the channels on the Brass pins

Pin and Channel	***Pin 1***		
	W_1	***W_2***	***W_3***
Width (µm)	212.14	189.59	155.57

Due to the design and set up of the mould and inserts all channels are filled with the same shot. This allows multiple experiments to be conducted simultaneously. *Figure 4-3* shows the picture of the mould and inserts.



(a) (b)

Figure 4-3- Picture of the mould (a) assembled mould and (b) pin inserts

The mould consists of three parts; a square housing, a circular insert, and the two pin inserts (pin A and pin B). The pins are located inside the circular insert. Four rectangular section alignment pins are also used to ensure the alignment of the fixed and the moving halves of the mould. Air evacuation channels are also placed on either side of the insert. *Figure 4-3 (b)* shows the schematics of the part on the mould and the location of the pins inside the circular insert. Six ejector pins are used for the demoulding of the part. Two of these are on the runner and each part has two on the dented section on either side. These are shown in *Figure 4-4*. *Figure 4-5* shows the actual polymeric part made with POM. The first one shows the shape of the overall part with the runner system (as in *Figure 4-3 (b)*). The second shows the single part once the runners are removed and the third shows a picture of the channels taken by the Hitachi S-2600N scanning electron microscopy.

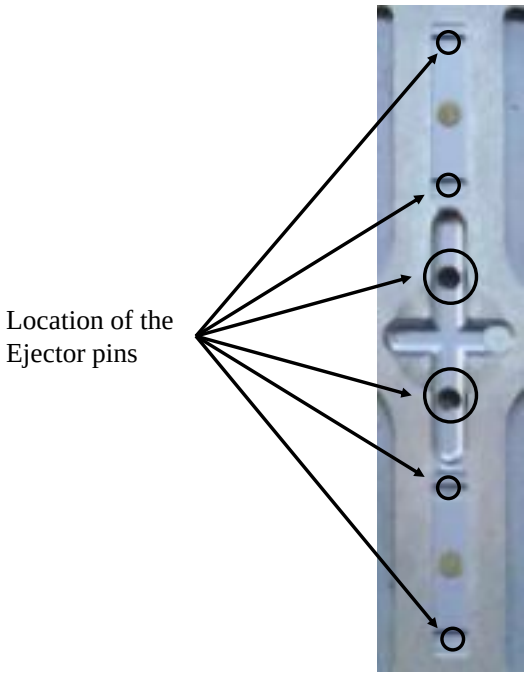


Figure 4-4- Location of the ejector pins on the mould

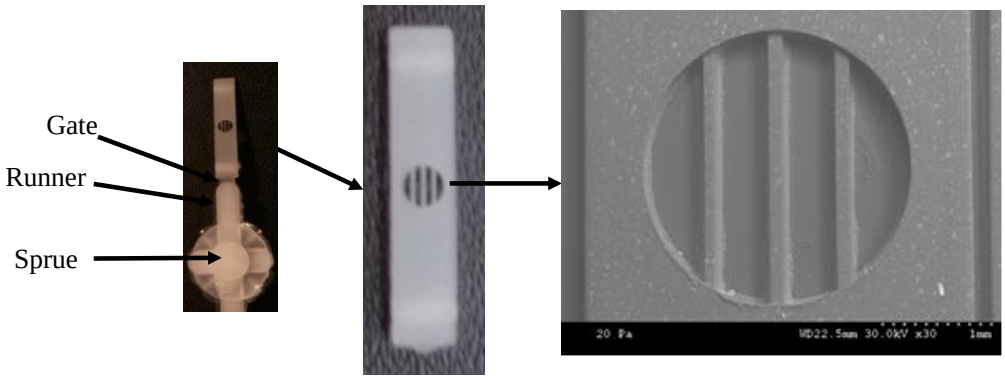


Figure 4-5- Moulded part produced in POM

In the moulded part in *Figure 4-5* the top piece is the part with the micro channels across the circle in the middle; and the middle section which forms the shape of a cross is the runner system. The polymer is injected in the middle to ensure the flow of the polymer melt is as uniform as possible. In this study one pin (pin A, shown in *Figure 4-3*) is used with three channels and the other section (Pin B) is covered with a blank pin.

Several sections of the part can be used to investigate the accuracy of the parts. For example the length and width of the overall part, the diameter of the circle, the thickness of the part, the dimensions of the legs (small dented sections on the mould)

and the width of the micro channels. The focus of this study is on the accuracy and replication of the micro channels in the middle of the circle. To determine the influence of the process parameters the dimensions of the features on the mould and the replicated part are compared. A drawing of the part without the channels is shown in *Figure 4-6*.

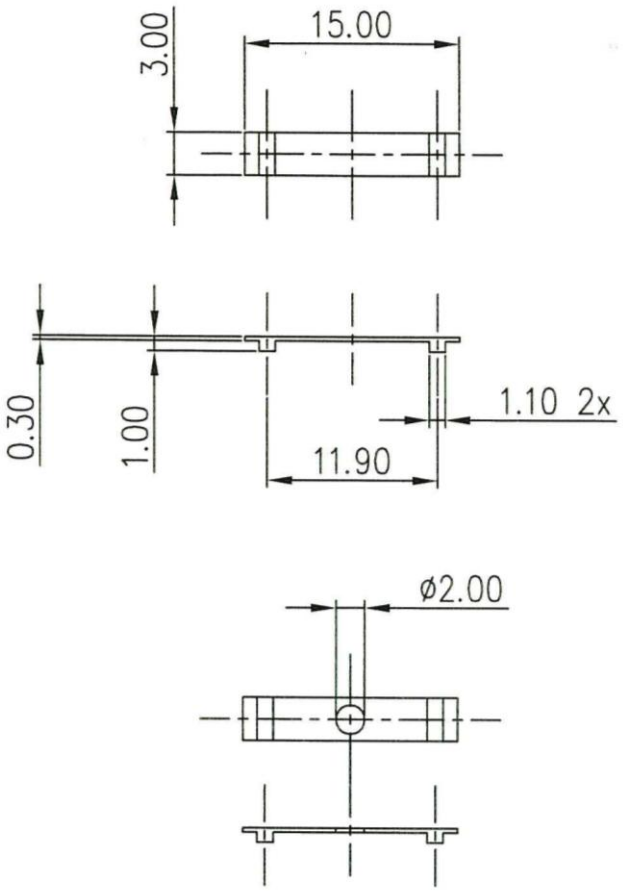


Figure 4-6- Schematics of the part and its dimensions

4.3.2 Materials

The materials used in this research are polyoxymethylene (POM) and Polypropylene (PP). POM is a semi crystalline polymer which has high toughness, hardness and stiffness, and is a good electrical insulator. It is a good chemical resistant and does not crack easily under stress [77]. POM has applications in the automotive, electrical appliances and electronics industries. It is also used in the medical industry and part of inhalers and insulin pens are made from POM [129]. PP is widely used in manufacturing of polymeric parts. Its low melt viscosity makes it very attractive in the manufacture of micro parts by µIM. It has high tensile strength and elasticity

modulus. Applications include manufacture of micro electrical and electronic components, optics and automotive industries. Its medical applications include manufacture of drug delivery systems and micro centrifuge tubes used in the fields of medical research and diagnostics [8].

For the purpose of this study the polymer was purchased from Ticona and its specific grade is POM Hostaform® C27021 TF [129]. This grade of POM has high resistance to thermal and oxidative degradation. It is used for the production of parts with sliding combination applications with very low coefficient of friction such as gear wheels. In molten form it has very low viscosity which makes it a suitable material for micro injection moulding. The grade of PP used is CPPP SW75AV from Carmel-Olefines, which has high melt flow rate and low viscosity. Properties and operating conditions for the polymers are shown in *Table 4-3* and *Table 4-4*.

Table 4-3- Properties of POM and PP

Property	***Value***	
	POM	***PP***
Density (g/mm^3)	1.41	0.9
Thermal conductivity (W/mmK)	310	2067
Specific heat capacity (J/gK)	2.3	2.62
Melt flow index (190˚C) (g/10min)	33.84	65

Table 4-4- Operating conditions of POM and PP

Process parameter	***Manufacturer's recommended value***	
	POM	***PP***
Melt Temperature (T_p) (ºC)	190-230	190-300
Mould Temperature (T_m) (ºC)	80-120	60-90
Injection Pressure (P_{inj}) (Bar)	60-120	600
Injection Velocity(V_{inj}) (mm/s)	100-300	500

All values for the parameters were selected based on the manufacturer's recommended values for applications in micro injection moulding, based on *Table 4-4* and screening of the process. The selected values for the mould and melt

temperature are the minimum and maximum temperatures. Injection velocity and pressure are selected based on the capabilities of the machine used in this study. *Table 4.5* shows the highest and lowest values used.

Table 4-5- Process parameters for POM and PP

Factor	***Low level***		***High level***	
	POM	***PP***	***POM***	***PP***
T_p ***(ºC)***	200	190	225	220
T_m ***(ºC)***	85	60	120	90
V_{inj} ***(mm/s)***	350	350	500	500
P_{inj} ***(Bar)***	600	600	800	800

Combination of the values in *Table 4-5* and Taguchi's L16 Orthogonal Array used in designing these experiments (*Table 4-1*) results in formation of *Table 4-6*. This table shows the values of each process parameter for each combination. Initial experimentation at the very beginning of this study showed that the holding pressure has minimal effect on the accuracy of the part. This is in agreement with some studies previously conducted by other researchers on similar features [85, 90], which was already presented in **Chapter 2**. Therefore, holding pressure is set at 1000 bar. Injection time and holding time were set at one and five seconds respectively. Shot volume is set at 160 mm^3. For each parameter combination, 20 samples are produced. The first ten are discarded to ensure that the process is stabilized and the following ten samples are used for measurements and analysis.

Table 4-6- Taguchi L16 OA design for investigating the effect of process parameters on dimensional accuracy

Run	Factor							
	T_p		T_m		V_{inj}		P_{inj}	
	POM	PP	POM	PP	POM	PP	POM	PP
1	200	190	85	60	350	350	600	600
2	200	190	85	60	350	350	800	800
3	200	190	85	60	500	500	600	600
4	200	190	85	60	500	500	800	800
5	200	190	120	90	350	350	600	600
6	200	190	120	90	350	350	800	800
7	200	190	120	90	500	500	600	600
8	200	190	120	90	500	500	800	800
9	225	220	85	60	350	350	600	600
10	225	220	85	60	350	350	800	800
11	225	220	85	60	500	500	600	600
12	225	220	85	60	500	500	800	800
13	225	220	120	90	350	350	600	600
14	225	220	120	90	350	350	800	800
15	225	220	120	90	500	500	600	600
2^4=16	225	220	120	90	500	500	800	800

4.3.3 Measurements

For each combination of process parameters, three samples were randomly selected and measured using the Hitachi S-2600N scanning electron microscope (SEM). The measurement tool was calibrated, using other standard samples with known dimensions. All three micro walls are measured on each sample. For each micro wall three measurements are selected in a manner to cover the length of the channel. Once dimensions are obtained they are compared with the dimensions of the channels in the mould. The value of the difference between the mould channels and polymeric micro walls' dimensions shows the error ($\Delta L = L_m - L_p$). The highest error for a channel is selected as the error for that channel. *Figure 4-7* shows the location that the three measurements were performed.

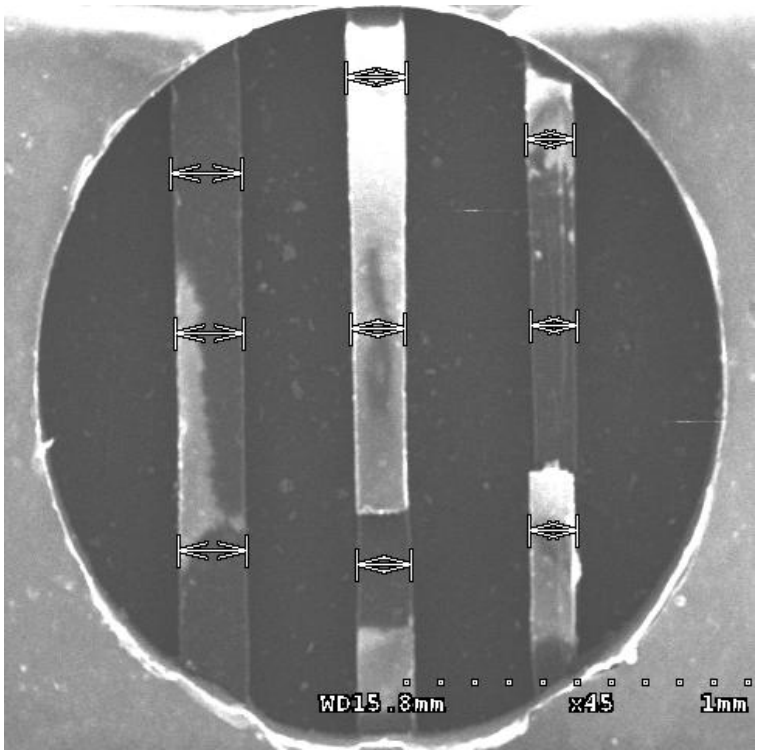


Figure 4-7- Measurement points for each part

4.4 Results

This section is designed to show the effect of process parameters on dimensional accuracy of the micro moulded parts. This is done graphically with the aid of statistical analysis software called Minitab. To do the statistical analysis, maximum values for dimensional error from the measurements is used. This is done with consideration for constructing the accuracy models. Since these results are used to develop the models empirically, this ensures that the values obtained from the models represent the worst case scenario. However, it must be mentioned that the measurement values for the micro walls in each batch are very close to each other. To illustrate this, an example is given below. *Figure 4-8* shows the three measurements performed for the second micro wall made out of POM in a randomly selected batch (7^{th} process parameter combination). The value that results in the highest dimensional error is the first one (165 µm). The average of the measurements for this batch is 168.3 with a standard deviation of 3.3. Considering the machine has an error value of 5 µm and the human error made in aligning the boundary of the measurements arrows, the maximum dimensional error can be used with high degree of confidence as the dimensional error for analysis.

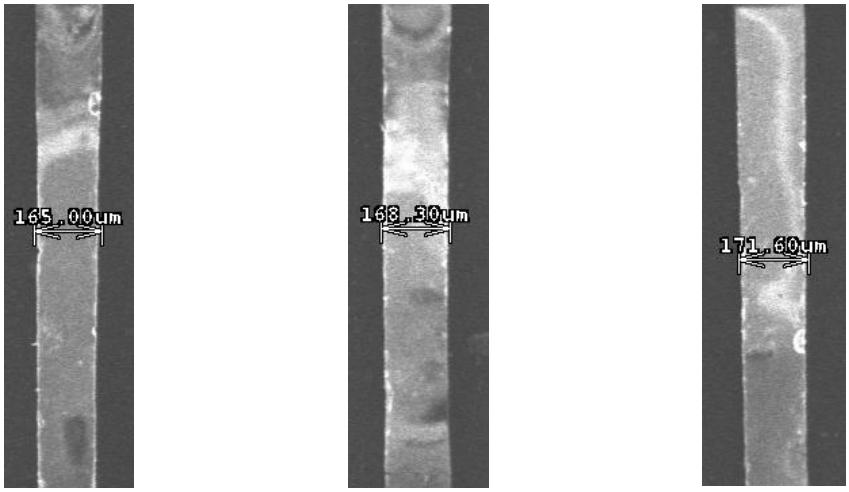


Figure 4-8- Three measurements of the dimension of the 2nd micro wall made out of POM

4.4.1 Accuracy of the replicated micro walls

Figure 4-9 shows the dimensional error for each micro wall made out of POM, for each combination of the process parameters. The micro walls in the figure are arranged from the one with the highest width (number 1) to the lowest width (number 3).

Figure 4-10 shows the dimensional error for each micro wall made out of PP, for each combination of the process parameters. The arrangement of the number of micro walls is the same as *Figure 4-9* (i.e. highest width is number 1 and lowest width is number 3).

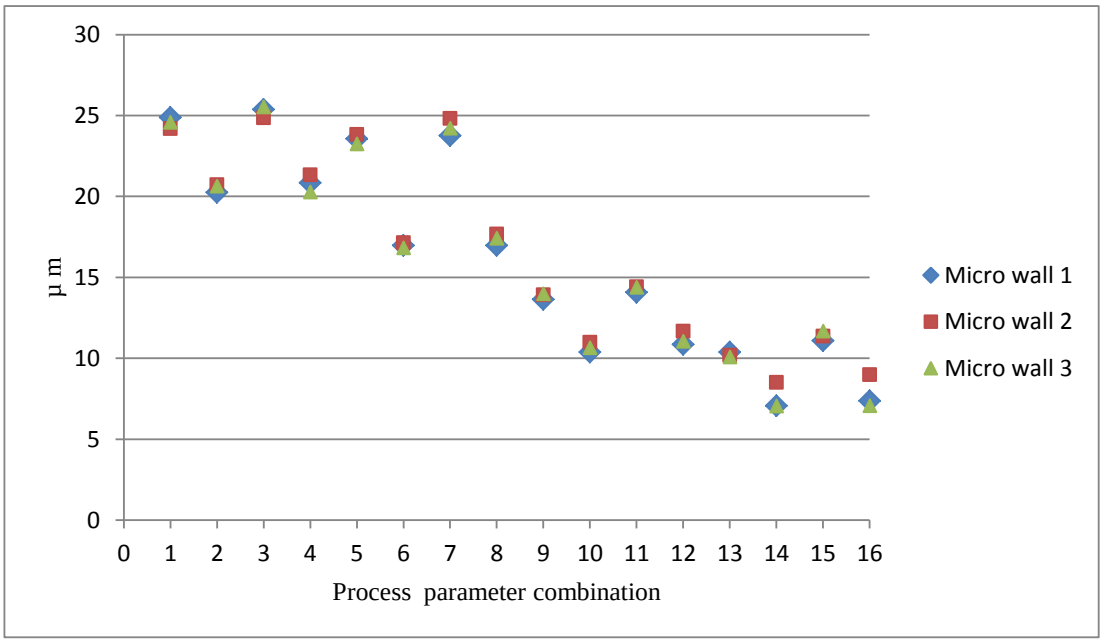


Figure 4-9- Dimensional error for each process parameter combination for POM (µm)

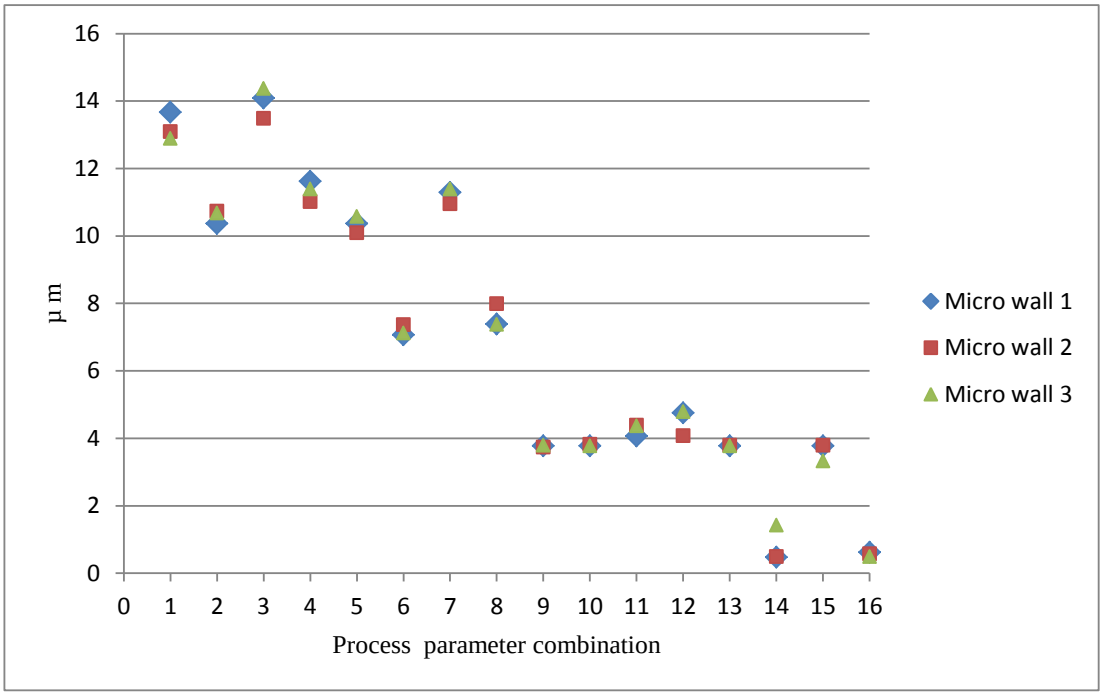


Figure 4-10- Dimensional error for each process parameter combination for PP (µm)

4.4.2 Statistical analysis

Once the errors are obtained, statistical analysis is performed to show the effect of process parameters on the dimensional accuracy of each channel. To do this an ANOVA method (Analysis Of Variance) is used. This method is widely used in the industry to simultaneously investigate the effect of several factors on a response. For this purpose, Main Effect Plots and Pareto Charts are used. Main Effect Plots show the effect of a factor on a response. Pareto Charts show the level of influence of a certain factor or its interactions with other factors. To achieve these plots Minitab is used. This software is commercially available and is extensively used in the industry for designing and analysing experiments. In this study, the factors are the four selected process parameters and the response is dimensional error.

Figure 4-11 to *Figure 4-16* show the Main Effect Plots and Pareto Charts for channels 1, 2 and 3 made out of POM. It can be seen from the Main Effect Plots that polymer melt temperature (T_p) had the highest effect on improving the dimensional accuracy of the micro walls. This is evident by the slope of the line between the two points. Injection pressure (P_{inj}) had the next greatest effect. Melt temperature (T_m) also had a positive effect on dimensional accuracy; however, this effect was considerably less than the previous two factors. Injection velocity (V_{inj}) also showed a small effect, however, with a negative effect on accuracy. Pareto charts in the figures also show the same effect and level of interactions between the four parameters.

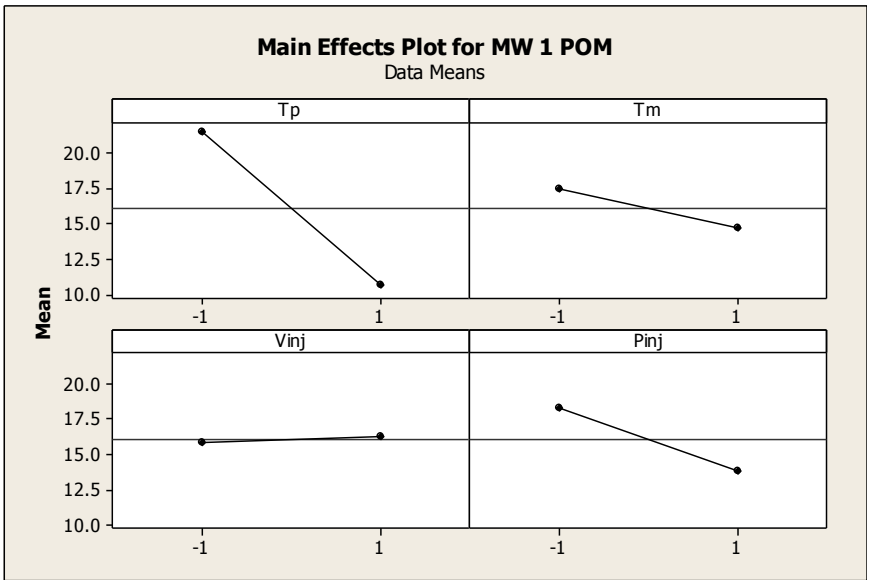


Figure 4-11- Main effects plot for micro wall 1 made out of POM

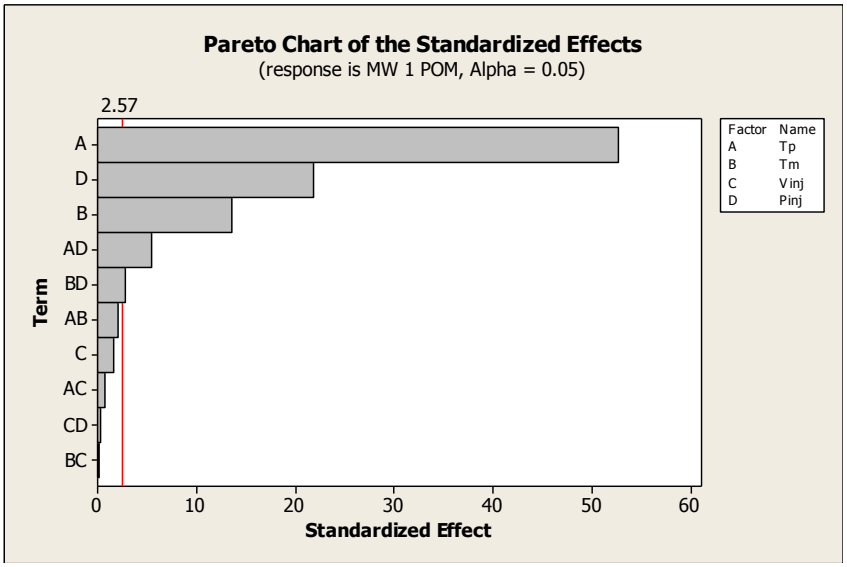


Figure 4-12-Pareto plot for micro wall 1 made out of POM

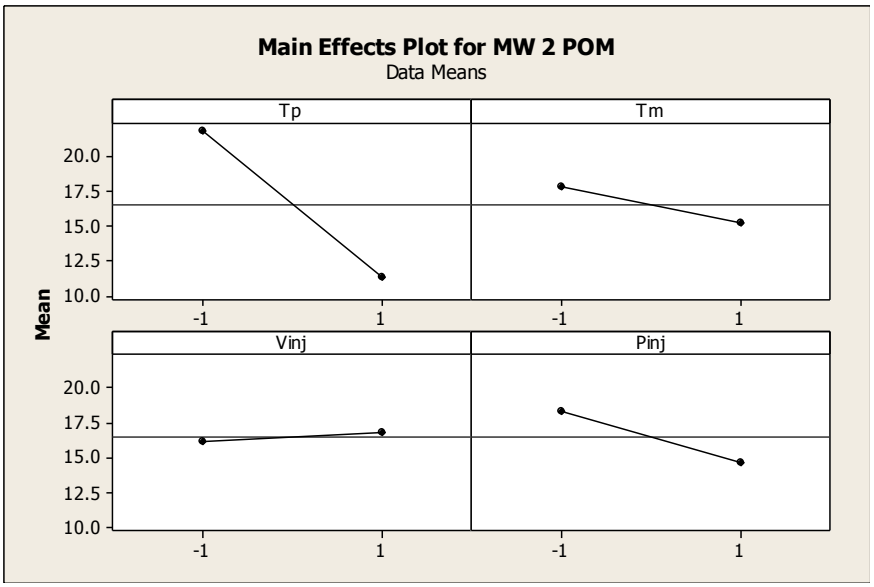


Figure 4-13- Main effect plot for micro wall 2 made out of POM

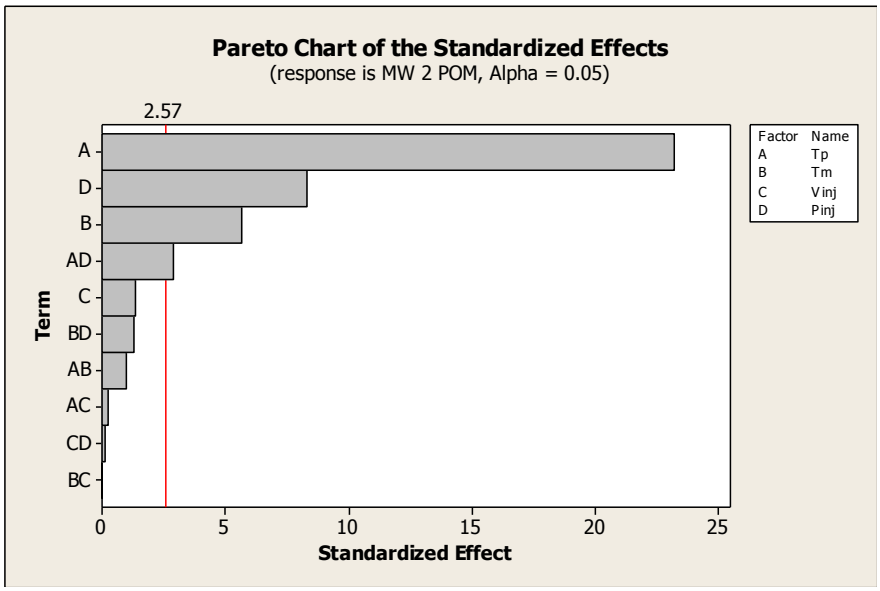


Figure 4-14-Pareto plot for micro wall 2 made out of POM

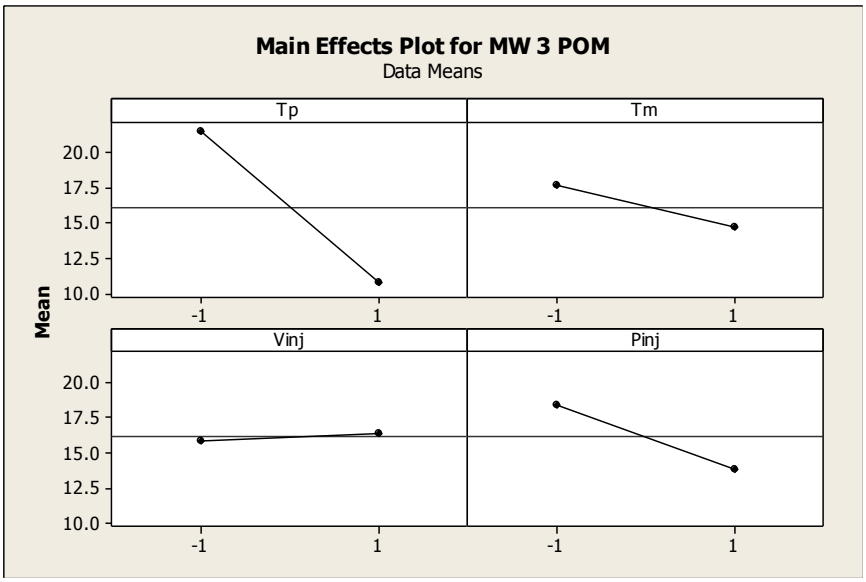


Figure 4-15- Main effect plot for micro wall 3 made out of POM

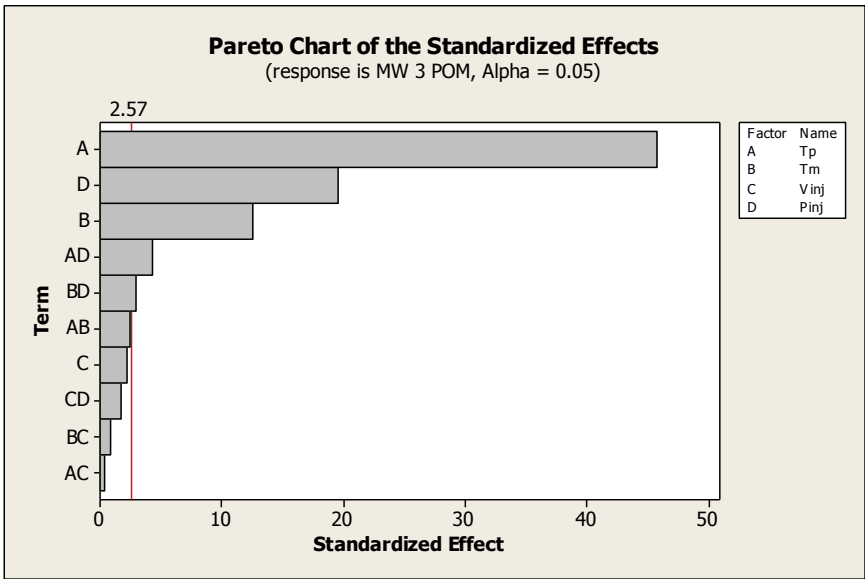


Figure 4-16-Pareto plot for micro wall 3 made out of POM

Figure 4-17 to *Figure 4-22* show the Main Effect Plots and Pareto Charts for channels 1, 2 and 3 made out of PP respectively. It can be seen from the Main effect plots that polymer melt temperature (T_p) had the highest effect on improving the dimensional accuracy of the micro walls. This is evident by the slope of the line between the two points. This is followed by injection pressure (P_{inj}). Melt temperature (T_m) also had a positive effect on dimensional accuracy; however, this effect was considerably less than the previous two. Injection velocity (V_{inj}) also showed a small effect, however, with a negative effect on accuracy. Pareto Charts in

the figures also show the same effect and level of interactions between the four parameters.

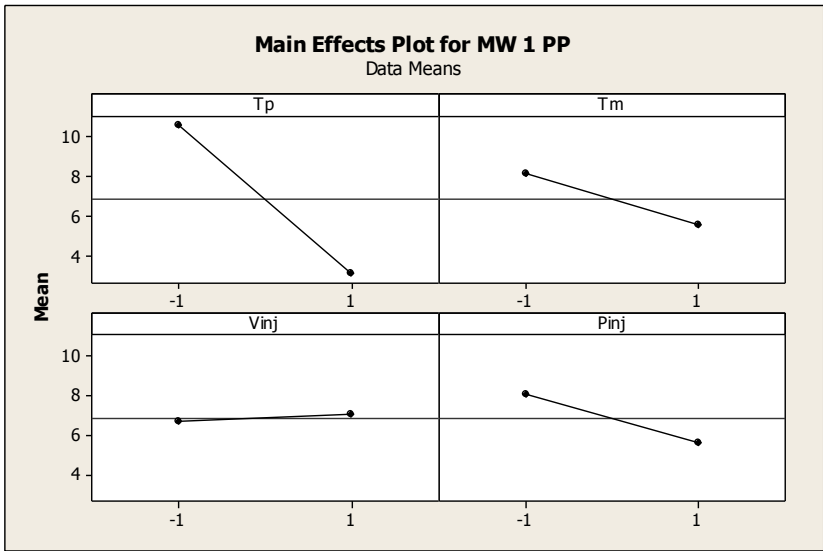


Figure 4-17- Main effect plot for micro wall 1 made out of PP

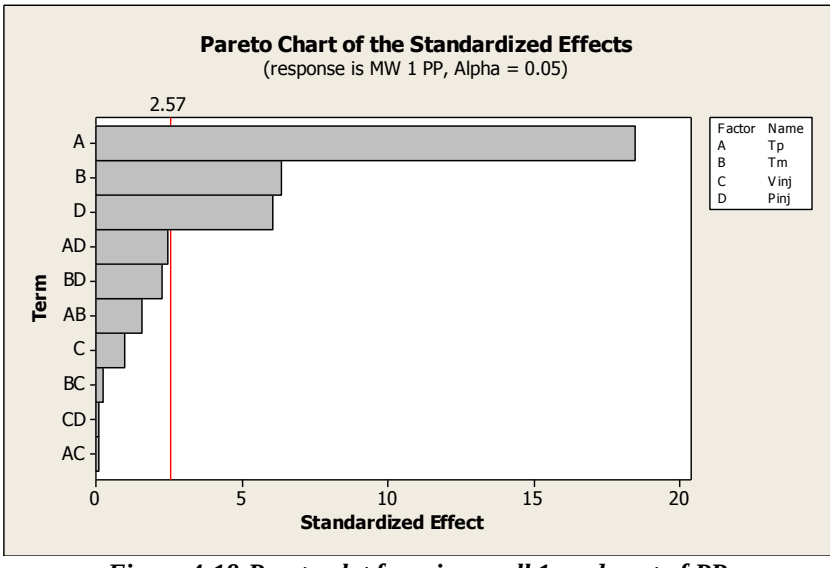


Figure 4-18-Pareto plot for micro wall 1 made out of PP

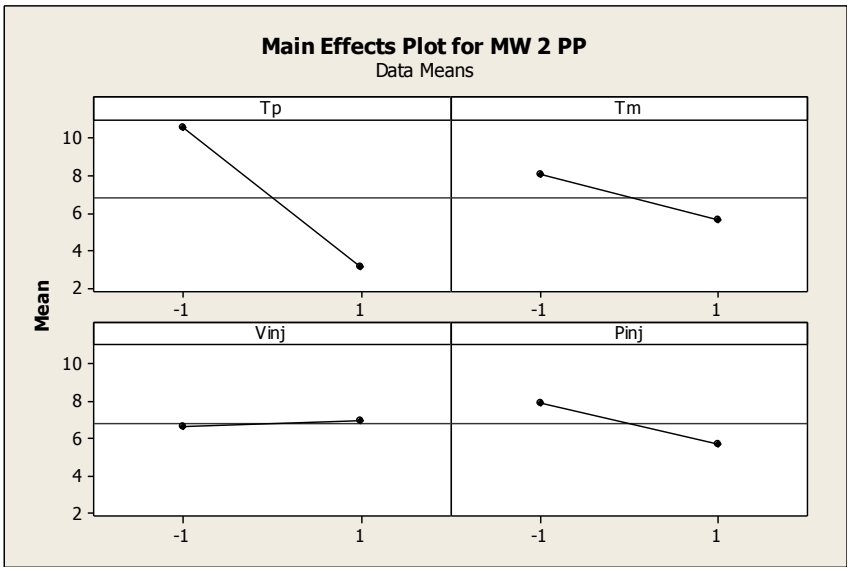


Figure 4-19- Main effect plot for micro wall 2 made out of PP

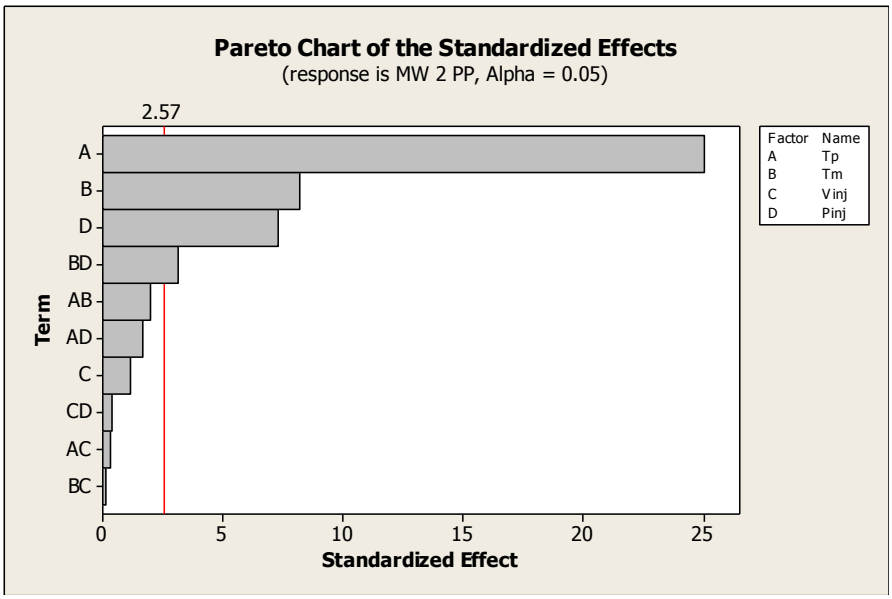


Figure 4-20-Pareto plot for micro wall 2 made out of PP

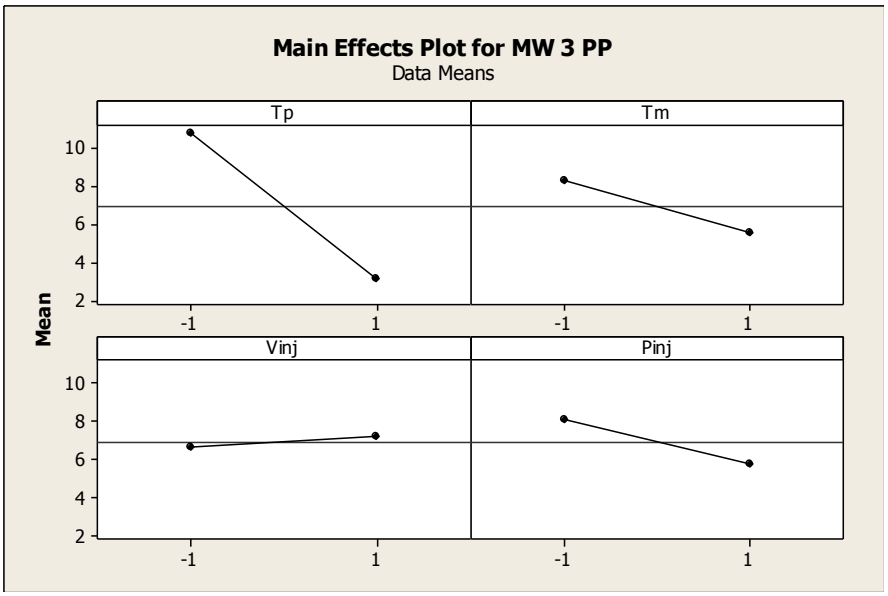


Figure 4-21- Main effect plot for micro wall 3 made out of PP

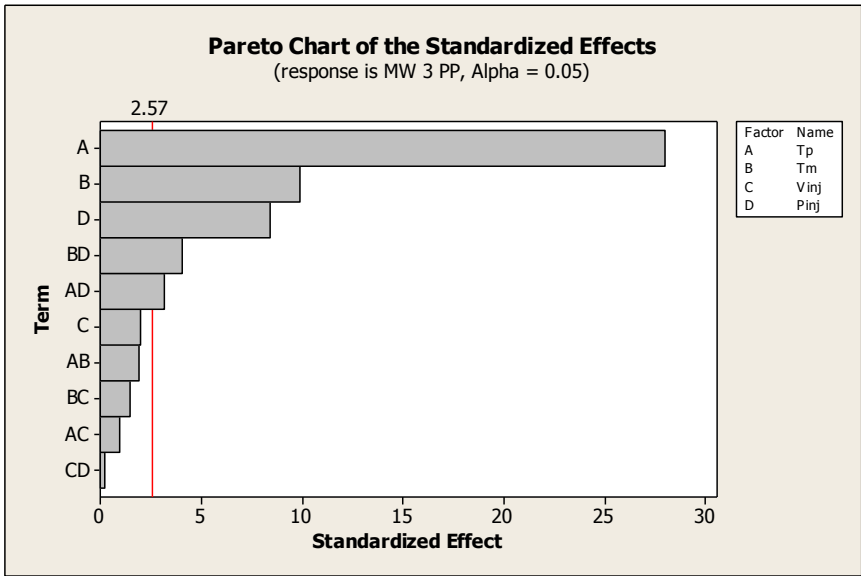


Figure 4-22-Pareto plot for micro wall 3 made out of PP

Since the effects of these parameters on dimensional accuracy are not likely to be linear they are further investigated. For each process parameter a set of values are investigated for POM and PP. Again, the range for temperature starts where complete micro walls are produced and stops where flash is formed excessively. For injection pressure and velocity the range starts from where a complete set of three micro walls are manufactured and stops just before the machine's maximum operating capability.

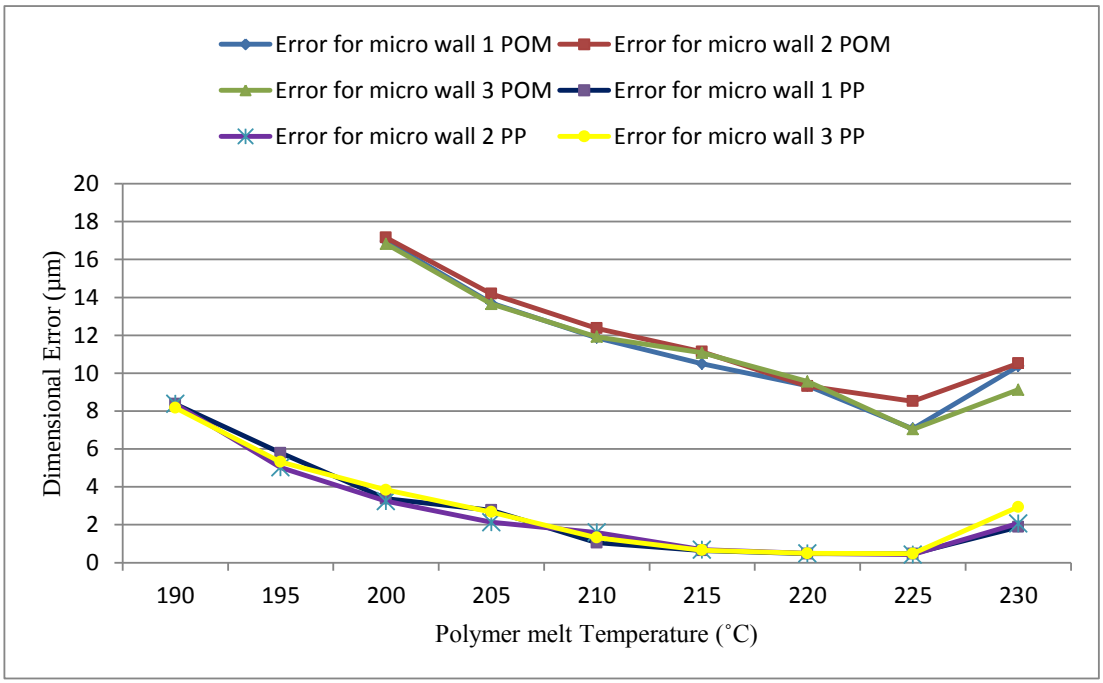


Figure 4-23-Effect of polymer melt temperature on dimensional accuracy of micro walls at Tm=120, Vinj=350 and Pinj=800

Figure 4-23 shows the effect of polymer melt temperature on dimensional accuracy of the micro walls. While the trend is not linear, it does show that as melt temperature increases, dimensional error decreases. This is not true for either polymer in the case of the parts produced at 230˚C. This is likely due to the flash formed on the part. In fact at this temperature, flash is visibly at an extreme case. This means some of the polymer volume that was intended to be injected in the mould cavity has leaked and this causes the reduction in dimensional accuracy.

Figure 4-24 shows the effect of mould temperature on dimensional accuracy of the micro walls made out of POM and PP. The figure shows that while the drop in dimensional error is not linear, the trend obtained earlier is correct and increasing mould temperature reduces error for all micro walls. It must be noted that the error values fall at a higher gradient for micro wall 2 compared to micro wall 1 and at an even higher gradient for micro wall 3. This shows that at smaller feature sizes, mould temperature becomes even more important and results in better and more accurate realization of micro parts. However, this is not true in the case of PP as PP is less sensitive to changes in temperature.

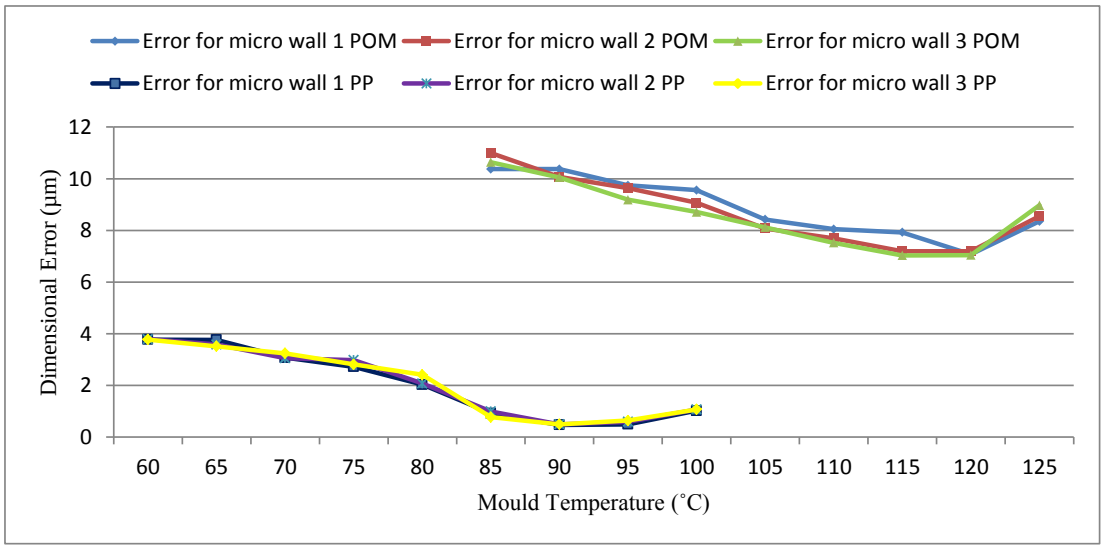


Figure 4-24- Effect of mould temperature on dimensional accuracy of micro walls at Tp=225, Vinj=350, Pinj=800

Figure 4-25 shows the effect of injection pressure on dimensional accuracy of micro walls made out of POM and PP. Results show that while dimensional accuracy does not fall in a linear manner, the trend shown in statistical analysis is correct and as injection pressure increases, dimensional accuracy generally improves. The trend shows that as pressure becomes higher, initially and at lower pressures the drop in error is at a higher gradient. As the pressure becomes higher, dimensional error reduces at a smaller gradient.

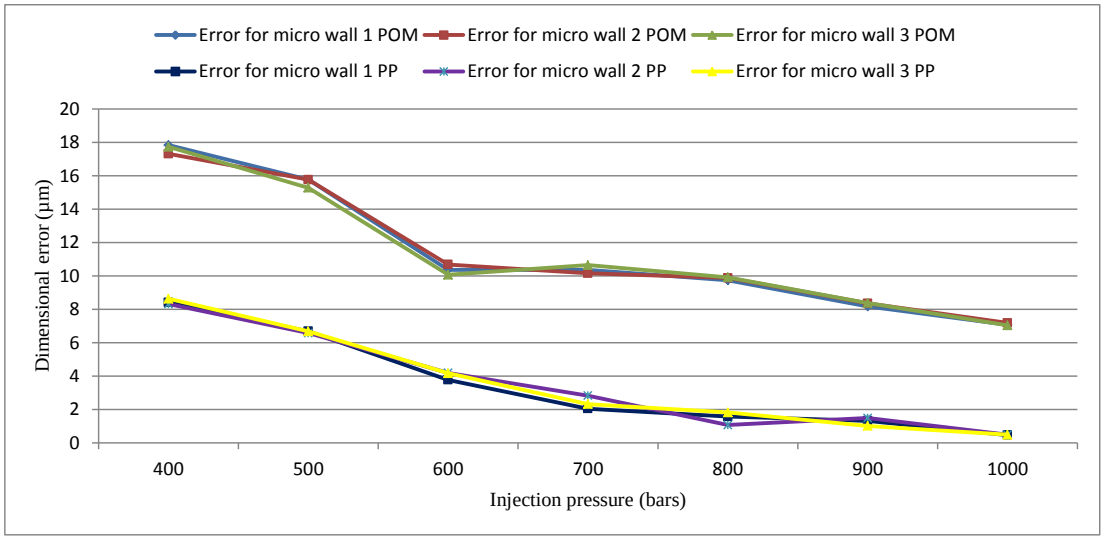


Figure 4-25- Effect of injection pressure on dimensional accuracy of micro walls at Tp=225, Tm=120 and Vinj=350

Figure 4-26 shows the effect of injection velocity on dimensional accuracy of micro walls made out of POM and PP. The values are selected by monitoring the process. Results are in agreement with the trend obtained from statistical analysis. Increase in injection velocity results in an increase in dimensional error. Nevertheless, it must be mentioned that this increase is very small.

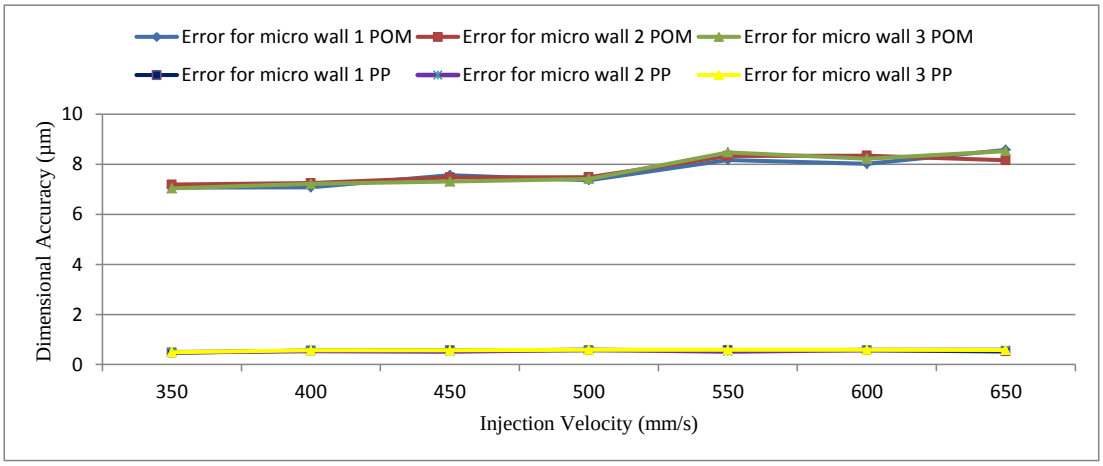


Figure 4-26- Effect of injection velocity on dimensoinal accuracy of micro walls at Tp=225, Tm=120 and Pinj=800

4.5 Discussion

4.5.1 Effect of process parameters

Experimental results showed that generally as the injection pressure and melt temperature increased, the error was reduced. *Figure 4-11* to *Figure* 4-22 confirm this trend and show that melt temperature and injection pressure have the highest effects. Both factors cause improvements on the dimensional accuracy of the micro walls. Interactions between polymer melt temperature and injection pressure also showed to have high influence on the reduction of dimensional error (Pareto Plots). However, the same trend cannot be observed when injection velocity is increased. These trends are present in most cases for both PP and POM.

Based on *equation 4.4* as the temperature of the polymer melt increases, viscosity decreases. This results in easier flow of polymer melt in the channels and therefore results in increased dimensional accuracy.

Pressure also had a significant effect on accuracy. The Main Effect Plots in the figures shows that as pressure was increased, dimensional error significantly decreased. The primary effect that increasing injection pressure has is that the polymer melt fills the cavities better and more fully. This is likely to be the main cause for the increase in accuracy. Increasing the injection pressure also has an effect on viscosity. Higher injection pressure increases the force on the polymer melt. Therefore, as the polymer is going through the gate and travels into the cavities, frictional forces increases which result in higher shear rate and shear heating of the polymer. This increase in melt temperature reduces the viscosity in the channels which results in better filling of the cavity. This is in agreement with what is stated in the literature, that once the size of the features enters the micro range, shear rates increase by a large factor; and while the principle is the same, equations used in conventional injection moulding (e.g. *Equation 4.2*) do not apply [21, 33].

In agreement with the literature, an increase in the mould temperature also had a positive effect on the dimensional accuracy of the moulded parts. Since the surface to volume ratio in µIM is high, the rate of heat transfer between the mould wall and the polymer melt is high; therefore the polymer loses its temperature very quickly and its viscosity increases. A higher mould temperature reduces the heat loss and therefore the melt temperature remains high. This assists with keeping the viscosity lower and results in better flow and filling of the cavity. It must be noted that as the size of the micro channels decreases, mould temperature becomes more important. This is evident in the Main effect plots and Pareto charts. This is because as the size of the mould cavity is reduced, the surface to volume ratio becomes higher and freezing occurs faster. Therefore higher mould temperatures are necessary as the size of the features, here micro channels, decreases. Furthermore, *Figure 4-24* shows that the error values fall at a slightly higher gradient for micro wall 2 compared to micro wall 1; and yet even at a higher gradient for micro wall 3 compared to the other two. This shows that at smaller feature sizes, mould temperature becomes even more important and high mould temperatures result in a better and more accurate realization of micro parts. However, this is not true in the case of PP. This is because PP's viscosity and flow is less sensitive to changes in temperature.

Injection velocity's influence on dimensional accuracy of the micro walls is unexpected. The effect of injection velocity can be explained by *Equation 4.3*. Increase in injection velocity causes increase in shear rate. This reduces the polymer melt's viscosity and results in better flow of the melt in the channels. However, results show that as injection velocity increases so does dimensional error. It is well known that as injection velocity increases air evacuation and ventilation becomes more difficult and incomplete filling may occur [36, 125]. Thus increasing the injection velocity in this study may have resulted in incomplete filling of the micro channels, hence, increase in dimensional error. It must be mentioned that the values shown in *Figure 4-26* are those obtained using the best of the other three conditions (higher melt and mould temperature, and injection pressure) and therefore the effect of velocity is even lower. However, a look at the numbers in *Figure 4-9* and *Figure 4-10* shows that at lower conditions, and especially lower melt temperature, velocity's negative effect is more evident. Nevertheless, the negative effect is still very small (around 2.8% on average).

4.5.2 Effect of polymer type

Dimensional variation can happen as a result of the shrinkage of the polymer melt when it cools down. In this experiment POM and PP were used which are semi crystalline polymers. Crystalline polymers are well known for the high strength of bonding between the molecules which results in more shrinkage [63]. When the parts are removed crystallization may have already happened or it may happen at a later time which results in a decrease or increase in dimensions of the part respectively. Adjusting to correct holding pressure can reduce the amount of shrinkage and result in higher accuracy. In fact, a few studies have shown that holding pressure is an important factor in filling micro cavities. The effect on dimensional accuracy could be the subject of further studies.

The polymers themselves also showed an effect on dimensional accuracy. Results showed that PP performed with higher accuracy in all cases (*Figure 4-9*, *Figure 4-10* and *Figure 4-23* to *Figure 4-26*). PP generally has lower viscosity than POM. The melt flow rate for the specific grade of PP used in this study is 65 g/10min and 33.84 g/10min for POM. The higher melt flow rate shows that PP has a lower viscosity and

flows easier in the channels and therefore can fill the channels better, which results in better dimensional accuracy. *Figure 4-23* to *Figure 4-26* show the best operating range for POM and PP. These are summarised in *Table 4-7* below. This range of values results in the smallest variation in dimensional accuracy. These are also shown in *Figure 4-27* and *Figure 4-28*.

Table 4-7- The best range of operating conditions for POM and PP

Process Parameter	***POM***	***PP***
Melt Temperature (T_p) (ºC)	215-225	210-225
Mould Temperature (T_m) (ºC)	105-120	85-95
Injection Pressure (P_{inj}) (Bar)	600-1000	700-1000
Injection Velocity(V_{inj}) (mm/s)	350-500	350-450

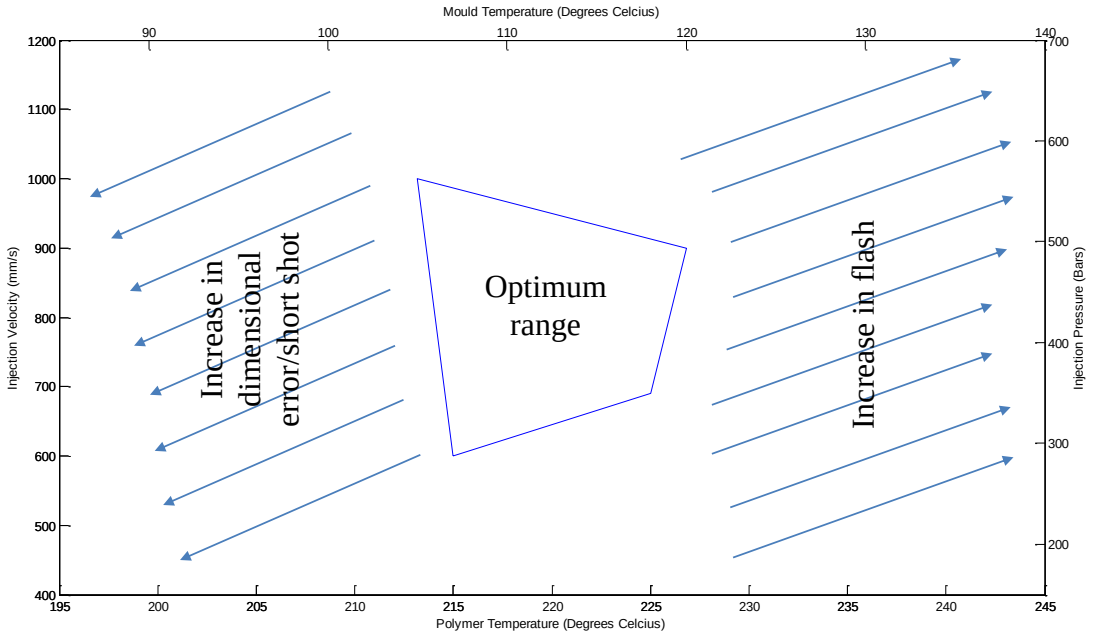


Figure 4-27- Optimum range of process parameters for POM

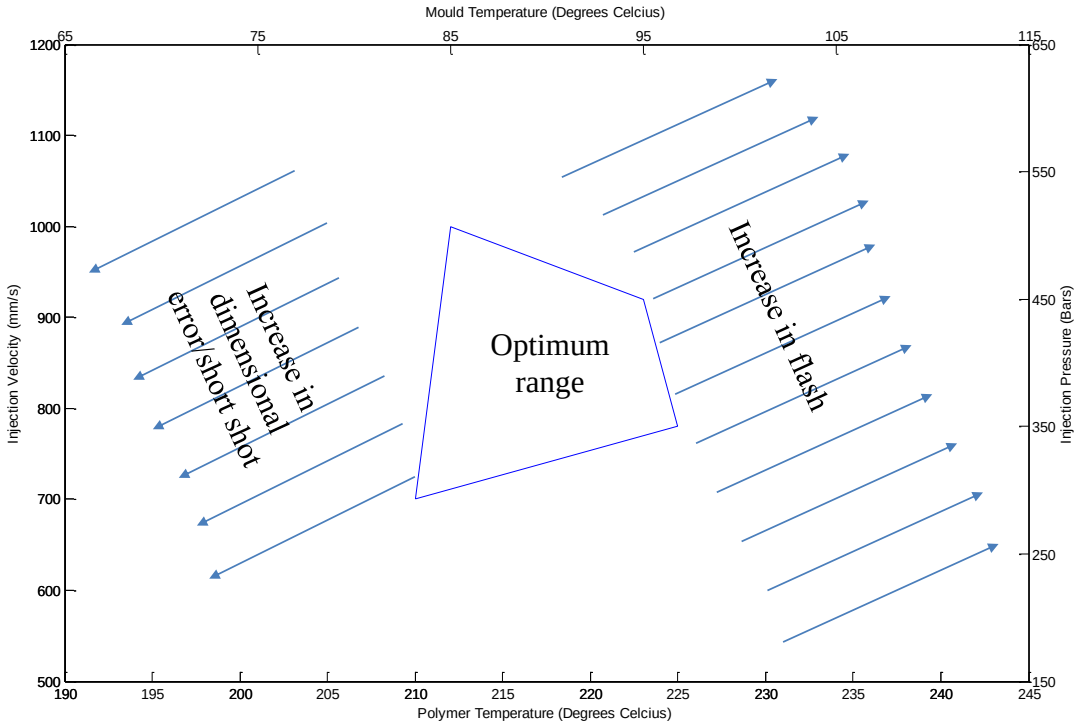


Figure 4-28- Optimum range of process parameters for PP

4.5.3 Effect of mould geometry

Finally, the smaller channels were shown to have higher percentage of dimensional error in most cases. As explained before, as the features become smaller the surface to volume ratio increases resulting in faster loss of heat and solidification of the polymer melt. This leads to higher viscosity which results in higher dimensional error. Also, as the entrance of the channels becomes smaller it becomes more difficult for the polymer to enter and flow inside the channel. This leads to faster temperature loss and increased viscosity, leading to increased error.

4.6 Chapter summary

The subject of investigation in this chapter was the effect of four process parameters on dimensional accuracy of micro moulded micro walls. The investigated process parameters are polymer melt temperature, mould temperature, injection velocity and injection pressure.

The experiments to understand the effects were designed based on Taguchi's Design of Experiments. It was explained that the main factor affecting the dimensional accuracy of the parts is the flow of the polymer melt in the cavities, this depends

heavily on the viscosity of the melt. Based on this, the process parameters that affect the viscosity of the melt were selected. Two polymers, PP and POM, were selected based on their applications and uses in the µIM domain. In addition, these are two polymers with low viscosity and good flowability. The design of the mould used in the study was also discussed in the chapter.

A full factorial design was used to investigate the effect of process parameters on the replication's dimensional accuracy. For each polymer the values were selected based on data from the literature review, the polymer data sheets and initial experimentations and investigations. The experiments were conducted on a Battenfeld Microsystem 50. Ten parts were made for each set of process parameter combinations. The widths of the micro walls were selected as the quality criterion. Measurements were conducted on a scanning electron microscope. Once the measurements were completed, the widths of the polymer parts were compared to the width of the micro channels on the mould insert. The difference is considered as the error, which is used for analysis.

Minitab 16 was used to conduct the statistical analysis. The effect of each process parameter on the dimensional accuracy was investigated individually by using main effect plots. The software also allows for investigation of the interactions between the process parameters by generating interaction plots. In addition, a Pareto analysis was done to understand which parameter had the highest effect on the dimensional accuracy.

Results showed that polymer melt temperature is the most influential factor in achieving higher dimensional accuracy, followed by injection pressure and mould temperatures. Injection velocity showed to have a negative influence on the dimensional accuracy of the width of the micro walls. The polymers themselves showed a high level of influence. PP parts showed better accuracy due to the fact that it has a lower viscosity compared to POM. The size of the channels also played a role, decreasing the width of the channels resulted in higher percentage of dimensional error. These results were confirmed by investigating each process parameter at several values to ensure that while the effect is not linear, the trends are still correct.

The results obtained from the experiments, together with the understanding of the interactions and influence of process parameters, are used in **Chapter 6**, where they are used in the generation of an empirical model that predicts the dimensional error in relation to the process parameters.

Chapter 5

Chapter 5 Effect of process parameters on the UTS of the micro injection moulded parts

5.1 Introduction

The importance and applications of µIM for manufacture of micro polymer parts were reviewed and explained in **Chapter 1** and **Chapter 2**. Due to the importance of micro products and their applications and the ever increasing use of µIM, the demand for higher quality and reproducibility has increased over the past years. One of the quality criteria that is still the subject of research and studies is the ultimate tensile strength (UTS) of the micro products. Generally, UTS of the parts depends on the polymer, mould design and the process [8]. Optimised selection of the process parameters can have a significant effect on the morphological and mechanical properties of the micro parts. Currently, this is the subject of experiments conducted based on trial and error. Therefore part of the focus of this study is devoted to the development of an empirical model that can be used for prediction of the UTS of a micro part. The applications and importance of such a model was also reviewed.

To produce such a model, the influence of process parameters on the UTS of the part must be identified. Therefore, this chapter focuses on investigating the effect of process parameters, their interactions and level of influence, on the UTS of micro walls. This is achieved by conducting several experiments on features with different sizes, and also with different polymers. To obtain the values for the UTS a mechanical testing machine is used to perform the "pull tests". Once the tests are complete and a value is obtained for each process parameter combination, statistical analysis (ANOVA) is performed to provide an insight into the effect the process parameters have on the UTS. The analysis shows the impact each process parameter has individually and also the level of interactions the parameters have. It also provides the means to understand the level of influence each process parameter, or combinations of them, have on the UTS. Finally, the results are explained and their implications discussed.

5.2 Design of experiments

To understand the role of process parameters in variation of the UTS of the micro parts a set of experiments are designed and conducted. The intention of these experiments is to investigate and identify the influence of each process parameter, its interactions with other process parameters and the level of influence on the UTS. Firstly the logic behind the experimental design is explained. This is followed by the experimental set up; presentation of the results of experiments. Finally, the results are discussed and the findings of the study are presented.

5.2.1 Selection of process parameters

To understand the role that the process of µIM plays on the variation of the UTS of the parts, the effect of each process parameter on the mechanical properties of the polymer parts need to be identified. The strength of the micro parts depends heavily on the orientation of the molecules, the bonding strength between them and how the crystals are formed in a polymer part. Direction of the flow determines the orientation of the molecules. If the molecules are oriented in the direction of the force, UTS is improved. The opposite effect is also true; if the molecules are oriented in the transverse direction, UTS is reduced. The crystalline structure is also an important factor in mechanical behaviour of the parts and specifically the UTS. Increased degree of crystallinity results in increased UTS. However, large spherulites reduce the strength of the part. Selection of the process parameters clearly needs to address this. The investigated process parameters need to be considered in a manner that their effect on orientation and formation of crystals can be investigated. In this section, four of the process parameters that can be directly changed on the machine and influence the mechanical properties of polymers are discussed. It is important to note that these parameters need to be selected in a manner that the results are comparable to those of the previous chapter (dimensional accuracy). These parameters are polymer melt temperature (T_p), mould temperature (T_m), injection velocity (V_{inj}) and injection pressure (P_{inj}).

Polymer melt and mould temperature are two very important factors in determining the mechanical properties of micro parts. This is because the temperature of the melt and the mould determine how quickly the temperature of the polymer decreases.

Loss of temperature, or cooling, is considered an important factor in the formation of the crystals in polymer parts. Faster cooling of the polymer melt means that the movement of the molecules is restricted in time and therefore smaller crystals are formed. Slower cooling of the polymer melt allows the molecules to move and orient in any direction. This results in the formation of large spherulites which reduces the UTS of the part.

Injection velocity and pressure also affect the mechanical properties of the polymer parts. Higher injection velocity and pressure also increase the UTS due to the higher concentration and compactness of the polymer molecules and therefore, higher degree of crystallinity.

In addition to what was explained above, the four process parameters are selected so that a comparison of the effect on UTS and accuracy can be done. This is crucial because if the process parameters' effects on the mechanical behaviour and accuracy of the part are not the same a solution must be found for manufacturing the final product. Therefore, the experiments were designed to investigate the same process parameters.

5.2.2 Experimental design

To understand the effect of process parameters on the UTS of the manufactured micro part a method has to be deployed to allow for simultaneous investigation of all the process parameters and their interactions and influences. To do this Taguchi's design of experiments is used. This method is commonly used in industrial applications where a response has to be investigated based on the effect of several factors. In this chapter, the response is UTS of the micro parts and the factors are the four process parameters (T_p, T_m, V_{inj} and P_{inj}). This method is selected because it allows both the effect of the process parameters independently and the effect interactions between them to be investigated. Thus the process variables and their effects on the UTS are systematically investigated.

For the purpose of this study, a two level full factorial design was used. In the design, a low and high level are used to investigate the effect of an increase or decrease in

each of the process parameters. Since there are four factors Taguchi's L16 Orthogonal Array (2^4) was formed. This allows for the investigation of sixteen different combinations of process parameters. This ensures that the effect of process parameters and their combinations on the UTS are captured for all possible variations and outcomes.

5.2.3 Selection of features

The proposed study could be conducted on a wide range of micro wall dimensions. However, it is out of the scope of this study to investigate all possible sizes due to restriction of time and resources. Therefore specific features have to be selected for experimentation. The features used in this study are micro walls which are used extensively in industrial applications such as the production of micro heat exchangers in micro fuel cells, micro fluidic devices and micro filters [83, 85, 91]. Micro walls also allow for the comparison of the results of the UTS and dimensional accuracy studies. A different feature results in a different flow of polymer melt in the cavity. This changes the formation of the crystals and orientation of the molecules. Therefore, a comparison between the two studies would be very difficult. In addition, the feature was selected due to its resemblance to a "Dog-bone" micro bar. Dog-bone shape bars are specifically used for the measurement of UTS of a specific material, or the investigation of the process variations. These parts have a straight bar in the middle and two thicker sections on either sides of the bar. The thicker sides are used for gripping the part in the tensile testing machine and UTS is measured for the middle section. *Figure 5-1* shows the schematics of the modified part used in this study. The full picture of the part and its relation to the mould was shown in *Figure 4-3* to *Figure* 4-5.

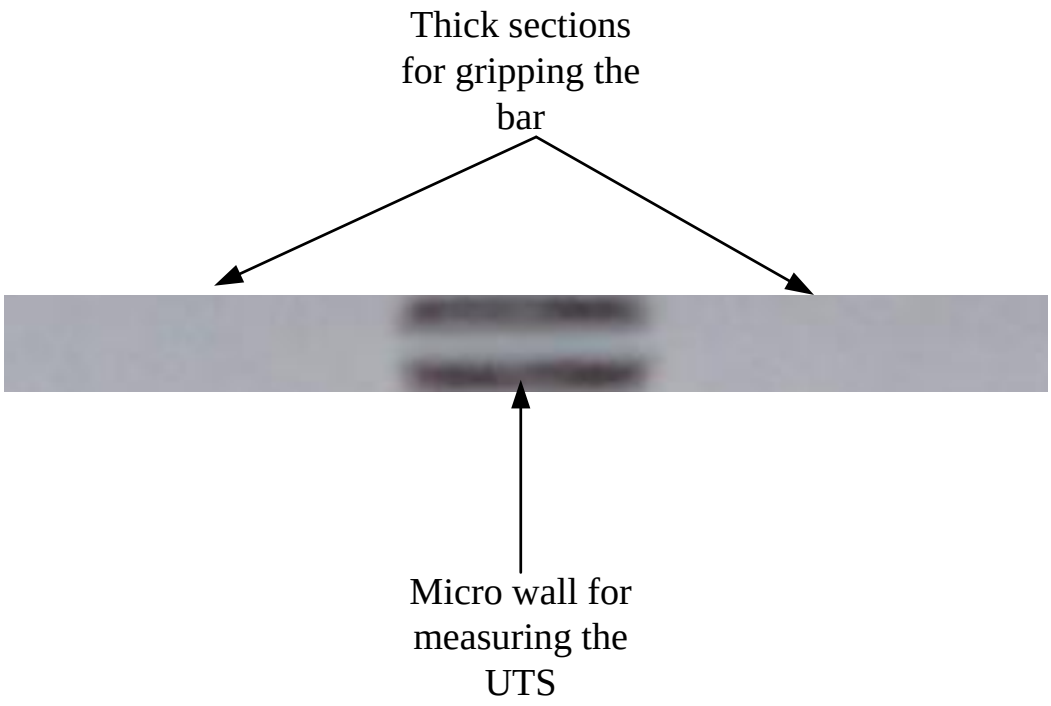


Figure 5-1- Schematics of a tensile test bar

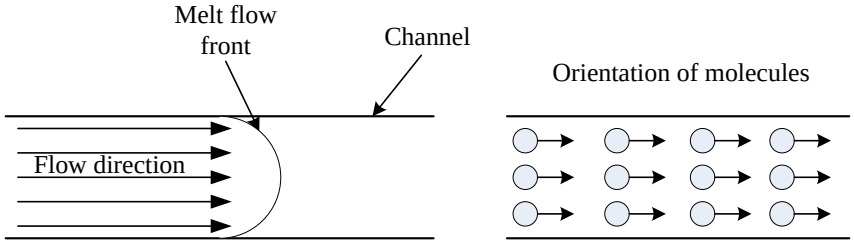
While the part in this study is not exactly in the shape of the tensile test bar, it is very similar in that the circular section in the middle holds the micro walls and the outer section of the overall part is a thicker section that can be used for gripping the part. The use of this part also allows for comparison of the results with other studies to see what effect the overall design of the part has. To conduct the pull test on a specific channel, the other channels and the sides of the part on the diameter of the circle (perpendicular to the micro walls) are cut. This is done after the part is loaded on the machine and is gripped firmly so that no stresses apply to the micro walls during the set up. The thicker section of the circle will guarantee that the stresses applied to the micro walls during the set up and gripping are kept at a minimum level. Dimensions of the micro walls are presented in *Table 5-1*.

Table 5-1- Dimensions of the micro walls used for tensile testing

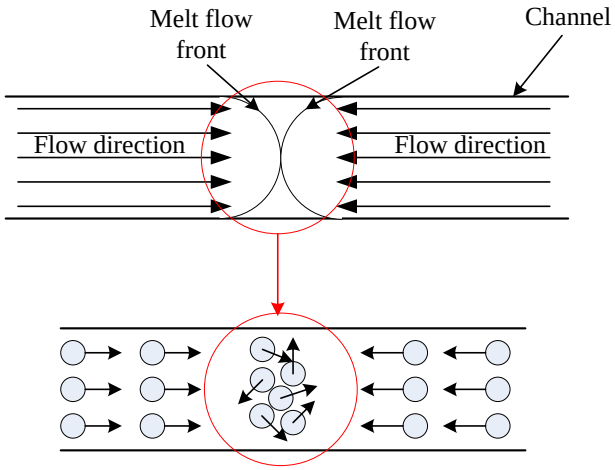
Micro wall	***Length (µm)***	***Width (µm)***	***Height (µm)***
1	1590	212.14	100
2	2000	189.59	100
3	1590	155.57	`100

5.2.4 Mould design

Design of the mould plays an important role in the mechanical behaviour of the final micro moulded product. As explained before, direction of the flow has a very high influence on the orientation of the molecules, and subsequently on the UTS. Gate design is another factor that affects the UTS of the parts. The number and location of gates dictates the flow of the polymer melt and its direction [103]. These could result in formation of "weld lines". Weld lines are formed when two flow fronts meet. They reduce the UTS because the formation of the molecules at weld lines and their orientation are different to the rest of the parts. This is because when the two melt fronts meet, under high pressure and velocity, the impact results in movement of the molecules in different directions and ultimately different orientations. This results in the formation of large spherulites and reduction of the UTS. However, when the flow is only in one direction, the arrangement and orientation of the molecules is also in one direction. This difference is shown in *Figure 5-2*. Therefore, where possible, weld lines should be avoided.



a) Flow of melt in one direction



b) Flow of melt in two directions & formation of weld line

Figure 5-2- a) orientation of molecules without weld lines, b) orientation or molecules in a weld line

5.3 Experimental set up

The experiments in this study are conducted using a Battenfeld Microsystem 50. This is a three stage micro injection moulding machine which is widely used in industrial manufacturing of micro moulded products. The three stage machines, their working principles and their advantages over other types were explained and examined in the **Chapter 2**.

5.3.1 Mould and insert

The mould and the inserts used to conduct these experiments are the same as the one used in **Chapter 4** *(Figure 4-2, Figure 4-3* and *Figure 4-4*). Subsequently the parts produced have the general shape as that of *Figure 4.6*. The main reason for this is to ensure that the effects of process parameters on the dimensional accuracy and UTS can be compared.

If any aspect in the design of the mould is different to that of the previous chapter, even if the feature has the same geometry, the flow characteristics will be different. These characteristics include shear rates at the gates and through the runners and cavities, viscosity of the melt, ejection characteristics such as force and its effect. As mentioned before, design of the mould and the direction of the flow have significant effects on the mechanical behaviour of the parts. Therefore, for a clear and valid comparison of the results it is absolutely crucial that the mould and its inserts to be exactly the same as in **Chapter 4**. .

While the flow of the polymer melt in one direction is desirable, it is not always possible. In a condition where weld lines exist, they are likely to be the cause of failure in a part.

The mould used in this study has one gate for each part. However, due to the flow of the polymer in different directions around the circular section in the middle, the micro walls are formed from two directions. This is identified by producing parts with short shots. Therefore, this study focuses on investigating the effect of process parameters on the strength of the weld lines for micro walls with different

dimensions. *Figure 5-3* shows the flow of the polymer melt around the circular section and in the channels.

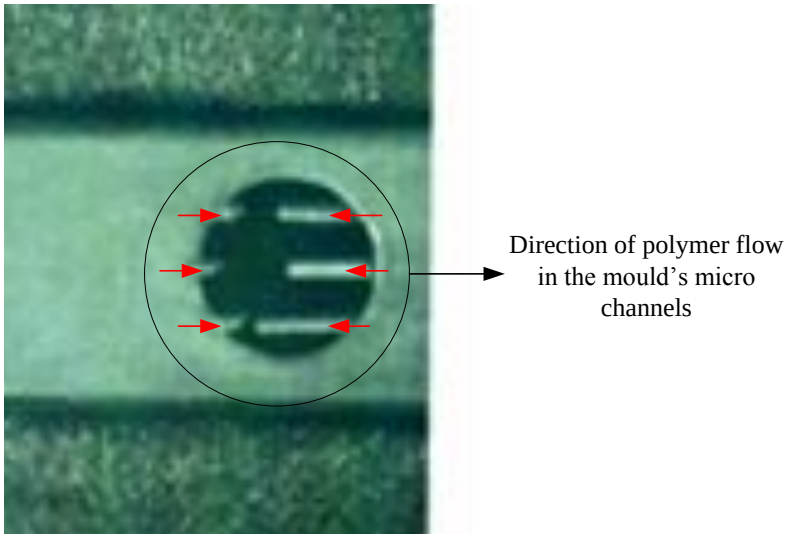


Figure 5-3- Direction flow in the mould's micro channels

5.3.2 Materials

In **Chapter 2** a list of commonly used polymers in µIM was presented. It was also explained that due to different characteristics of polymers, and different chemical and physical properties, their flow behavior is different. This was also investigated in **Chapter 4**. Different flow characteristics, such as viscosity, resulted in different accuracies in the final products. Therefore, to be able to clearly and viably compare the results of mechanical testing and dimensional accuracy, it is important to use the same polymers. As a result**,** the two polymers used in the previous chapter are employed to conduct these studies, these are POM and PP. The properties of these two polymers were presented previously (*Table 4-3*). The values used for the process parameters are those shown in *Table 4-7* to ensure minimal variation in the dimensions of the micro walls. *Table 5-2* shows the combination of values for the conducted experiments.

Table 5-2- Taguchi L16 OA design for investigating the effect of process parameters on UTS

Run	***Factor***							
	T_p		T_m		V_{inj}		P_{inj}	
	POM	***PP***	***POM***	***PP***	***POM***	***PP***	***POM***	***PP***
1	215	210	105	85	500	400	700	700
2	215	210	105	85	500	400	1000	1000
3	215	210	105	85	650	600	700	700
4	215	210	105	85	650	600	1000	1000
5	215	210	120	95	500	400	700	700
6	215	210	120	95	500	400	1000	1000
7	215	210	120	95	650	600	700	700
8	215	210	120	95	650	600	1000	1000
9	225	220	105	85	500	400	700	700
10	225	220	105	85	500	400	1000	1000
11	225	220	105	85	650	600	700	700
12	225	220	105	85	650	600	1000	1000
13	225	220	120	95	500	400	700	700
14	225	220	120	95	500	400	1000	1000
15	225	220	120	95	650	600	700	700
2^4=16	225	220	120	95	650	600	1000	1000

5.3.3 Tensile strength testing

For each of the process parameter combinations three random parts are selected. Firstly, these parts are measured using a Hitachi S-2600N scanning electron microscope (SEM). This machine is calibrated using a set of features with known dimensions. Once these measurements are done, the testing of the UTS is done using an Instron 5969 tensile testing machine. This machine is widely used to conduct pull tests for determining the UTS of a product. Pull tests are conducted at the rate of 1 mm/s. Two parts are used to measure the UTS for each micro wall. UTS is considered the tensile strength under at the maximum load.

As mentioned in section **5.2.3** the parts used in this study are not exactly the shape of a conventional dog-bones used for this purpose. However, they have the same characteristics as there are two large sections on either side of the micro walls.

5.4 Results

This section of the chapter provides the results obtained from tensile testing and shows the effect of process parameters on the UTS of the micro walls. This is done graphically with the aim of statistical analysis software Minitab. The values used for statistical analysis are the minimum UTS obtained from the measurements. Considering that these results are used to develop the UTS models empirically, the minimum values are used to ensure that the models consider the worst case scenario. However, it must be noted that the values are very close to each other, considering machine error of 10%. To put the values used in the context of mean and standard deviation a random batch is selected (7^{th} combination of process parameters). *Figure 5-4* shows the measurements taken from the machine. The first two are measurements for micro wall 1, the second two are for micro wall 2 and the third two are measurements taken for micro wall 3.

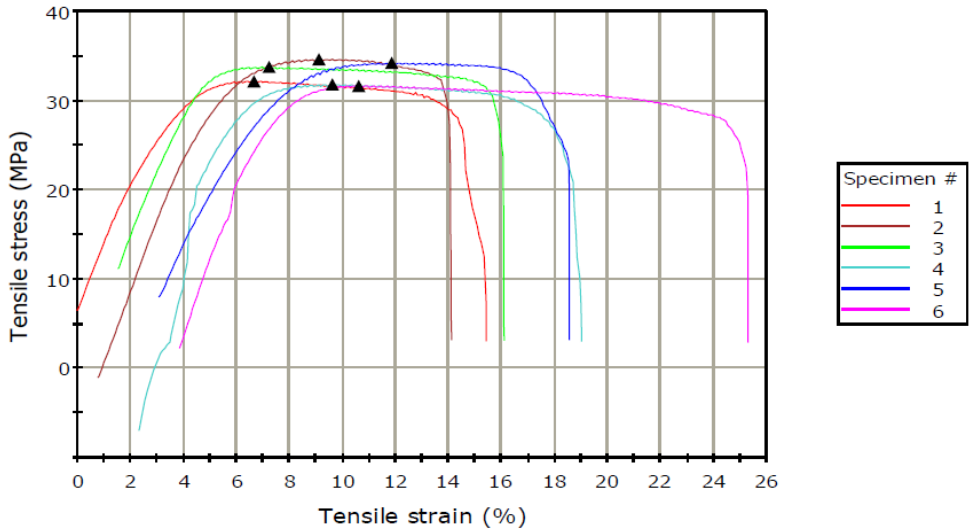


Figure 5-4- UTS measurements for the micro walls made out of POM

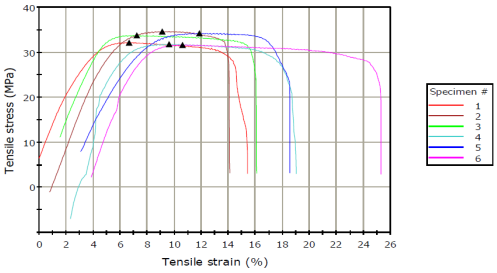
The values are presented in *Table 5-3*. As it can be seen the values used compared to the mean values, and the standard deviation is well below the machine error of 10%.

Table 5-3- UTS values obtained for micro walls made out of POM

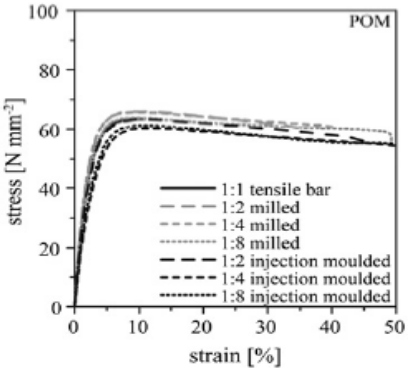
	UTS (MPa)		
	Micro wall number		
	1	***2***	***3***
Measurement 1	31.78	33.74	34.17
Measurement 2	34.61	31.74	31.62
Mean	33.19	32.74	32.89
Standard deviation	2.00	1.41	1.80

5.4.1 Typical UTS curve of replicated micro walls

This section provides an example of the UTS curves for POM and PP and compares the curves and the values with an example in literature review for POM and PP parts made with. *Figure 5-5* shows a comparison of the results obtained with two studies. The first is a study of tensile bars made with conventional injection moulding [99]. The process conditions for both these cases are very similar to those in the current study. Unfortunately as mentioned in the literature review, studying the effect of process parameters on UTS of POM micro bars is a new area and a study with similar processing conditions with similar dimensions could not be found. However, a comparison of the results for micro and conventional injection moulding shows relatively similar curves. However, the values for UTS are nearly twice as much in CIM than those in µIM. As explained in the literature, this is due to the dimension of the cross section of the bars in the two studies. Also, the parts produced in the mentioned study are made under the conditions that do not have weld lines.



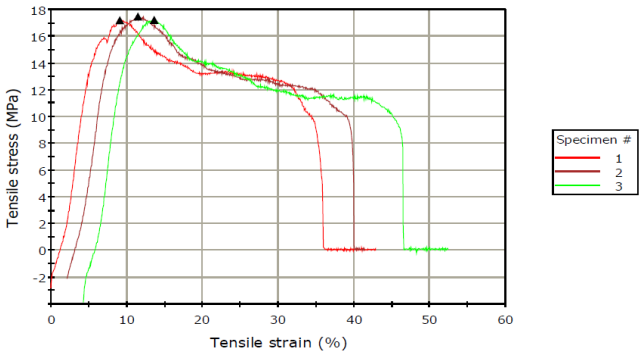
micro injection moulding- study



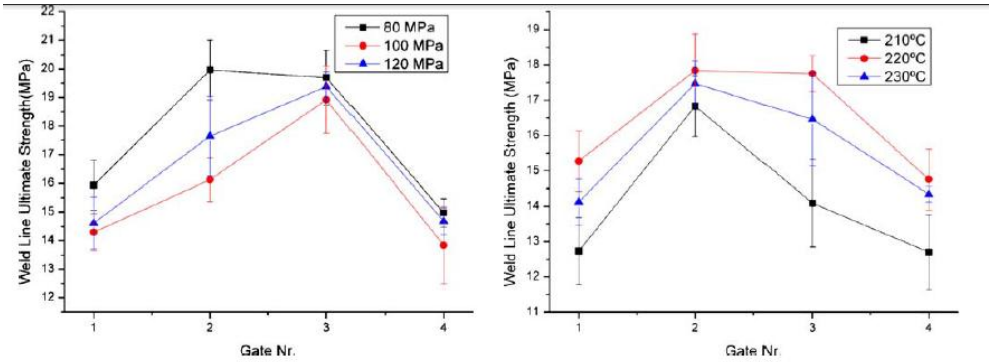
Conventional injection moulding- literature

Figure 5-5- Comparison of the results obtained with conventional and micro injection moulding in the literature for POM

Figure 5-6 shows a typical UTS curve for micro bars made out of PP in this study and an example in the literature [103]. As it can be seen from the figures, the values for UTS are in a similar range. Stress-strain curves for the study were not available.



micro injection moulding- study



UTS of PP parts made by micro injection moulding under different melt temperature and injection pressure

Figure 5-6- Comparison of the results obtained with micro injection moulding in the literature for PP

Figure 5-7 shows the UTS for each micro wall made out of POM, for each combination of the process parameters. The micro walls in the figure are arranged from the one with the highest width (number 1) to the lowest width (number 3).

Figure 5-8 shows the dimensional error for each micro wall made out of PP, for each combination of the process parameters. The arrangement of the number of micro walls is the same as *Figure 5-7* (i.e. highest width is number 1 and lowest width is number 3).

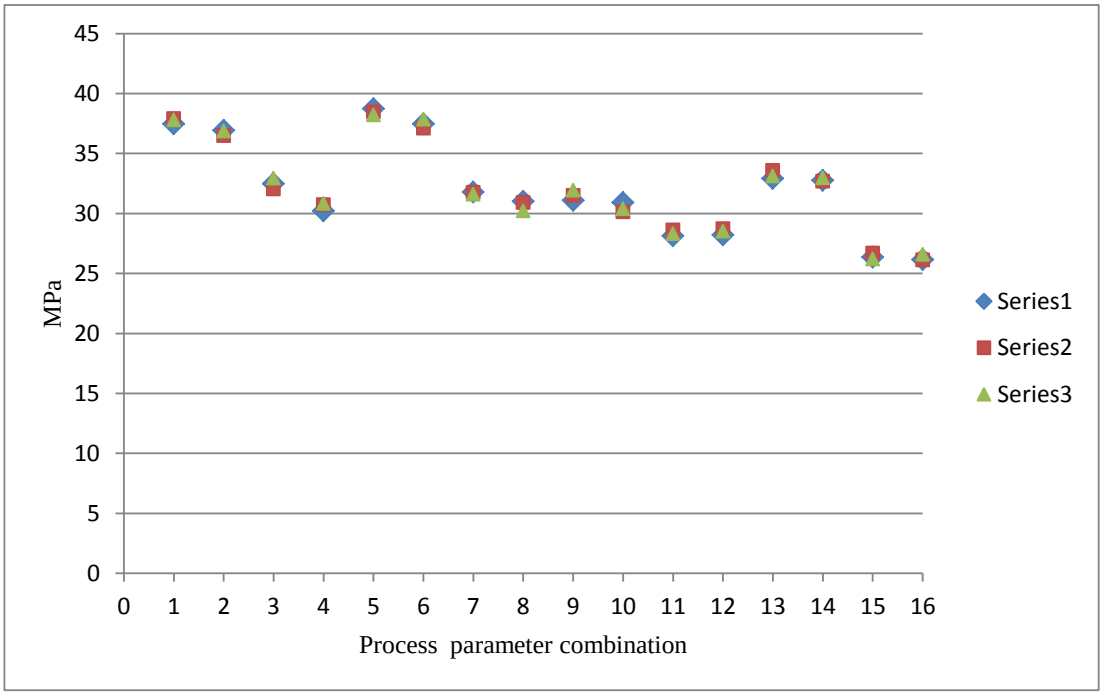


Figure 5-7- UTS for each process parameter combination for POM (MPa)

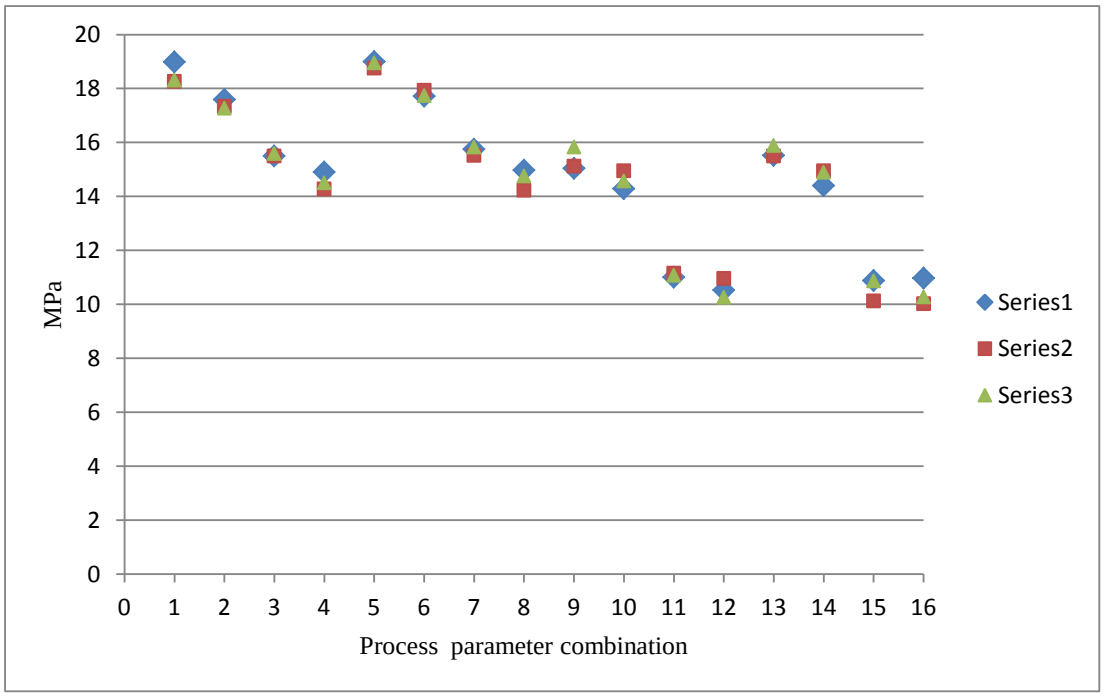


Figure 5-8- UTS for each process parameter combination for PP (MPa)

5.4.2 Statistical analysis

Once the UTSs are obtained statistical analysis is performed to show the effect of each process parameter on the mechanical behavior of each channel. To do this an ANOVA method (Analysis Of Variance) is used. This method is widely used in the industry to investigate the effect of several factors on a response simultaneously. For this purpose, Main effect plots and Pareto charts are used. Main effect plots show the effect of a factor on a response. Pareto charts show the level of influence of a certain factor or its interactions with other factors. To produce these plots Minitab was used. This software is commercially available and is extensively used in the industry for designing and analysing experiments. In this study, factors are the four selected process parameters and the response is dimensional error.

Figure 5-9 to *Figure 5-14* show the Main effect plot and Pareto chart for micro walls 1, 2 and 3, made out of POM. It can be seen from the Main effect plot that polymer melt temperature had the highest effect on the UTS of the micro walls. This is evident by the slope of the line between the two points. Pareto analysis also confirms this by showing that factor A (T_p) has the highest effect. The next most influential factor is the injection velocity. This order is reversed for the third micro wall. Injection pressure has a low effect on UTS in all cases. Mould temperature also has a

low effect for UTS in all cases, with the difference that mould temperature is the only parameter that has a positive effect on the UTS.

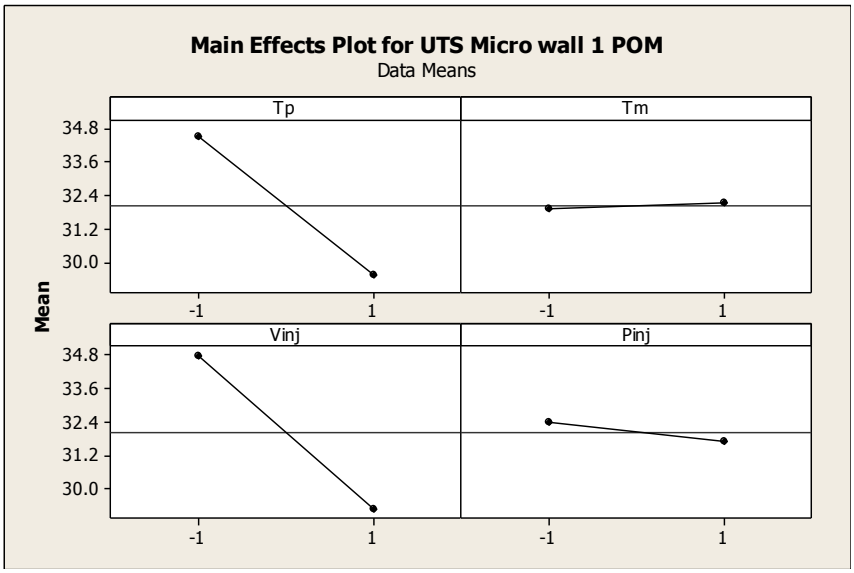


Figure 5-9- Main effect plot for micro wall 1 made out of POM

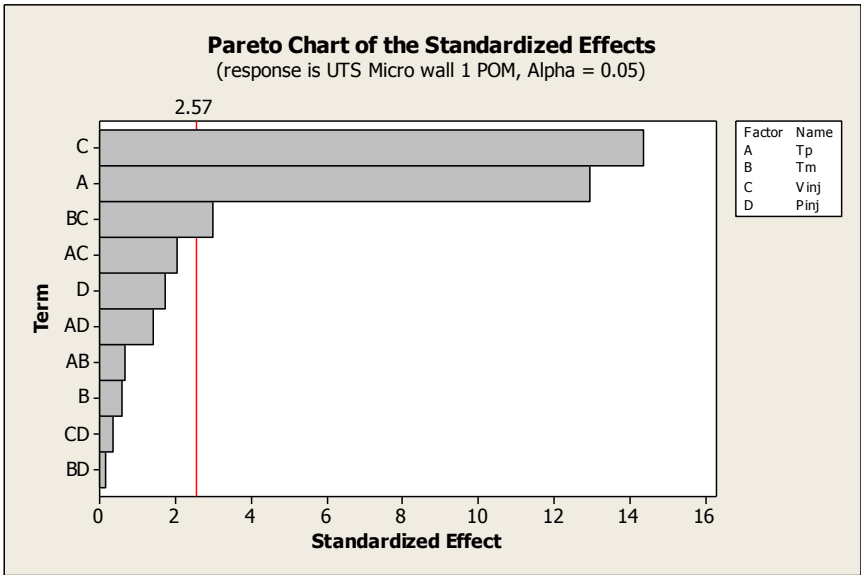


Figure 5-10-Pareto plot for micro wall 1 made out of POM

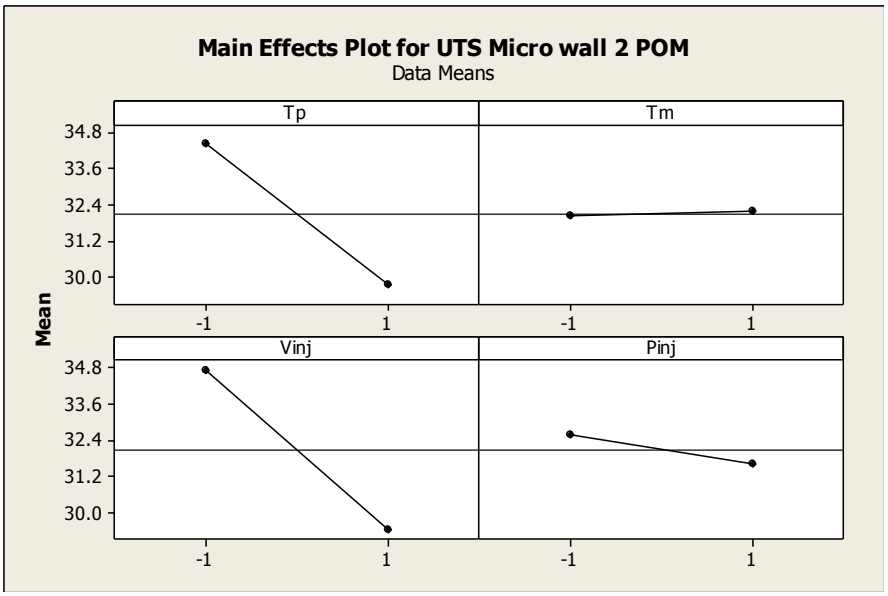


Figure 5-11- Main effect plot for micro wall 2 made out of POM

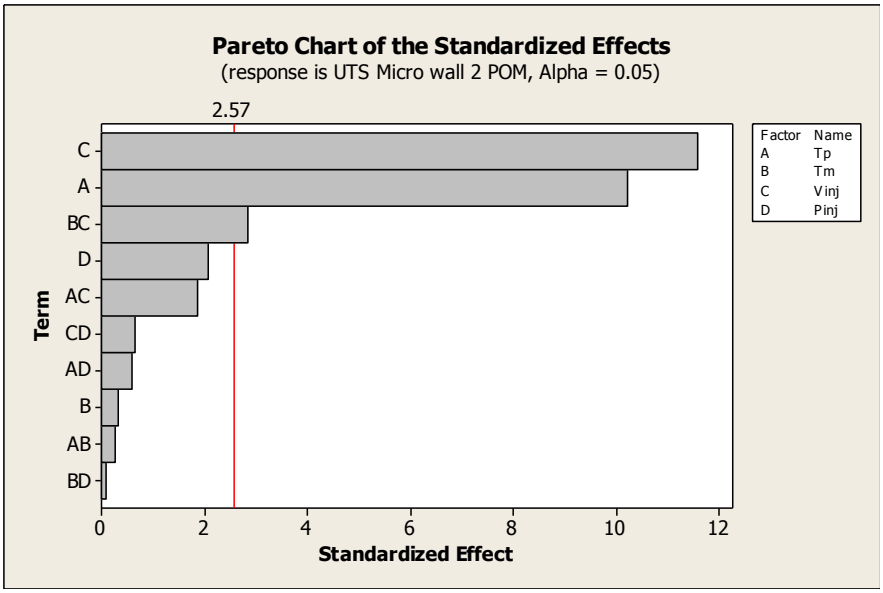


Figure 5-12- Pareto plot for micro wall 2 made out of POM

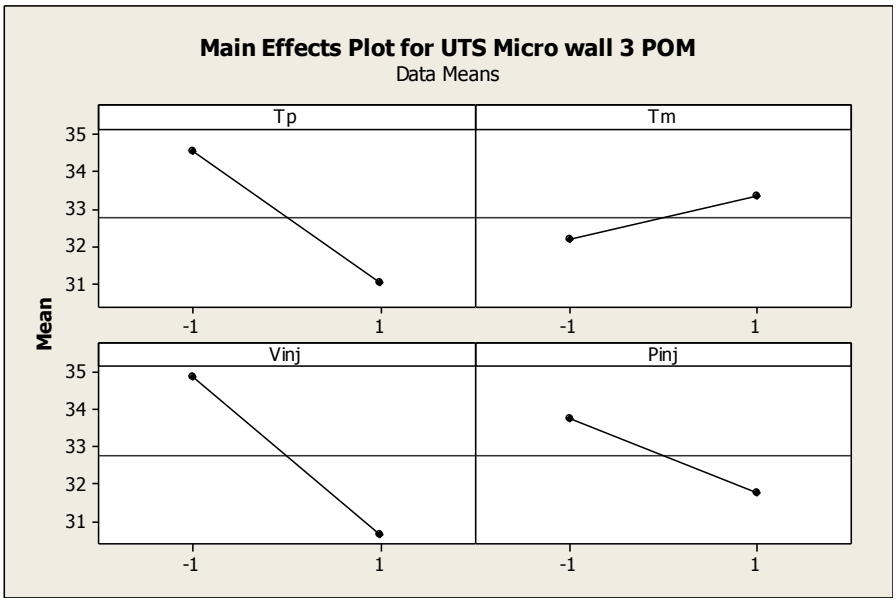


Figure 5-13- Main effect plot for micro wall 3 made out of POM

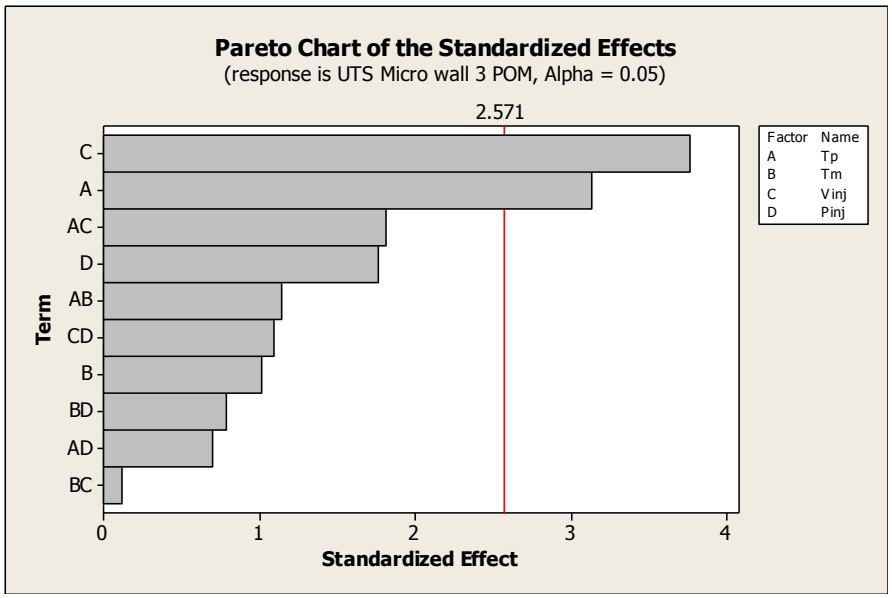


Figure 5-14- Pareto plot for micro wall 3 made out of POM

Figure 5-15 to *Figure 5-20* show the Main effect plot and Pareto chart for micro walls 1, 2 and 3, made out of PP. It can be seen from the Main effect plot that polymer melt temperature had the highest effect on the UTS of the micro walls. Pareto analysis also confirms this by showing that factor A (T_p) has the highest effect. The next most influential factor is the injection velocity followed by injection pressure. The only parameter that has a positive effect on UTS is mould temperature, as was the case with POM. However, mould temperature seems to have a lower effect than seen with POM, this is because PP is less susceptive to changes in temperature.

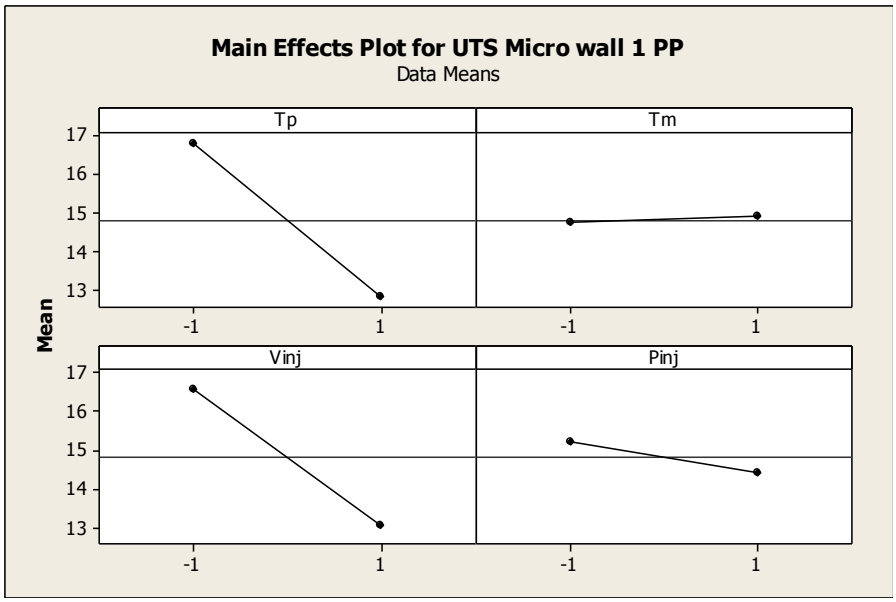


Figure 5-15- Main effect plot for micro wall 1 made out of PP

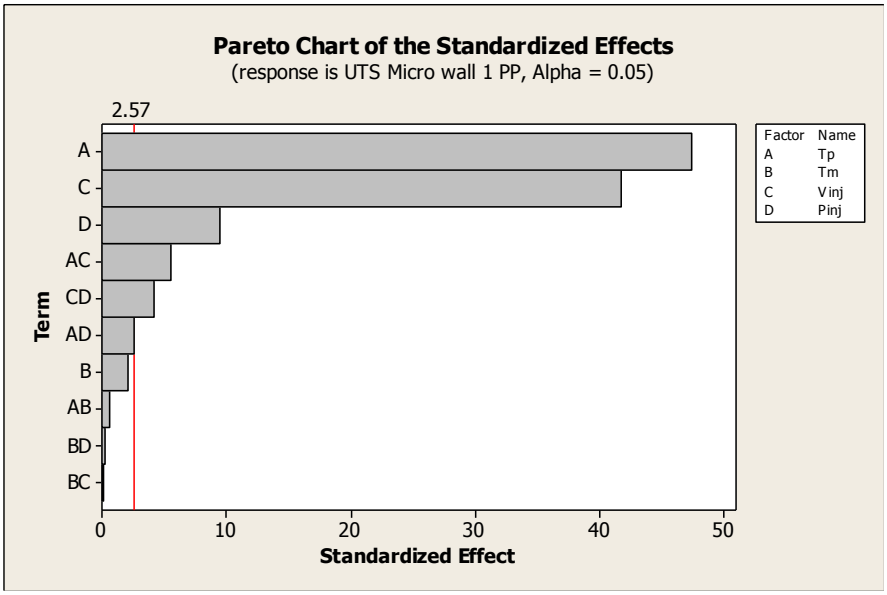


Figure 5-16- Pareto plot for micro wall 1 made out of PP

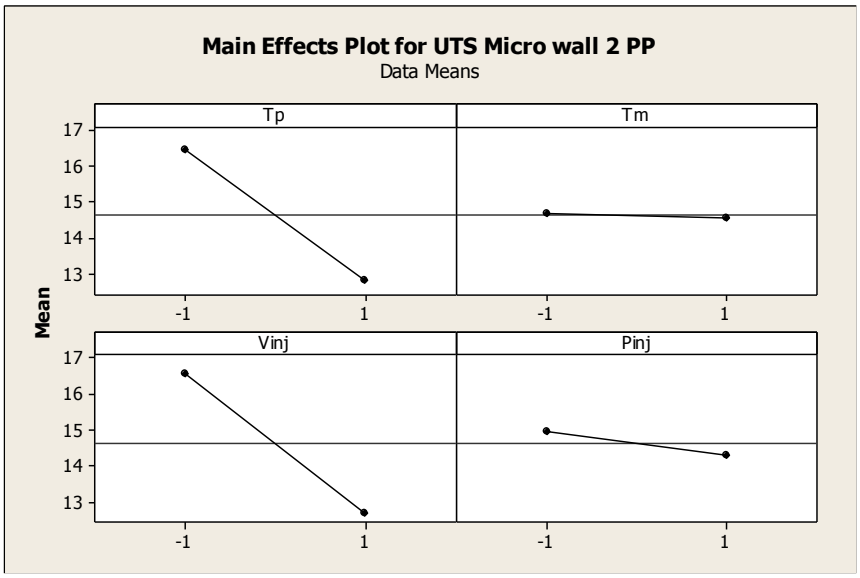


Figure 5-17- Main effect plot for micro wall 2 made out of PP

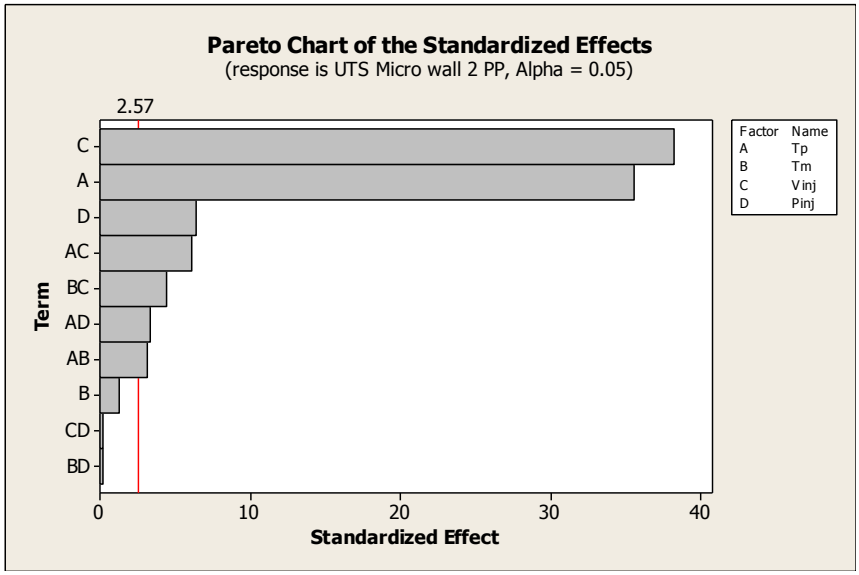


Figure 5-18- Pareto plot for micro wall 2 made out of PP

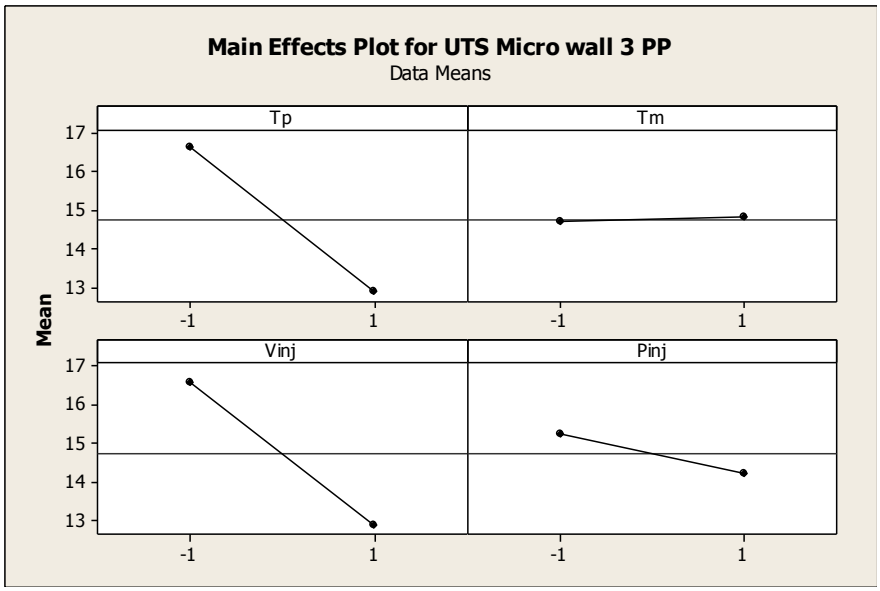


Figure 5-19- Main effect plot for micro wall 3 made out of PP

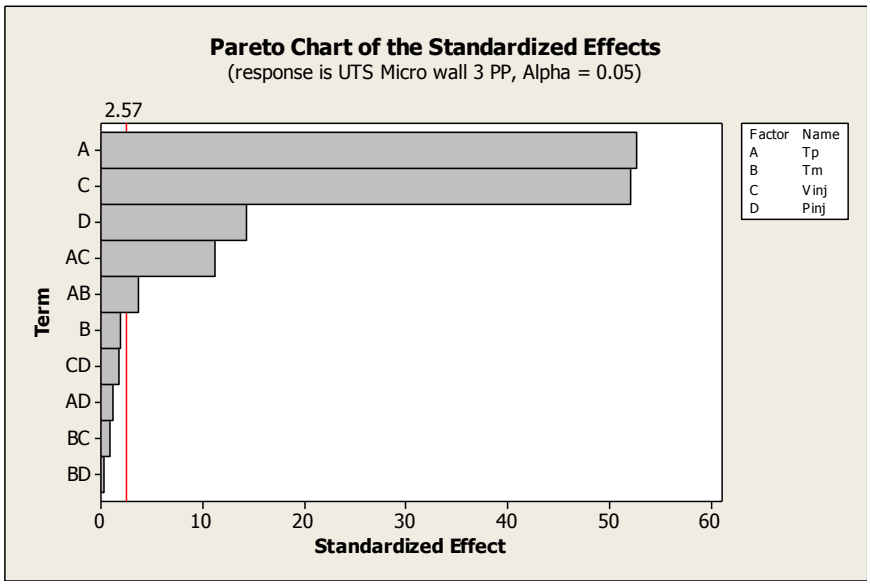


Figure 5-20- Pareto plot for micro wall 3 made out of PP

Similar to **Chapter 4**, for each of the process parameters a set of values are selected to ensure that the trends obtained are correct and the non-linearity does not change the general trend. The values are selected based on *Table 4-7* to ensure minimum variation in dimensions of the micro walls. The results are presented below.

Figure 5-21 shows the effect of polymer melt temperature on the UTS of the micro walls. While the trend is nonlinear, the drop in UTS shows that the trend obtained from statistical analysis is correct for both polymers.

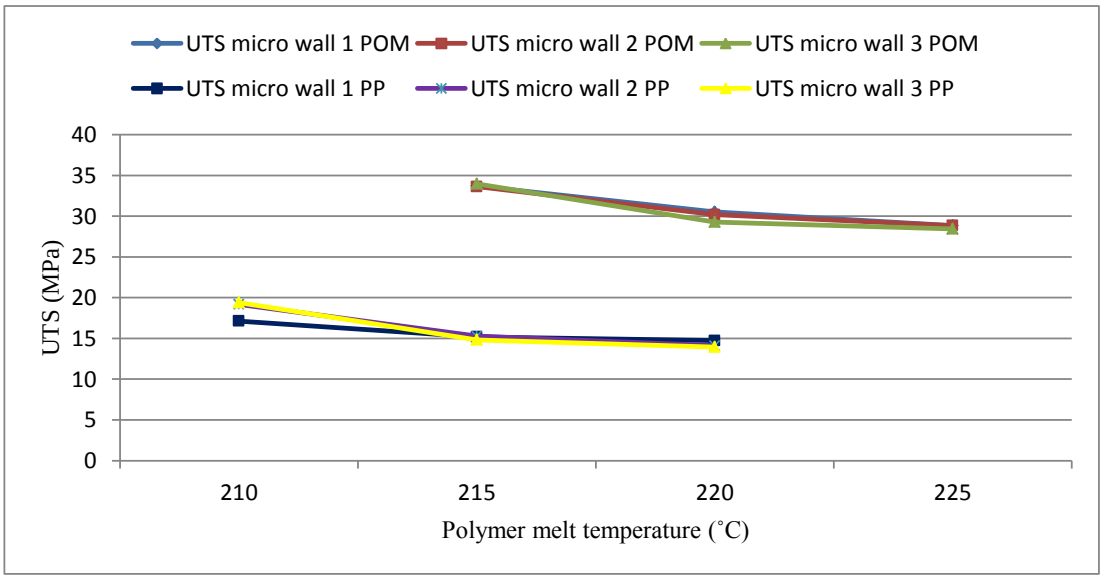


Figure 5-21- Effect of polymer melt temperature on UTS at Tm=100, Vinj=550 and Pinj=700

Figure 5-22 shows the effect of mould temperature on UTS of the three micro walls for POM and PP. Again, while the effect is nonlinear, it shows that as mould temperature increase, so does UTS.

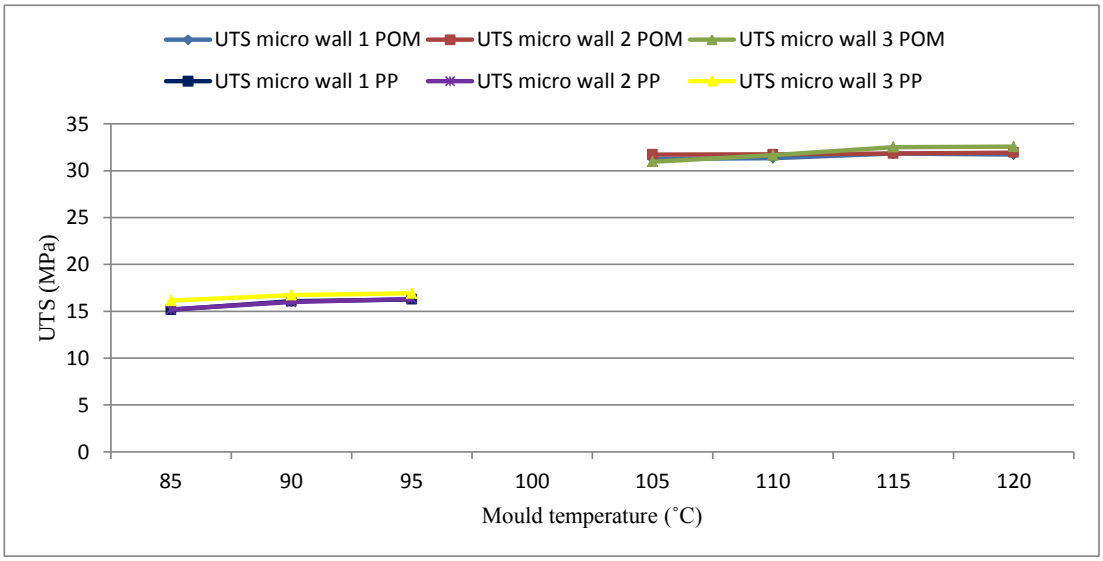


Figure 5-22- Effect of mould temperature on UTS of micro walls at Tp=215, Vinj=550 and Pinj=700

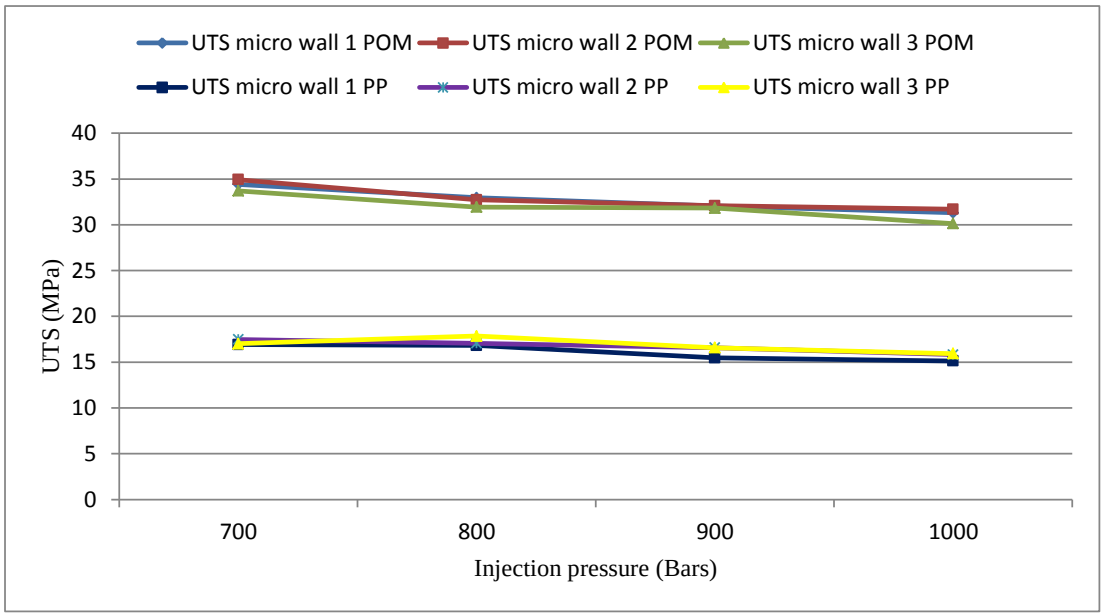


Figure 5-23- Effect of injection pressure on UTS of micro walls at Tp=215, Tm=100 and Vinj=550

Figure 5-23 shows the effect of injection pressure on the UTS of the micro walls. In the case of both materials, the trend shows a slight decline in UTS as pressure increases. The variation in UTS is particularly small for PP.

Figure 5-24 shows the effect of injection velocity on UTS of the micro walls. Again, while the effect is not linear, the trend obtained from statistical analysis is correct and as injection velocity increases, there is a steady decline in UTS.

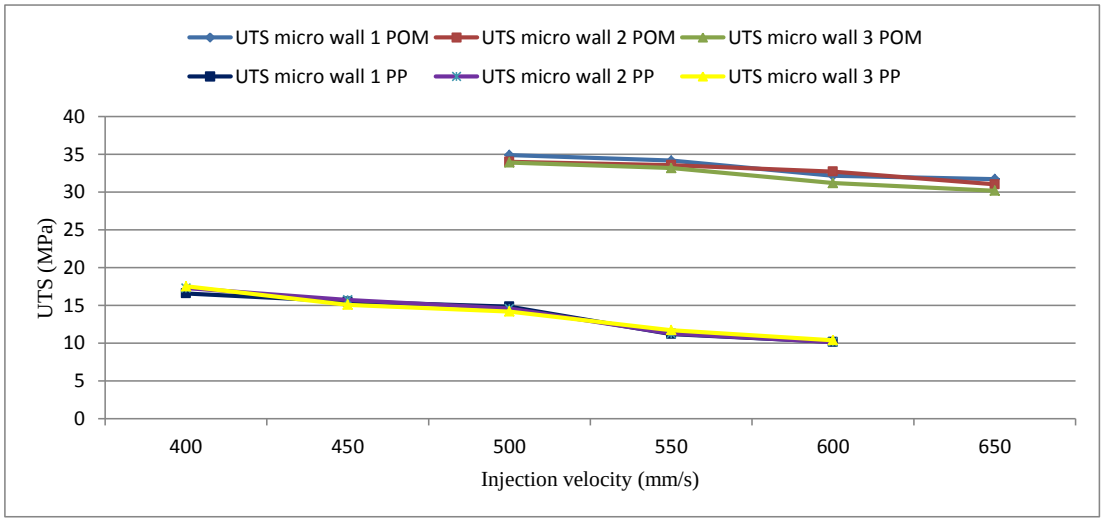


Figure 5-24- Effect of injection velocity on UTS of micro walls at Tp=215, Tm=100 and Pinj=700

5.5 Discussion

5.5.1 Effect of process parameters

Experimental results show that generally, an increase in polymer melt temperature, injection velocity and injection pressure lead to a decrease in the UTS of the micro walls. However, increasing the mould temperature results in higher UTS. These results are evident in the main effect plots. From these plots and the Pareto charts, it can be seen that injection velocity, melt temperature and mould temperature have the highest effects on the UTS of the parts respectively. Injection pressure has little effect on the UTS.

The characterisation of the UTS in this study is highly dependent on the characterisation of the weld lines created in the parts as a result of the mould design. Higher melt temperature results in easier movement of the polymer molecules in a direction. Therefore, the molecules have more freedom of orientation. This is reinforced by the fact that the higher temperature results in slower cooling of the part. This causes the formation of large spherulites which is the reason for reduction of the UTS. In addition to this, because of the higher level of freedom in movement, the molecules are more likely to orientate in different directions at the point of contact between the two flow fronts. Because of the non-uniform orientation of the molecules the strength of bonding between them is smaller and this reduces the UTS. However, the lower melt temperature allows for faster cooling of the parts and restricts the movement of the molecules. Therefore, there is less time for the molecules to move and they are more likely to have an orientation that is more uniform. This is also true at the point of contact where the weld line is formed.

Effect of injection velocity can also be explained by its effect on the formation of weld lines. Increased injection velocity causes the molecules to move faster. At the point of contact between the two flow fronts, when the molecules come in contact with each other, they are more likely to orientate in different directions. This again reduces the bonding strength between the molecules and causes the part to break under lower force. Therefore, the UTS is reduced at higher injection velocities.

At higher mould temperatures polymer melt freezes at a slower rate, which result in lower viscosity. This means that the two polymer front meet when the polymer molecules are free to move and the molecules to bond. This results in stronger bonding of the two polymer fronts and higher UTS. Mould temperature had a smaller effect on the UTS of the PP parts. This is because PP is less susceptible to change in temperature.

5.5.2 Effect of polymers

Comparison of the two materials shows that parts made out of POM have higher UTS. These are shown in *Figure 5-21* to *Figure 5-24*. In all cases, micro walls made out of POM have considerably higher UTS than those made out of PP. This could be contributed to the fact that molecules in PP can flow more easily and thus orientate in more directions than POM. In addition, a comparison of the yield strength of POM with other polymers shows that at higher temperatures, it has higher strength. This is shown in *Figure 5-25*.

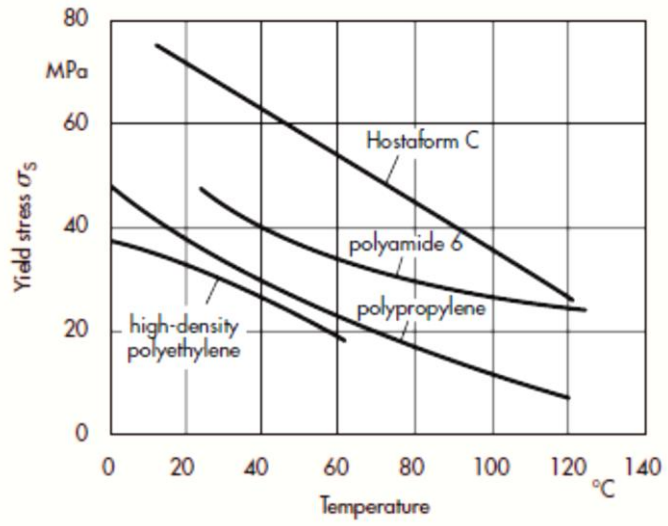


Figure 5-25- comparison of the yield strength of POM and PP [129]

5.5.3 Effect of mould geometry

The size of the micro channels did not have an effect on the UTS of the parts. This is because the channels with higher cross section area broke at a higher maximum load and those with smaller cross section failed at a lower maximum load.

The value of the UTS for the channels is considerably lower than those provided by polymer manufacturer. This is in agreement with other studies and shows that when calculating the UTS for micro parts, the effect of the processing conditions need to be considered and conventional tests cannot be used.

5.6 Chapter summary

The effect of process parameters on the UTS of micro walls was investigated in this chapter. Four process parameters were selected for the investigation. These were polymer melt temperature, mould temperature, injection velocity and injection pressure. These factors were selected because of the effect each of these have on the mechanical behavior of polymers. In addition, to make a comparison of the effects with the previous chapter it was necessary to investigate the same parameters. To investigate the effect of process parameters Taguchi's Design of Experiments was employed in order to identify the effects simultaneously.

The features used in this chapter are the same as those used in **Chapter 4**. This is to ensure that the flow of the polymer melt inside the features remains the same. This is important for making a comparison as changes in the flow direction could cause different effects on the parts. For the same reason, the design of the mould remains the same.

A full factorial DOE was employed to conduct the experiments. Battenfeld Microsystem 50 was used to manufacture the parts. Ten samples were made and discarded in order to allow for stabilisation of the process. The following ten samples were made for data collection. The quality criterion here was the UTS of the micro walls. The values for process parameters were selected based on the results of the previous chapter to ensure that dimensional variation in the channels remained at a minimum level. The pull tests were conducted on an Instron 5969 machine for each of the micro walls.

Minitab 16 was used to conduct the statistical analysis to identify the effect of the four process parameters. Effects of individual parameters were investigated using

Main effect plots. Pareto charts were used to identify the effect of interactions between the parameters, and the strength of the influence of the parameters.

Results showed that an increase in injection velocity and polymer melt temperature had the highest effects on reducing the UTS, while increasing the mould temperature resulted in increased UTS. Injection pressure had a negative effect, however, the effect was not significant. These were confirmed by investigating each process parameter individually at several values.

Micro walls made out of POM proved to have higher strengths.

The understanding obtained in this chapter and the level of interactions and influences presented in the results are used in the next chapter in formation of a model that can predict the UTS of micro walls.

Chapter 6

Chapter 6 Empirical modelling of dimensional accuracy & UTS of micro moulded parts

6.1 Introduction

Extensive research was conducted on the µIM domain and several knowledge gaps were identified and presented in **Chapter 2**. One of the main challenges in this field is to predict if a part can be made and with what dimensional accuracy and what mechanical properties. This highlights the need for a model that can predict the accuracy of a micro moulded part and its mechanical properties, based on the process parameters and the polymer used to manufacture it. Models and simulation tools exist for conventional IM such as MouldFlow and C-MOLD, which can predict the flow of a polymer inside a mould insert cavity. These models were reviewed and it was concluded that they are not suitable for µM. The reasons for this and the important factors resulting in differences in the results were examined and explained [107, 109, 110]. The same arguments are applicable in modelling of the UTS of the parts. Although there have been some studies [8, 98] in modelling of the tensile strength in relation to a specific part, they have focused on specific polymers. Therefore, the focus, and the main contribution of this study is to generate a model that can predict the accuracy of a micro moulded part and one that can predict its UTS. In these models dimensional accuracy and UTS are functions of the process parameters used, the machine, and the polymer used. Such models are useful because they reduce the need to conduct enormous number of experiments to investigate if a part can be made to the required accuracy and mechanical properties. This will significantly reduce the cost and effort required to develop or manufacture a product.

This chapter describes the work undertaken in this study to generate these models. Firstly the parameters and requirements of the model are identified based on the results of previous studies, the product and machine. A method is then identified to find a relationship between the parameters. This method is then employed to create general models in the form of mathematical equations. Then the results of experiments are used to find the constants of the equations, and create a model specifically for the problem definition of this study. This is shown in *Figure 6-1*.

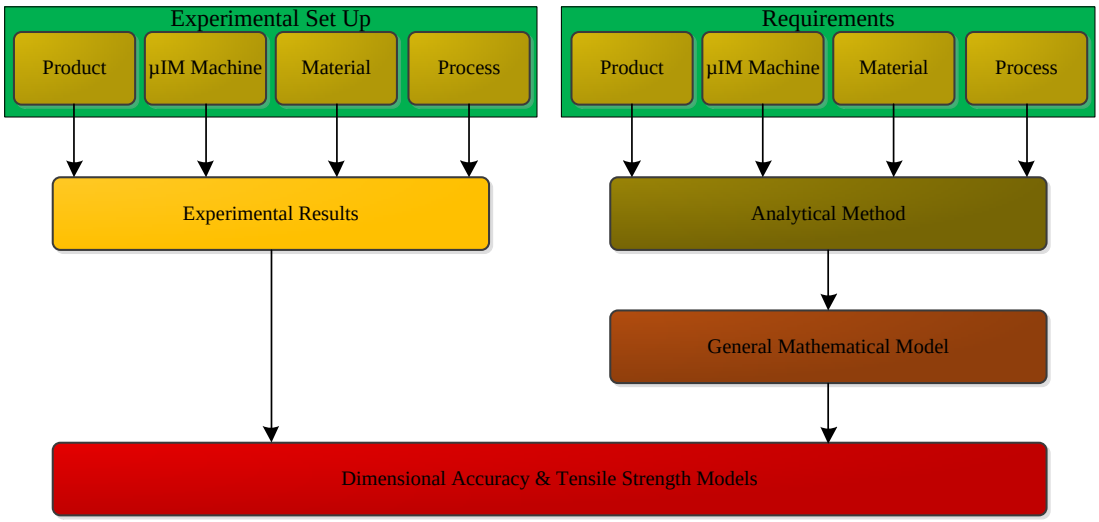


Figure 6-1- Formation of models based on machine, polymer and product characteristics

Different mould designs, runners, gate dimensions and features result in different accuracies. However, due to limited time and resources it is out of the scope of this work to investigate all these factors. Therefore, the mould used for the purpose of the experiments, is that used in the previous chapters with the same geometry as shown in *Figure 4-6*; and the set up and design of the mould used is that shown in *Figure 4-3*. This is so that the empirical analysis that is used in this chapter is in synchronization with the previous chapters.

First, the method for construction of the model is identified and introduced and the reasoning behind the application of this method for the purpose of this study is explained. Applying the method to µIM provides a general mathematical model, which can then be tailored to the problem definition of this study, by using empirical data.

6.2 Dimensional analysis

6.2.1 Nature of dimensional analysis

In investigating a physical phenomenon researchers often try to form equations using mathematical analysis. The reason for this is that analytical equations are correct for any system of units. This results in each group of terms in the equation having the same dimensional representation. This is the *law of dimensional homogeneity*. This law can be used to form equations where a relationship between several variables is

unknown. By using a procedure called *dimensional analysis* a set of dimensionless groups can be formed and a relationship between them can be formed. The advantage of this method is that the number of experiments required to find the relationship is greatly reduced [130]. This reduces the cost and time that one has to spend to be able to form the required function. An example is employed here to explain the advantages of dimensional analysis over a purely empirical approach. This is to determine a relationship between five variables of *Y*, *X*, *Z*, *O* and *B*, where *Y* would be stated as a function of the other four variables.

$$Y=f\,(X, Z, O, B)$$

To determine the mathematical relationship between the variables empirically, an enormous number of experiments have to be conducted. This is because only one variable can be changed at a time to achieve many plots. A possible solution can be seen in *Figure 6-2* where *Y* is plotted against *X* for various values of *Z*. However, each diagram corresponds to a specific value of *O* and *B*.

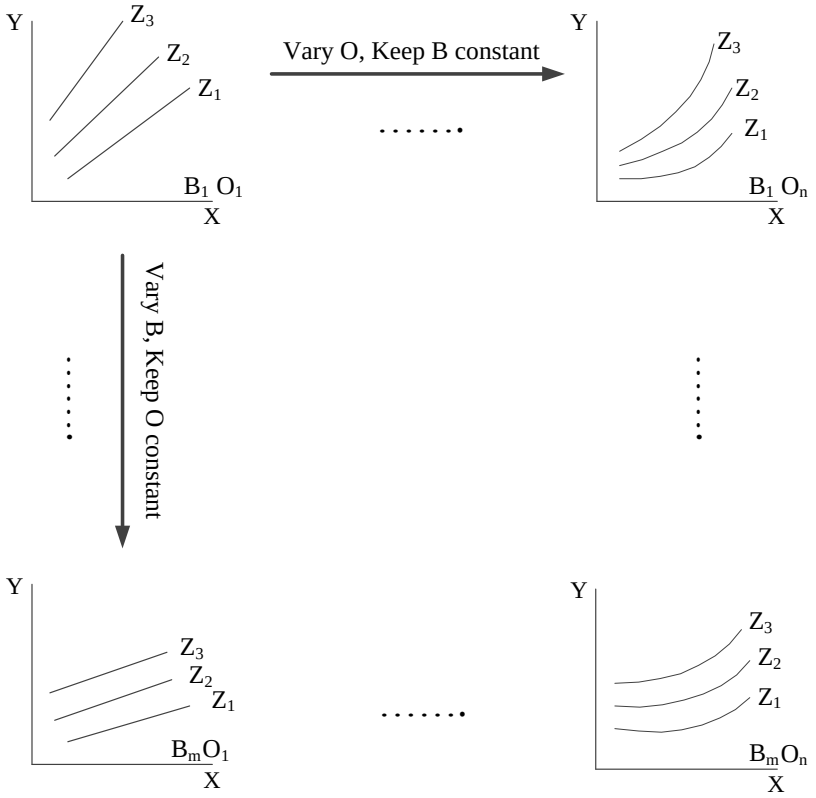


Figure 6-2- Plots required forming an equation between Y and X

In addition, depending on the nature of the experiments and the physical phenomena being modelled, several conditions for each of the variables need to be considered (e.g. limits on the values). Thus approaching this problem with experiments alone is a very time-consuming and costly investigation.

Dimensional analysis allows for a general equation to be formed analytically. This general equation would be valid because the same unit system is used for all groups of expressions in the equation. Going back to the above example, assuming two dimensionless groups of $\pi_1 = \frac{Y}{BOZ}$ and $\pi_2 = \frac{OBX}{Z}$ exist, a plot can be formed between the two expressions, where

$$\pi_1 = f(\pi_2)$$

Therefore,

$$\frac{Y}{BOZ} = f(\frac{OBX}{Z})$$

Where the function *f* is unknown. This is shown in *Figure 6-3*.

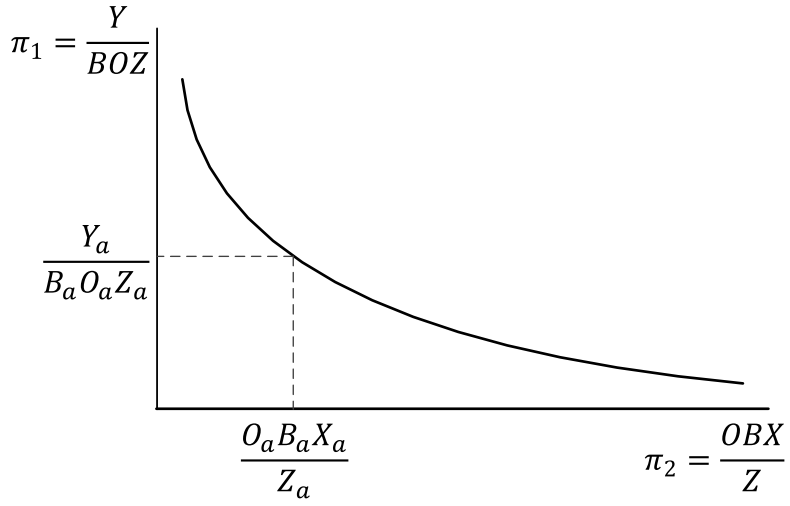


Figure 6-3- Plot of the two dimensionless numbers

While the nature of the function between π_1 and π_2 is not known having values for each of the variables in π_2 gives a value for π_1. This makes it much less costly and time consuming to obtain a function between the variables. In addition, since the

groups are dimensionless, the function is correct for any physical phenomena. To be able to form a relationship between the variables through dimensional analysis the number of dimensionless groups needs to be identified.

6.2.2 Buckingham's π Theorem

Buckingham's π Theorem is used to identify the number of dimensionless groups required to find a relationship between several variables. According to Buckingham's π Theorem, "the number of independent dimensionless groups that may be employed to describe a phenomenon known to involve *n* variables is equal to the number *n-r*, where *r* is usually the number of basic dimensions needed to express the variables dimensionally" [130, 131]. There are two main systems of basics dimensions. The first is *MLTθ* which represents mass, length, time and temperature. The second is *FLTθ* which represents force, length, time and temperature. In this study the former, which is more commonly used in SI systems, is used. In the previous example, there are five variables so *n*=5; and assuming the basic dimensions are *MLT* (meaning none of the variables contain the basic dimension of temperature θ), *r*=3. Therefore, two dimensionless groups are required to form the equation. Buckingham's π theorem states that there can be no more dimensionless groups that can be employed. Any other group developed, can be derived mathematically from the two already formed.

However, the computation of *r* is not always correct based on the theorem [130]. For instance in stress analysis where problems include force and length, two expressions are required based on *FLTθ* (*F* and *L*) and three based on *MLTθ* (*M*, *L* and *T*). Nevertheless, there is a procedure that can be used for determining the correct value of *r*. The variables *Y*, *X*, *Z*, *O* and *B* are listed on a horizontal axis and the basic dimensions (e.g. M, L and T) are listed on a vertical one, such as *Figure 6-4*. The numbers for each variable are then added below them and in front of the dimension. These are the power of each basic dimension for the particular variable. Based on the figure, variable *Y* has the dimensions of MT^2/L while *O* has the dimensions of L^2T.

	Y	*X*	*Z*	*O*	*B*
M	1	0	3	0	1
L	-1	-2	1	2	1
T	2	1	1	1	1

Figure 6-4- Dimensions of variables for calculation of "r"

The matrix that is formed from these numbers is called the "*dimensional matrix*"[130]. For the example above, this matrix is

$$\begin{bmatrix} 1 & 0 & 3 & 0 & 1 \\ -1 & -2 & 1 & 2 & 1 \\ 2 & 1 & 1 & 1 & 1 \end{bmatrix}$$

The determinant of a matrix can only be calculated if it has the same number of rows and columns. Therefore, the above matrix has to be squared up, by adding two rows of zeros, so the determinant can be obtained. However, the determinant of such a matrix is zero. The size of the next smaller matrix that has a determinant other than zero is the rank of the dimensional matrix. In the above example, the next square matrix with the determinant other than zero is one with three rows and columns. Several possibilities exist for this example. However, if the first three rows are assumed, the determinant becomes

$$\begin{vmatrix} 1 & 0 & 3 \\ -1 & -2 & 1 \\ 2 & 1 & 1 \end{vmatrix} = 6$$

making the rank of the dimensional matrix three. The correct value of *r* in Buckingham π's theorem is equal to the rank of the dimensional matrix [130]; in this case three.

Once the number of required dimensionless groups is identified, the groups themselves can be formed. Firstly, a set of repeatable and non-repeatable variables have to be selected. Each non-repeatable variable can only exist in one dimensionless group. This is because if several variables exist in several groups at the same time, forming a function or a plot becomes considerably more difficult. Once repeatable and non-repeatable variables are selected, the dimensionless groups of π_1, π_2, … π_n can be calculated. For each π one non-repeatable and the repeatable variables are

used to form the group. The power of the non-repeatable variable is kept as one and the other variables have unknown powers of *a*, *b*, *c*, etc. However, the powers can be calculated by writing the dimension of the variables in the groups. These powers are then found by adding the powers for the same basic dimensions and making them equal to zero. Then solving the equations will provide the value of the powers. Once the dimensionless groups are formed, one becomes a function of the others:

$$\pi_1 = f(\pi_2, \pi_3, \ldots)$$

In the example in *Figure 6.3*, a dimensionless group with variables *Y*, *B*, *O* and *Z* is formed, where *Y* is the non-repeatable variable and the other three are repeatable. Based on *Figure 6.3* each of the variables has the following dimension:

$Y \equiv ML^{-1}T^2$
$B \equiv MLT$
$O \equiv L^2T$
$Z \equiv M^3LT$

Y has the power of one and *B*, *O* and *Z* have the powers *a*, *b* and *c* respectively. Therefore π_1 is

$$\pi_1 = YB^aO^bZ^c$$

The value of the powers is calculated by replacing each variable with its dimensions.

$$YB^aO^bZ^c \equiv (ML^{-1}T^2)(MLT)^a(L^2T)^b(M^3LT)^c$$

For π_1 to be dimensionless the sum of the powers for each basic dimension has to be zero. Therefore,

L: $-1 + a + 2b + c = 0$
M: $1 + a + 3c = 0$
T: $2 + a + b + c = 0$

Solving these equations gives the values for *a*, *b* and *c*. This results in identification of the dimensionless expression of π_1.

It must be noted that while this method is widely used for determining the relationship between several variables, it does not seem to have been applied for modelling in CIM. This could be due to the fact that PVT data and conventional equations used for analysis of the flow and viscosity can successfully be applied to CIM, due to the considerably larger dimensions of the features and runners in CIM. Even application of the technique for modelling and determination of polymer viscosity has been limited to parts with dimensions considerably larger than those investigated in this study. This seems to be the first time this technique is used for modelling dimensional accuracy and UTS in µIM.

6.3 Use of dimensionless analysis in construction of the empirical model for dimensional accuracy of µIM parts

In this section the procedure for formation of the empirical accuracy model is explained. Firstly, a general model is formed based on the procedure explained above. Then the constants and powers of the general equation are explained. These are calculated based on empirical data obtained from the planned experiments.

6.3.1 Construction of the general accuracy model

Dimensional analysis is used in this study to form the model for predicting the dimensional accuracy of micro moulded parts. In this model change in dimension of the parts is a function of the process parameters and characteristics of the machine, and the physical properties of polymers. Advantages of dimensional analysis in creation of a model over purely empirical methods were discussed earlier in the chapter. In this section the application of dimensionless analysis and Buckingham's π theorem to µIM is described.

The selected variables from the process, machine, polymer and product are shown in *Figure 6-5*.

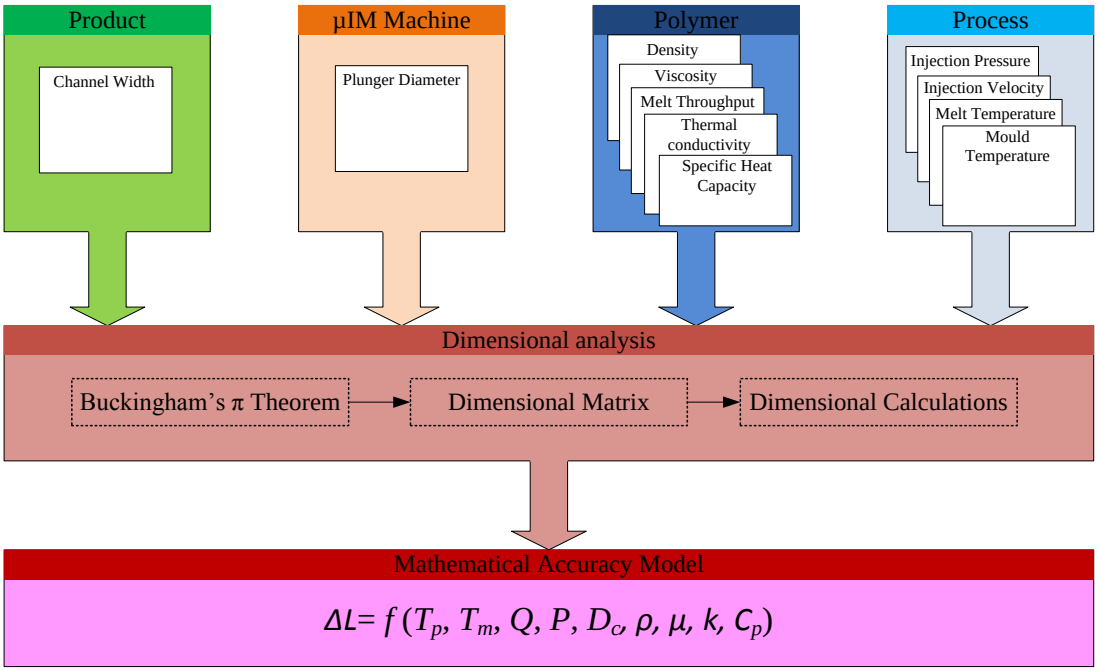


Figure 6-5- Variables used in formation of the accuracy model

Effect of viscosity on the filling of the cavities and on the dimensional accuracy of micro moulded parts was discussed in **Chapter 4**. Therefore, the main factor in selection of the variables is the effect they have on viscosity. The variables selected from the process, are those investigated in **Chapter 4**. These are polymer melt temperature at the nozzle (T_p), injection velocity (V_{inj}), injection pressure (P_{inj}) and mould temperature (T_m). There are several characteristics of the machine that can be considered for the purpose of this model, however in this case characteristics have been selected on the basis that they affect the viscosity of the polymer. *Equation 5.3* shows that viscosity of the polymer is affected by the plunger diameter (D_p). Moreover, plunger diameter is one of the common factors in the characterisation of a µIM machine. Transfer of heat between the melt and the mould wall also affects the viscosity of the melt. Loss of heat from polymer melt reduces its temperature and results in an increase in viscosity. Therefore, the physical characteristics of the polymer, considered in the model, are density (ρ), specific heat capacity (C_p) and thermal conductivity (k). Melt throughput (Q) and viscosity (µ) are also considered in this model. Several sections of the part can be considered and used to measure the dimensional error. However, the width of the micro channels in the middle are those with the smallest micro dimensions. The width of the micro channels are also the only section of the part that vary in the part produced in this study. This is a necessity

for the model if it is to cover a range of dimensions. Therefore, the selected characteristic of the part is the width of the channels (D_c).

In order to simplify the model and reduce the number of variables, some of the variables are put together. Injection velocity and plunger diameter are represented by the melt throughput in the model. Melt throughput is defined as

$$Q = \frac{\pi V D_p^2}{4} \qquad \textit{Equation 6.1}$$

And dimensional error is represented as

$$\Delta L = L_m - L_p \qquad \textit{Equation 6.2}$$

where L_m is the width of the channel on the pin (mould inserts) and L_p is the width of the channel on the moulded part.

The variables used in the proposed model and their dimensions are summarised in *Table 6-1*.

Table 6-1- Variables used in the accuracy model and their dimensions

Variable	***Notation***	***Dimension***
Dimensional error	ΔL	L
Polymer melt temperature	T_p	θ
Mould temperature	T_m	θ
Melt throughput	Q	L^3T^{-1}
Injection pressure	P	$ML^{-1}T^{-2}$
Channel width	D_c	L
Polymer density	ρ	ML^{-3}
Viscosity	μ	$ML^{-1}T^{-1}$
Polymer's thermal conductivity	k	$MLT^{-3}\theta^{-1}$
Polymer's specific heat capacity	C_p	$L^2T^{-2}\theta^{-1}$

The general equation is,

$$\Delta L = f(T_p, T_m, Q, P, D_c, \rho, \mu, k, C_p) \qquad \textit{Equation 6.3}$$

There are nine variables with four basic dimensions (M, L, T and θ). According to Buckingham's π Theorem the number of dimensionless groups is six (10-4=6) which are π_1, π_2, π_3, π_4, π_5 and π_6. Due to the fact that Buckingham's π Theorem may not result in correct value for "r", one must validate the number of dimensionless groups by formation of the dimensional matrix. This is shown below in *Figure 6-6*.

	ΔL	T_p	T_m	Q	P	D_c	ρ	μ	k	C_p
L	1	0	0	3	-1	1	-3	-1	1	2
M	0	0	0	0	1	0	1	1	1	0
T	0	0	0	-1	-2	0	0	-1	-3	-2
θ	0	1	1	0	0	0	0	0	-1	-1

Figure 6-6- Dimensions of the variables in μIM accuracy model

The dimensional matrix is then

$$\begin{bmatrix} 1 & 0 & 0 & 3 & -1 & 1 & -3 & -1 & 1 & 2 \\ 0 & 0 & 0 & 0 & 1 & 0 & 1 & 1 & 1 & 0 \\ 0 & 0 & 0 & -1 & -2 & 0 & 0 & -1 & -3 & -2 \\ 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & -1 & -1 \end{bmatrix}$$

Following the method introduced previously, the least number of columns and rows that result in a determinant of a number other than zero is clearly four (e.g. last five rows). Therefore, the rank of the dimensional matrix, and the value of *r*, is four. So six dimensionless groups (*n*-*r*=10-4=6) are required to form the mathematical equation that predicts the dimensional error as a function of the other eight variables. This confirms that in this case Buckingham's π theorem was correct.

Once the number of dimensionless groups is identified one can form them by dimensional analysis. The six dimensionless groups require six non-repeatable variables. These are selected in a manner to isolate the process parameters, dimensional error and a polymer characteristic. These variables are T_p, T_m, Q (which includes the injection velocity) and P from the process, ΔL as the output of the model and K from the polymer. Therefore, there are four repeatable variables; D_c, C_p, μ and ρ. Each of the non-repeatable variables exists in one dimensionless group, with the four repeatable ones. Therefore, π_1 is calculated as:

$$\pi_1 = \Delta L D_c^a \rho^b \mu^c C_p^d \equiv L\, L^a\, (ML^{-3})^b\, (ML^{-1}T^{-1})^c\, (L^2T^{-2}\theta^{-1})^d \qquad \textit{Equation 6.4}$$

Since π_1 is a dimensionless number, the sum of the powers for M, L, T and θ should be zero. Therefore,

$$\text{L: } 1 + a - 3b - c + 2d = 0 \qquad \textit{Equation 6.5}$$

$$\text{M: } b + C = 0 \qquad \textit{Equation 6.6}$$

$$\text{T: } -c - 2d = 0 \qquad \textit{Equation 6.7}$$

$$\theta\text{: } -d = 0 \qquad \textit{Equation 6.8}$$

By solving the above equations, values for d, c, and b are zero and $a = -1$. Therefore,

$$\pi_1 = \Delta L D_c^{-1} \rho^0 \mu^0 C_p^0$$

$$\pi_1 = {}^{\Delta L}/_{D_c} \qquad \textit{Equation 6.9}$$

This procedure is then carried out for each of the non-repeatable variables to form the dimensionless groups. So π_2 is calculated as:

$$\pi_2 = T_p D_c^a \rho^b \mu^c C_p^d \equiv \theta\, L^a\, (ML^{-3})^b\, (ML^{-1}T^{-1})^c\, (L^2T^{-2}\theta^{-1})^d \qquad \textit{Equation 6.10}$$

Since π_2 is a dimensionless number, the sum of the powers for M, L, T and θ should be zero. Therefore,

$$\text{L: } a - 3b - c + 2d = 0 \qquad \textit{Equation 6.11}$$

M: $b + C = 0$ *Equation 6.12*

T: $-c - 2d = 0$ *Equation 6.13*

θ: $1 - d = 0$ *Equation 6.14*

solving these equations gives, $d = 1$, $c = -2$, $b = 2$ and $a = 2$. Therefore,

$$\pi_2 = T_p D_c^2 \rho^2 \mu_0^{-2} C_p^1$$

$$\pi_2 = \frac{T_p D_c^2 \rho^2 C_p}{\mu^2} \quad \textit{Equation 6.15}$$

π_3 is calculated as:

$$\pi_3 = T_m D_c^a \rho^b \mu^c C_p^d \equiv \theta\, L^a\, (ML^{-3})^b\, (ML^{-1}T^{-1})^c\, (L^2T^{-2}\theta^{-1})^d \quad \textit{Equation 6.16}$$

Since π_2 is a dimensionless number, the sum of the powers for M, L, T and θ should be zero. Therefore,

L: $a - 3b - c + 2d = 0$ *Equation 6.17*

M: $b + C = 0$ *Equation 6.18*

T: $-c - 2d = 0$ *Equation 6.19*

θ: $1 - d = 0$ *Equation 6.20*

solving these equations gives, $d = 1$, $c = -2$, $b = 2$ and $a = 2$. Therefore,

$$\pi_3 = T_m D_c^2 \rho^2 \mu_0^{-2} C_p^1$$

$$\pi_3 = \frac{T_m D_c^2 \rho^2 C_p}{\mu^2} \quad \textit{Equation 6.21}$$

π_4 is calculated as:

$$\pi_4 = Q D_c^a \rho^b \mu^c C_p^d \quad \textit{Equation 6.22}$$
$$\equiv (L^3T^{-1})\, L^a\, (ML^{-3})^b\, (ML^{-1}T^{-1})^c\, (L^2T^{-2}\theta^{-1})^d$$

Since π_3 is a dimensionless number, the sum of the powers for M, L, T and θ should be zero. Therefore,

L: $3 + a - 3b - c + 2d = 0$ *Equation 6.23*

M: $b + C = 0$ *Equation 6.24*

T: $-1 - c - 2d = 0$ *Equation 6.25*

θ: $-d = 0$ *Equation 6.26*

Solving these equations gives, $d = 0$, $c = -1$, $b = 1$ and $a = -1$. Therefore,

$$\pi_4 = QD_c^{-1}\rho^1\mu^{-1}C_p^0$$
$$\pi_4 = \frac{Q\rho}{\mu D_c} \quad \textit{Equation 6.27}$$

π_5 is calculated as:

$$\pi_5 = PD_c^a\rho^b\mu^c C_p^d \quad \textit{Equation 6.28}$$
$$\equiv (ML^{-1}T^{-2})\ L^a\ (ML^{-3})^b\ (ML^{-1}T^{-1})^c\ (L^2T^{-2}\theta^{-1})^d$$

Since π_4 is a dimensionless number, the sum of the powers for M, L, T and θ should be zero. Therefore,

L: $-1 + a - 3b - c + 2d = 0$ *Equation 6.29*

M: $1 + b + C = 0$ *Equation 6.30*

T: $-2 - c - 2d = 0$ *Equation 6.31*

θ: $-d = 0$ *Equation 6.32*

Solving these equations gives $d = 0$, $c = -2$, $b = 1$ and $a = 2$. Therefore,

$$\pi_5 = PD_c^2\rho^1\mu^{-2}C_p^0$$
$$\pi_5 = \frac{PD_c^2\rho}{\mu^2} \quad \textit{Equation 6.33}$$

π_6 is calculated as:

$$\pi_6 = KD_c^a\rho^b\mu^c C_p^d \quad \textit{Equation 6.34}$$
$$\equiv (MLT^{-3}\theta^{-1})\ L^a\ (ML^{-3})^b\ (ML^{-1}T^{-1})^c\ (L^2T^{-2}\theta^{-1})^d$$

Since π_5 is a dimensionless number, the sum of the powers for M, L, T and θ should be zero. Therefore,

L: $1 + a - 3b - c + 2d = 0$ *Equation 6.35*

M: $1 + b + C = 0$ *Equation 6.36*

T: $-3 - c - 2d = 0$ *Equation 6.37*

θ: $-1 - d = 0$ *Equation 6.38*

Solving these equations gives,$d = -1$, $c = -1$, $b = 0$ and $a = 0$. Therefore,

$$\pi_6 = K D_c^0 \rho^0 \mu^{-1} C_p^{-1}$$

$$\pi_6 = \frac{K}{\mu C_p} \quad \textit{Equation 6.39}$$

If the calculations are performed correctly, π_1, π_2, π_3, π_4, π_5 and π_6 must be dimensionless. To validate that the performed equations are correct, dimensions of each of the groups is calculated:

$$\pi_1 = {\Delta L}/{D_c} \equiv {L}/{L} = 1$$

$$\pi_2 = \frac{T_p D_c^2 \rho^2 C_p}{\mu^2} \equiv \theta L^2 \frac{M^2}{L^6} \frac{M^{-2}}{L^{-2}T^{-2}} \frac{L^2}{T^2\theta} = 1$$

$$\pi_3 = \frac{T_m D_c^2 \rho^2 C_p}{\mu^2} \equiv \theta L^2 \frac{M^2}{L^6} \frac{M^{-2}}{L^{-2}T^{-2}} \frac{L^2}{T^2\theta} = 1$$

$$\pi_4 = \frac{Q\rho}{\mu D_c} \equiv \frac{L^3}{T} L^{-1} \frac{M}{L^3} \frac{M^{-1}}{L^{-1}T^{-1}} = 1$$

$$\pi_5 = \frac{P D_c^2 \rho}{\mu^2} \equiv \frac{M}{LT^2} L^2 \frac{M}{L^3} \frac{M^{-2}}{L^{-2}T^{-2}} = 1$$

$$\pi_6 = \frac{K}{\mu C_p} \equiv \frac{ML}{T^3\theta} \frac{M^{-1}}{L^{-1}T^{-1}} \frac{L^{-2}}{T^{-2}\theta^{-1}} = 1$$

Therefore, all groups are dimensionless.

Based on Buckingham's π Theorem, one of the dimensionless groups is a function of the other four. Since the objective here is to calculate the dimensional error as a

function of the other variables π_1 is the one isolated on the left side of the equation. Therefore,

$\pi_1 = f(\pi_2, \pi_3, \pi_4, \pi_5, \pi_6)$ *Equation 6.40*

This means the general accuracy equation is

$$\frac{\Delta L}{D_c} = f\left(\frac{T_p D_c^2 \rho^2 C_p}{\mu^2}, \frac{T_m D_c^2 \rho^2 C_p}{\mu^2}, \frac{Q\rho}{D_c \mu}, \frac{P D_c^2 \rho}{\mu^2}, \frac{K}{\mu C_p}\right)$$ *Equation 6.41*

6.3.2 Obtaining the nature of "f" based on empirical data

Dimensional analysis was used in the previous section to develop a mathematical model for the calculation of the dimensional error, for polymer parts that are manufactured by µIM. This model is correct for any geometry and design. This section focuses on using empirical data from **Chapter 4** to form a model that is correct for the specific design and geometry used in this study.

Since the six expressions (π_1 to π_6) are dimensionless, any mathematical operation involving these will result in a dimensionless number. Inverting the last three expressions gives

$$\frac{\Delta L}{D_c} = f\left(\frac{T_p D_c^2 \rho^2 C_p}{\mu^2}, \frac{T_m D_c^2 \rho^2 C_p}{\mu^2}, \frac{D_c \mu}{Q\rho}, \frac{\mu^2}{P D_c^2 \rho}, \frac{\mu C_p}{K}\right)$$ *Equation 6.42*

Since the function *f* is unknown, the expressions inside can be combined by any mathematical operation [132]. The product of π_2, π_4, π_6 on one hand and π_3 and π_5 on the other hand gives:

$\pi_1 = f(\pi_7, \pi_8)$ *Equation 6.43*

$$\frac{\Delta L}{D_c} = f\left(\frac{T_p \rho C_p^2 D_c^3}{QK}, \frac{T_m \rho C_p}{P}\right)$$ *Equation 6.44*

At this point experimental data is used to find the nature of the function *f*. In the expression above π_1 represents the dimensional error, π_7 represents the polymer temperature and π_8 represents injection pressure. Since mould temperature and injection velocity had very little effect (*Figure 4-24* and *Figure 4-26*) the assumption is that they are constant. The values are those that resulted in the smallest dimensional error (120 ˚C and 350 mm/s). This is why they are included within the expressions and are not isolated (unlike the melt temperature and injection pressure). Three pressures of 400, 600 and 800 bar are selected for both polymers. For each of these pressures, the polymer melt temperature is varied within the range that avoids short shots and flash formations (These were obtained in **Chapter 4**). The expression that includes dimensional error (π_1) is located on the Y- axis and the expression that includes the polymer melt temperature (π_7) is located on the X- axis. Three curves are obtained for each micro wall. These are shown for the injection pressure of 600 bar in *Figure 6-7*. It can be seen that while change in D_c moves the points forward on the X-axis, it does not seem to have a large effect on the dimensional accuracy. Therefore, the effect on dimensional accuracy is mainly due to polymer melt temperature and injection pressure. The figure shows that for each channel dimension, the error moves up on the Y-axis, however, the distribution of the data points (and therefore, the equation for each channel) remains the same. The equations will have different constants. This movement on the Y-axis is explained by the fact that π_1 is the percentage error. Since the value of ΔL is very close for the three channels, it is expected that the smaller channel has a higher percentage error. Therefore, D_c can be removed from π_7 and added as a constant to the overall equation. However, to keep the expression dimensionless, D_c is replaced with D_p which is the plunger diameter. This also assists in keeping the X-axis values the same for all the pressures.

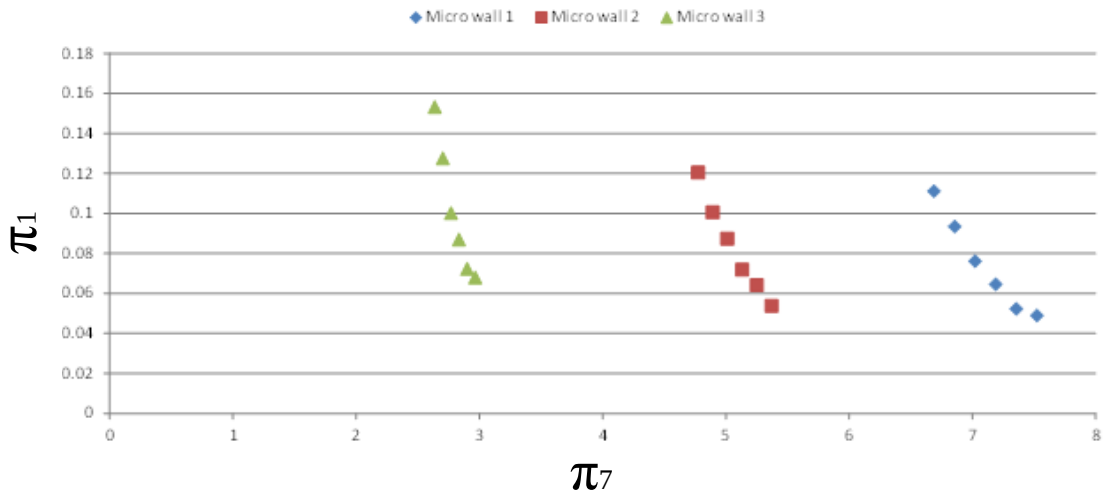


Figure 6-7- Effect of micro channel dimension on dimensional accuracy of the micro walls at Pinj=600 bar

For each dimension of micro wall a set of data is used and a best fit line is drawn to find the closest function. For this purpose, the curve fitting function of MATLAB is used. The micro walls are first investigated separately to ensure that the form of the function is the same for all of them. The two polymers are also investigated separately due to their different flow characteristic.

The equations with smallest statistical error (smallest SSE and R^2 closest to 1) are shown for micro walls 1, 2 and 3 made out of POM in *Figure 6-8*, *Figure 6-9* and *Figure 6-10* respectively.

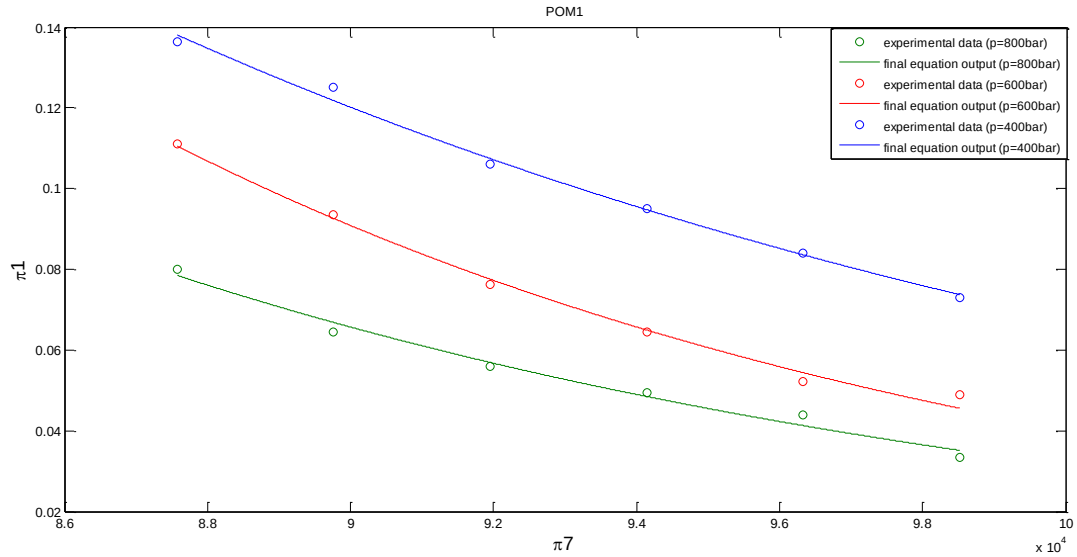


Figure 6-8- Best fit for micro wall 1 accuracy data for POM

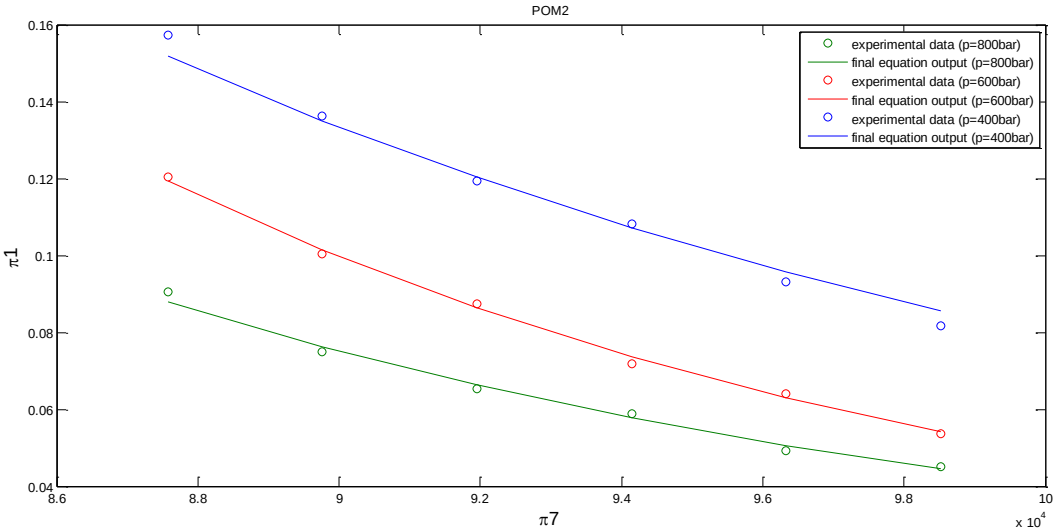


Figure 6-9- Best fit for micro wall 2 accuracy data for POM

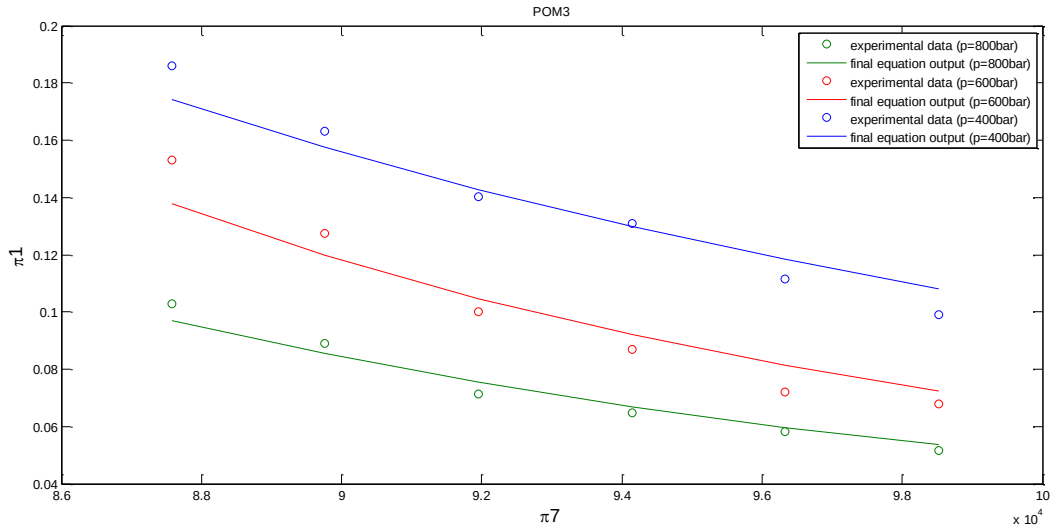


Figure 6-10- Best fit for micro wall 3 accuracy data for POM

It can be seen from the figures that for different values of π_8 (injection pressure), all lines have an exponential form ($\pi_1 = aEXP(b\pi_7)$). However, to obtain an overall function for all the micro walls, a parameter "c" needs to be added to compensate for the displacement of the data points on the Y-axis. Therefore, the overall function has the form of $\pi_1 = aEXP(b\pi_7) + c$. Since change in "a" and "b" is the result of change in injection pressure, they can be written as a function of π_8. "c" can be expressed as a function of injection pressure and channel dimension, D_c. To keep "c" a dimensionless number, it is written as a function of π_8 and $l = {D_c}/{D_p}$, where D_p is the plunger diameter and has a value of 0.005 (m). For "a", "b" and "c" the best fitting functions with smallest statistical errors are of 2nd order polynomial shape.

These for "a" and "b" are shown in *Figure 6-11*. In this figure, "a" and "b" are calculated as functions of π_8. However, "c" (movement in Y direction) is also a function of the channel dimensions and therefore is expressed as $c = m\pi_8^2 + n\pi_8 + p$, where "m", "n" and "p" are 2nd order polynomial functions of $l = {D_c}/{D_p}$ (e.g. $m = q_1 l^2 + q_2 l + q_3$). The calculations are available in *Appendix E*.

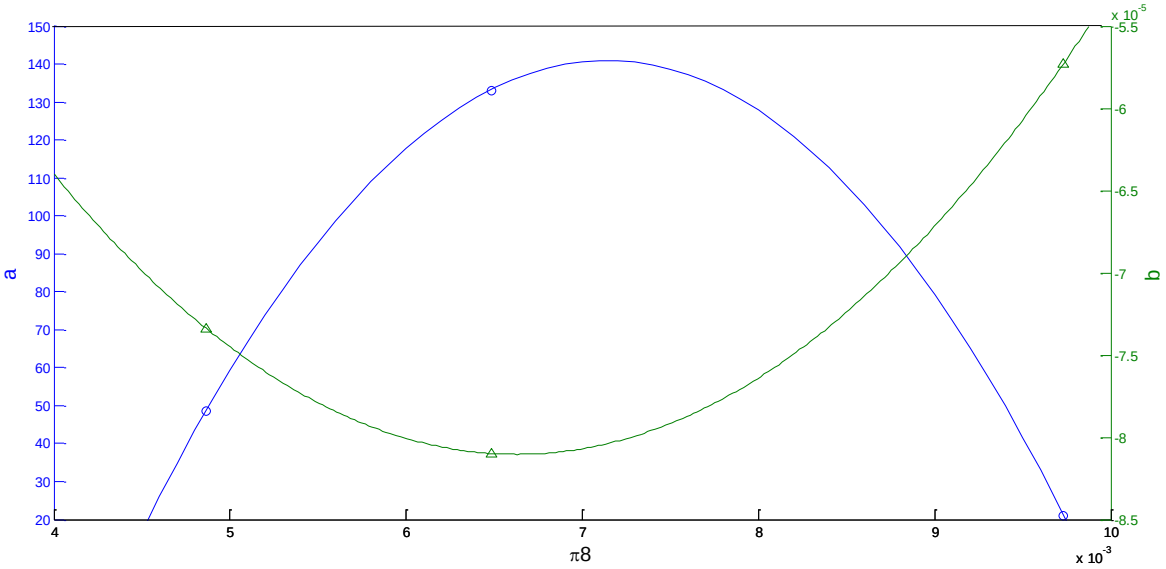


Figure 6-11- Calculation of constants "a" and "b" for all micro walls made out of POM

The final model for estimation of dimensional accuracy for POM is shown in *Equation 6.45*.

$$\pi_1 = (-1.783 \times 10^7 \pi_8^2 + 2.546 \times 10^5 \pi_8 - 767.9)EXP((2.465\pi_8^2 - 0.03267\pi_8 + (2.723 \times 10^{-5}))\pi_7) + \left((-1.562 \times 10^7 l^2 + 1.214 \times 10^6 l - 2.337 \times 10^4)\pi_8^2 + (2.609 \times 10^5 l^2 - 2.04 \times 10^4 l + 395.8)\pi_8 + (-963.6l^2 + 73.59l - 1.388)\right) \quad \textit{Equation 6.45}$$

The same method is applied to PP. However, the results of dimensional accuracy for PP shows that at the injection pressure of 800 bar, the data points show a steeper decline compared to the other two. This is true for all three micro walls and is shown in *Figure 6-12*, *Figure* 6-13 and *Figure 6-14*. This proves that the behavior of the polymer at the pressure of 800 bar is different from those below (400 and 600 bar). Therefore, this case needs to be modelled differently. The modelling procedure is the same as the one used for POM. For each set of data points the best curve is

calculated through curve fitting function of MATLAB. The constants are obtained in the same manner too.

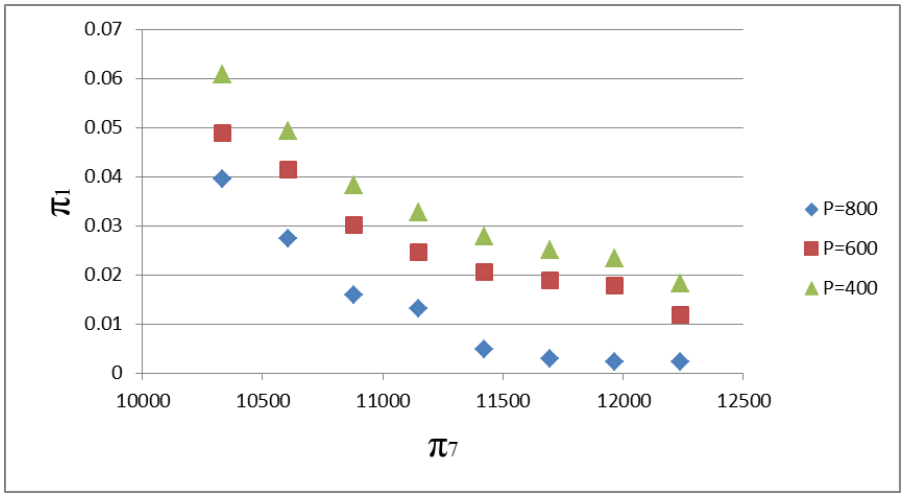


Figure 6-12- π_1 vs π_7 for different pressures for micro wall 1 made out of PP

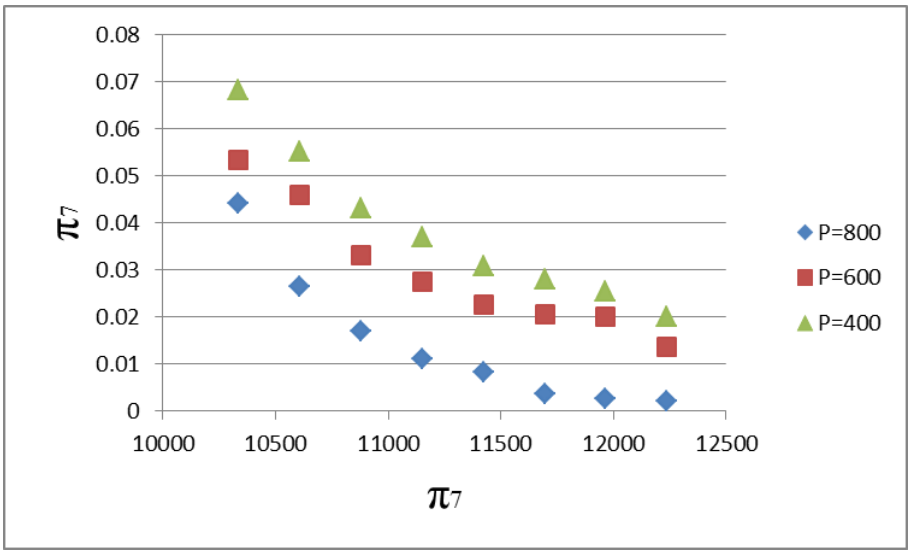


Figure 6-13- π1 vs π7 for different pressures for micro wall 2 made out of PP

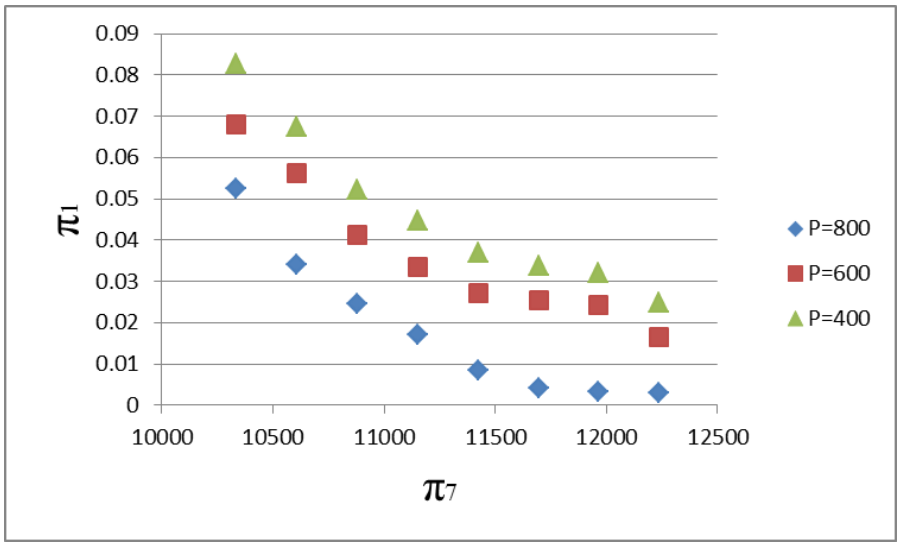


Figure 6-14- π1 vs π7 for different pressures for micro wall 3 made out of PP

The modelling procedure is the same as the one used for POM. The derivation of the equations for PP is shown in *Appendix E*. The final model for P_{inj} of 400 and 600 bar is shown in *Equation 6.46*; and for P_{inj} of 800 bar is shown in *Equation 6.47*.

$$\pi_1 = (-2.514 \times 10^4 \pi_8 + 180.6) EXP((0.04693\pi_8 - 0.8964 \times 10^{-3})\pi_7) + \left(-3403\left(\frac{D_c}{D_p}\right)^2 + 114.1\left(\frac{D_c}{D_p}\right) + 1.2789\right)\pi_8 + \left(43.78\left(\frac{D_c}{D_p}\right)^2 - 3.62\left(\frac{D_c}{D_p}\right) + 0.07476\right) \quad \textit{Equation 6.46}$$

$$\pi_1 = (7.984 \times 10^5) EXP(-0.001626\pi_7) + (27.17(\frac{D_c}{D_p})^2 - 2.429(\frac{D_c}{D_p}) + 0.05415) \quad \textit{Equation 6.47}$$

6.4 Use of dimensionless analysis in construction of the empirical model for UTS of µIM parts

In this section the procedure for formation of the empirical mechanical model is explained. Firstly, a general model is formed based on dimensional analysis. The powers and constants are calculated based on empirical data obtained from the planned experiments.

6.4.1 Construction of the general UTS model

Advantages of using dimensional analysis were discussed at the beginning of this chapter. This method was used for the generation of a model which predicts the dimensional error. The same method is applied in this section to generate a model which predicts the UTS of a micro wall based on characteristics from the part, moulding machine, polymer and the process. The selected variables are shown in *Figure 6-15*.

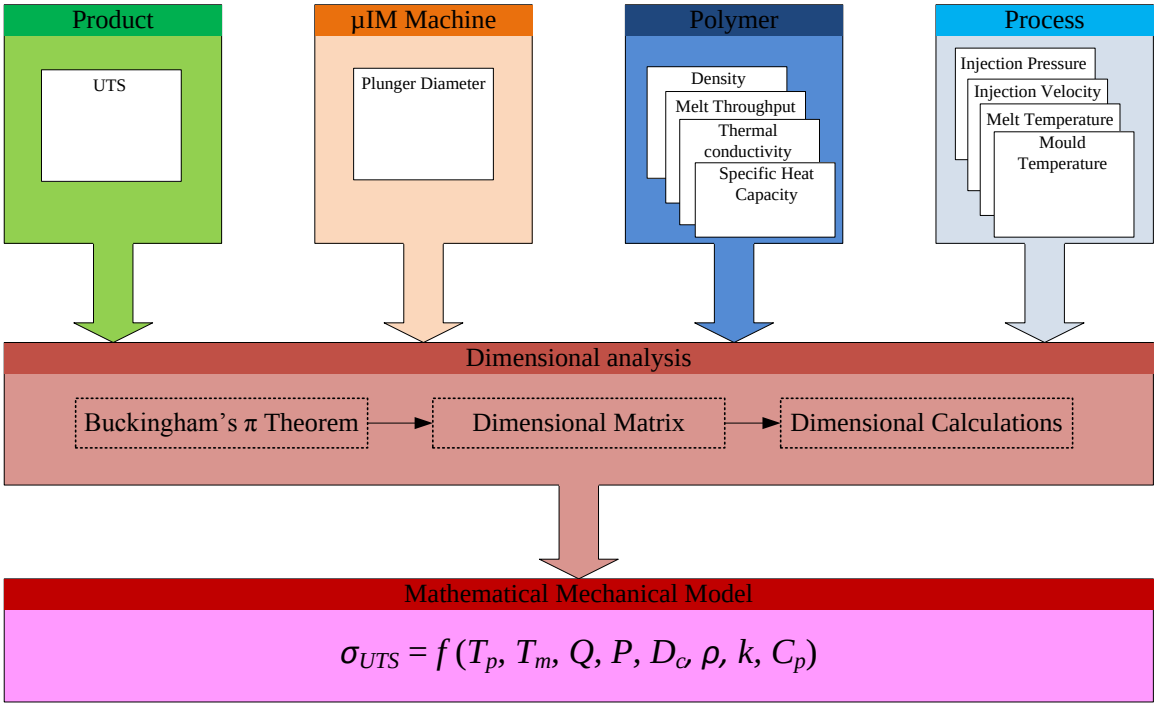


Figure 6-15- Variables used in formation of the mechanical model

The variables used in formation of the mechanical model are the same as those used to form the accuracy model, with the exception of viscosity. While direction of flow affects the mechanical properties of a part, viscosity does not play a major role. A study by Kuo et. al. [104] showed that the change in the UTS due to the flow is related to the cross section of the micro bars rather than the viscosity of the polymer melt. It was also determined in **Chapter 5** that the size of the micro walls did not have an effect on the UTS. Therefore, compared to the accuracy model, viscosity of the polymer melt and channel dimension are removed from the variables. The process parameters that were selected before are used here. Effect of melt and mould temperatures (T_p and T_m), injection velocity (V_{inj}) and pressure (P_{inj}) on the UTS of

the micro walls were discussed and analysed in **Chapter 5**. Due to the importance of these characteristics and the fact that these are the main parameters that can be changed on the machine these have to be included in the model. In addition, the same parameters as were used in the accuracy model have to be used to ensure that the results and effects of these parameters can be compared. Due to the effect of temperature on the UTS, thermal conductivity (k), specific heat capacity (C_p) and polymer density (ρ) are included in the model. Melt throughput (Q) is also considered in the model to include injection velocity and the plunger diameter. The variables and their dimensions are summarised in *Table 6-2*.

Table 6-2- Variables used in the mechanical model and their dimensions

Variable	***Notation***	***Dimension***
Ultimate Tensile Strength	σ_{UTS}	$ML^{-1}T^{-2}$
Polymer melt temperature	T_p	θ
Mould temperature	T_m	θ
Melt throughput	Q	L^3T^{-1}
Injection pressure	P	$ML^{-1}T^{-2}$
Polymer density	ρ	ML^{-3}
Polymer's thermal conductivity	k	$MLT^{-3}\theta^{-1}$
Polymer's specific heat capacity	C_p	$L^2T^{-2}\theta^{-1}$

The general equation is

$$\sigma_{UTS} = f(T_p, T_m, Q, P, \rho, k, C_p) \qquad \textit{Equation 6.48}$$

The method for calculation of the dimensionless groups is the same as the one used for the accuracy model. Details of the calculations and the explanation are provided in *Appendix F*.

The general mechanical equation is

$$\frac{\sigma_{UTS}}{P} = f\left(\frac{T_p \rho C_p}{P}, \frac{T_m \rho C_p}{P}, \frac{K}{P^{1/4}\rho^{3/4}C_p Q^{1/2}}\right) \qquad \textit{Equation 6.49}$$

6.4.2 Obtaining the nature of "f" based on empirical data

A general mathematical model was developed in the previous section for the calculation of the UTS. In this section, the nature of function *f* is found based on empirical data from **Chapter 5**.

The product of the last two expressions gives

$$\pi_1 = f(\pi_2, \pi_5) \qquad \textit{Equation 6.50}$$

Which is

$$\frac{\sigma_{UTS}}{P} = f\left(\frac{T_p \rho C_p}{P}, \frac{T_m K \rho^{1/4}}{P^{5/4} Q^{1/2}}\right) \qquad \textit{Equation 6.51}$$

The method that was employed to find the relationship for the accuracy model is also used here. The nature of the function *f* and the constants of the equations are calculated using empirical data.

As explained in **Chapter 5**, the value of UTS is a property of the polymer itself and the selected values for process parameters. The size of the micro walls does not make a difference in the UTS because the micro walls with the higher cross section area require a larger amount of maximum force to break. Those with the smaller cross section area require a smaller force and this variation in force results in the UTS to be the same for all micro channels. Therefore, MATLAB calculations are only performed for one of the micro channels to obtain a relationship that relates UTS to the process parameters and the polymer properties. The procedure is the same as those used for obtaining the accuracy models. The two process parameters that show the smallest effect (injection pressure and mould temperature) are considered at their optimum levels and injection velocity and polymer melt temperature are used as variables. Several velocities (between 350 to 700 mm/s) are investigated in intervals of 50 mm/s, at three different melt temperatures for each polymer (215, 220 and 225 for POM and 210, 215 and 220 for PP). Based on calculations performed by MATLAB, the best equation with the smallest error is a 2nd order polynomial equation where π_1 (the expression with UTS) is on the Y-axis and π_6 (the expression

with velocity) is on the X-axis. The general form of the equation is $\pi_1 = az^2 + bz + c$ where the normalised function "z" is defined as $z = (\pi_5 - \mu)/\sigma$. In this instance μ is the average of the data points and σ is the standard deviation. These values for POM and PP functions are generated automatically by MATLAB. $Z_{POM} = (\pi_5 - 1.0977 \times 10^{-5})/1.1129 \times 10^{-6}$ and $Z_{PP} = (\pi_5 - 5.1791 \times 10^{-5})/5.2507 \times 10^{-6}$. Since the constants of the equations are different due to the change in melt temperature, "a", "b" and "c" are obtained as a function of π_2 (the expression with melt temperature). The method used is the same as that employed for calculation of the accuracy models. Details of calculations and figures are available in *Appendix G*. The final models are shown in *Equation 6.52* for POM and *Equation 6.53* for PP.

$$\pi_1 = (-92222\pi_2^2 + 1882.1\pi_2 - 9.6217)Z_{POM}^2 + (2.469.3\pi_2^2 - 49.255\pi_2 + 0.32821)Z_{POM} + (2.7498\pi_2^2 - 5755.5\pi_2 + 30.542) \quad \textit{Equation 6.52}$$

$$\pi_1 = (-55713\pi_2^2 + 829.77\pi_2 - 3.0998)Z_{PP}^2 + (-88233\pi_2^2 + 1249.3\pi_2 - 4.3728)Z_{PP} + (1.7854\pi_2^2 - 2798.4\pi_2 + 11.1) \quad \textit{Equation 6.53}$$

6.5 Experimental validation with the Brass insert

To ensure that the above models yield correct results with good accuracy, four sets of parameters are selected for the manufacture of the micro walls and testing of the models. These are shown below in *Table 6-3* for POM and *Table 6-4* for PP.

Table 6-3- validation of the accuracy model for POM using the brass insert

		T_p	T_m	V_{inj}	P_{inj}	*Model (µm)*	*Experimental (µm)*	*Difference (µm)*
Micro wall 1 POM	1	200	120	350	800	16.69	16.97	0.28
	2	225	120	350	800	7.44	7.07	0.37
	3	200	120	350	600	23.55	23.57	0.02
	4	225	120	350	600	9.71	10.37	0.66
Micro wall 2 POM	1	200	120	350	800	16.68	17.15	0.47
	2	225	120	350	800	8.42	8.52	0.1
	3	200	120	350	600	22.68	22.83	0.15
	4	225	120	350	600	10.31	10.18	0.13
Micro wall 3 POM	1	200	120	350	800	15.11	16.82	1.71
	2	225	120	350	800	8.33	7.04	1.29
	3	200	120	350	600	21.49	23.23	1.74
	4	225	120	350	600	11.33	10.07	1.26

Table 6-4-validation of the accuracy model for PP using the brass insert

		T_p	T_m	V_{inj}	P_{inj}	*Model (µm)*	*Experimental (µm)*	*Difference (µm)*
Micro wall 1 PP	1	190	90	350	800	8.53	7.07	1.46
	2	220	90	350	800	0.60	0.47	0.13
	3	190	90	350	600	10.24	10.37	0.12
	4	220	90	350	600	3.10	3.77	0.66
Micro wall 2 PP	1	190	90	350	800	7.83	7.37	0.46
	2	220	90	350	800	0.74	0.49	0.25
	3	190	90	350	600	9.72	10.09	0.37
	4	220	90	350	600	3.34	3.79	0.45
Micro wall 3 PP	1	190	90	350	800	7.01	7.12	0.10
	2	220	90	350	800	1.2	1.42	0.22
	3	190	90	350	600	9.06	10.58	1.52
	4	220	90	350	600	3.83	3.77	0.06

The UTS models are also validated in the same manner. The results are shown below in *Table* 6-5.

Table 6-5- Selected values for testing the UTS model

		T_p	T_m	V_{inj}	P_{inj}	*Model (MPa)*	*Experimental (MPa)*	*Difference (MPa)*
POM	1	215	120	500	700	39.52	38.72	0.8
	2	215	120	650	700	28.03	31.78	3.75
	3	225	120	500	700	34.88	32.92	1.96
	4	225	120	650	700	23.19	26.06	2.87
PP	1	210	95	400	700	19.04	18.99	0.05
	2	210	95	600	700	14.46	15.75	1.29
	3	220	95	400	700	14.27	15.52	1.25
	4	220	95	600	700	9.98	10.83	0.85

6.6 Discussion

6.6.1 Accuracy models

Two models were developed to estimate the effect of process parameters on the dimensional accuracy of micro parts. For each polymer a separate model was developed due to the fact that POM and PP behave differently under the same processing conditions. While both are semi crystalline polymers, they have very different melt flow rates (PP's melt flow index is 92% higher than POM) and therefore, viscosity of PP is greatly reduced under the same processing conditions. This allows for considerably better filling of the cavities and significant reduction of the dimensional error. This can be confirmed by looking at the results of dimensional accuracy of the two polymers in **Chapter 4** (*Figure 4-9* and *Figure 4-10*). Since the physical and rheological properties of the two polymers are different, one single model cannot be developed for both. While the general shape of the equations is the same (exponential), the constants are different.

In modelling the effect of process parameters for PP, it was observed that at the pressure of 800 bar, the constants of the equations were significantly different and an

attempt to form one single equation would result in significant error for all micro walls. Therefore, this case was separated from the other pressures. This could be explained by the fact that PP has a very low viscosity and at higher pressures, the polymer fills the cavity at a higher rate. Therefore, as the temperature was increased the combination of increasingly lower viscosity and higher pressure, resulted in faster decline in dimensional accuracy. The same behavior could be repeated for POM. However, since POM has higher viscosity this phenomenon would probably happen at a considerably higher pressure (which is not available on the machine used in this study, since the highest injection pressure can be applied at 1050 bar).

The models were experimentally validated with the brass inserts for all micro walls and polymer, considering the constraints and limits that were explained in the chapter. The difference between the results from the models and experimental measurements was well below 1µm in most cases. At the worst case, the difference was 1.74 µm (this is for the cases where the dimensional error is in the range of 20+ µm).

6.6.2 UTS models

Two models were also developed for estimation of the UTS of the micro walls. The same method deployed for accuracy models was used for modelling the UTS. The models have a 2^{nd} order polynomial shape. The two polymers behaved similarly in regards to the effect of process parameters. This was shown in **Chapter 5** and the figures and form of the equations confirmed this. The constants of the equations are however different for each of the polymers. The models were experimentally validated and the highest error was around 10% for POM (case 2 and 4). This could however be the error from the testing machine.

6.6.3 Application of the models

The aim of the study was to develop a methodology for modelling the effect of process parameters on dimensional accuracy and UTS of the micro parts. The models were experimentally validated, and the results showed that they successfully predicted dimensional accuracy and UTS with small errors. However, it must be noted that several factors were not considered in the models. Firstly, viscosity of the

polymer melt was eliminated in the calculation of the πs for both accuracy and UTS models. This is due to the fact that, as explained in the literature review, the viscosity of polymer melt in μIM cannot be accurately calculated. Attempts to constructing the models with approximation of viscosity resulted in large errors. However, this could not ignore the fact that the results of dimensional error and UTS were very different for POM and PP. This is due to the fact that the two polymers have different flow behaviors, and their crystallinity and structure are different. Therefore, one single model cannot be developed for both polymers in either dimensional error or UTS. It must be noted that modelling of viscosity and UTS even in large cavities is often done on polymer basis and a general relationship does not exist.

The other main factor that was not considered in this study is the design of the mould. Since design of the mould can change stresses applied to the polymer melt and its flow behavior, it has a significant effect on the characteristics of the final product. However, investigation of the effect of mould design on quality of the micro moulded parts requires consideration of several factors such as size and shape of the runners, size, shape and location of the gates, and configuration of the part cavities in relation to the polymer melt flow and its direction. However, investigating even one of these factors is a massive undertaking, and outside of the scope of this work due to restriction of time and resources. Therefore, this study focused on one design.

The third main factor that was not considered in the study is the flash formed on the parts as a result of the polymer melt escaping the mould cavity. Quantifying the flash on the parts can be useful in finding minima for dimensional error. Also, if all the polymer melt is injected in the cavity, the final part can be made with higher mechanical strength. This is especially evident in the results obtained in **Chapter 4** for polymer melt and mould temperature as dimensional error reaches a minimum value and then increases as the flash in formed around the micro walls (*Figure 4-23* and *Figure 4-24*).

Therefore, it must be mentioned that for the models to be fully applicable in industrial scale, these factors must be considered. Design of the mould and its characteristics, and its effect on part quality must be quantifiably verified and included in the model. The same is applied for quantifying the size of flash formed

on the parts and the amount of polymer that does not entre the part cavity. Also, calculation of the melt viscosity and characterization of the polymer melt flow are important factors that need to be included in the models to accurately identify the length of the flow and filling of the cavities.

It must be mentioned that while these are the short comings of the models, they can be successfully used to predict the UTS and dimensional error of the micro walls manufactured with the current design, within the range of dimensions investigated. Experimental validation of the models showed that they can be used to estimate these two quality factors with very good confidence.

6.7 Chapter summary

This chapter presents a method with which the models for predicting the dimensional accuracy and UTS are constructed. The method used for constructing the models is dimensional analysis. This method is widely used by researchers in explaining a physical phenomenon where a relationship between a set of variables is unknown. The method is employed to find a relationship between the two quality factors investigated in this study, dimensional accuracy and UTS, and several variables which involve characteristics of the process, the polymers and the micro moulding machine. The objective is to simply find a mathematical relationship between the quality criteria and four process parameters (polymer melt and mould temperature, injection velocity and injection pressure), polymer density, specific heat capacity and thermal conductivity, and the machine's plunger diameter.

By using dimensional analysis, several expressions are formed which can be related to the dimensional accuracy and UTS. However, the specific function that relates these expressions together must be found by using empirical data. This is done by using the results from the previous two chapters (**Chapter 4** for the accuracy model and **Chapter 5** for the UTS model).

For each of the three micro walls, a plot of the dimensionless groups is produced and then they are combined through numerical operations. This is done for each of the polymers separately because they have very different characteristics and the range of the data obtained is very different.

Once the models are produced, they are validated by experimental means. A set of randomly selected values for the process parameters are used to perform experiments on the brass pin and obtain the UTS and dimensional accuracy. Then the results of these two were compared with the calculations from the models. The calculated results showed to have close agreement with the experimental ones.

The models are further validated in **Chapter 7**, where a different insert with different channel dimension is used. This is done in the third section of the next chapter.

Chapter 7

Chapter 7 Validation

7.1 Introduction

The definition of a validation method for any model requires analysis of the model's domain. The models proposed in this study target a domain that is vast and complicated. Several factors such as mould design, runners and gates, features, polymer and many others can affect the dimensional accuracy and UTS of a micro moulded part. To validate the models for even one of these factors requires a massive amount of time and resources, both financially and in terms of labour. Therefore, a simple method of validation is proposed for each of the contributions. These are explained in the following sections.

The importance of µIM and its applications in the field of polymer micro manufacturing were discussed in **Chapter 1** and **Chapter 2**. A literature review was conducted to examine and understand the current developments in the field. From the review and the researched application areas of micro moulding it was concluded that the quality of the parts replicated with this technology are of high importance. Since achieving the quality criterion is currently done by means of experimentation this study focuses on modelling the effect of process parameters on two quality aspects, the dimensional accuracy and UTS of micro moulded parts. Firstly, the effects of process parameters on these two aspects were investigated by means of experimentation. The results were then interpreted through the use of statistical analysis, and specifically the ANOVA method. The second step involved the construction of the general mathematical equations for the purpose of relating the quality criteria (dimensional accuracy and UTS) to the process parameter. These equations also use the characteristics of the polymer and the micro moulding machine to make a more thorough relationship. Then the most influential process parameters were investigated further and in more detail to study their relationship with the appropriate quality aspect. Once this relationship was determined, the final model with the powers and constants of each variable was completed.

This chapter focuses on validating the approach and the final models by considering a scenario for manufacturing a product by µIM. The approach for validation of each contribution is explained and the results are compared with those obtained in the

previous three chapters. The focus of the first two sections of the validations is on proving that the effects of process parameters shown in **Chapter 4** and **Chapter 5** are the same regardless of the specifications of the product. The third section of the validation focuses on the assessment of the two models in **Chapter 6** for determination of the dimensional accuracy and UTS.

7.2 Validation of the effect of process parameters on the dimensional accuracy of µIM parts

This section focuses on the effect of process parameters on the dimensional accuracy of micro moulded parts. In this scenario, a different mould insert is used to investigate the effects obtained in **Chapter 4**.

Changes in design result in significant changes in the flow of the polymer melt. This in turn results in different flow characteristics such as viscosity, shears rates, and frictional forces which all affect the filling of the cavities, and therefore, the dimensional accuracy of the final product. As a result, it is important to stress that the design of the mould must remain the same in order to verifiably investigate the effect of process parameters for different parts and polymers. The mould inserts however are changed to produce a product with different dimensions. These inserts have the same general shape as the brass pins. However, they are made out of stainless steel and are manufactured by Wire EDM. The dimension of the channels is 150 µm. The two polymers used previously in the study are used here. This is intended to allow the general trend of the effect of parameters to be studied, even under conditions where some of the part characteristics are changed (i.e. mould material and dimension). A polymer with different morphology is likely to behave differently under the conditions of this study.

To validate the trends obtained in **Chapter 4** a set of new and controlled experiments are conducted. The method for conducting the experiments is the same as before. To ensure that all the effects for different process parameters combinations are captured Taguchi's design of experiment is employed. The four process parameters used previously (T_p, T_m, V_{inj} and P_{inj}) are varied. A two level full factorial design is

employed, which results in 2^4=16 different combinations. These are the same values used in *Table 4-6*.

Once the parts are manufactured, the same method of measurement is applied to them to determine the variation in dimension. The first 10 parts are discarded in order to allow for stabilization of the process and the following 10 are used for data analysis. Three random parts out of 10 are selected for measurement. Three sections of each micro wall are measured to determine the dimensional error. The approximate point of measurements for each micro wall was shown in *Figure 4-7*. The highest error for a part is selected as the dimensional error for that part. *Figure 7-1* and *Figure 7-2* show the dimensional errors for POM and PP respectively.

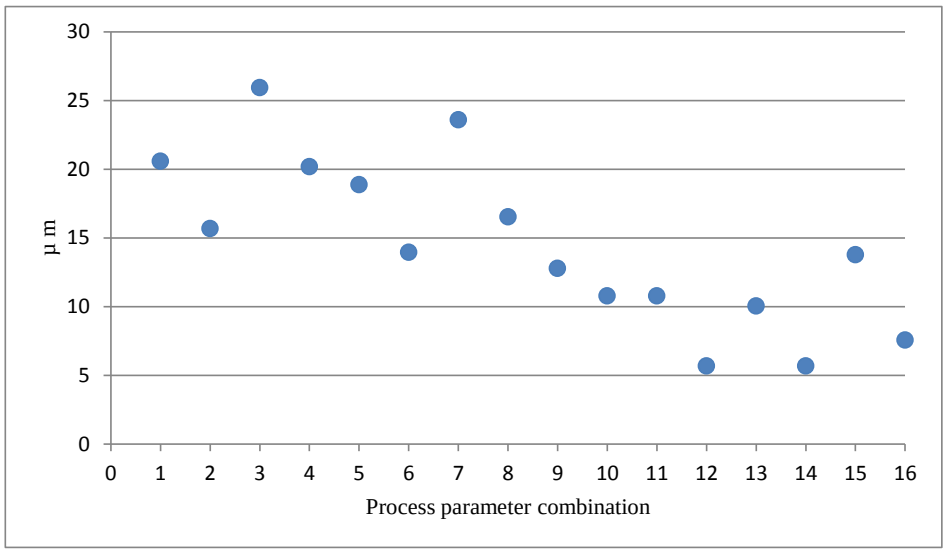


Figure 7-1- Dimensional error for each process parameter combination for POM (µm)

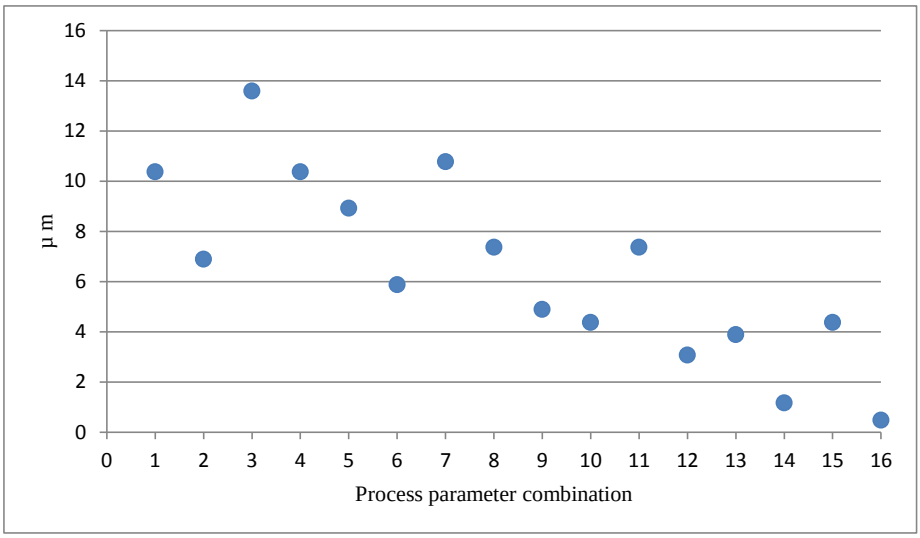


Figure 7-2- Dimensional error for each process parameter combination for PP (µm)

Statistical analysis of the results is presented in *Figure 7-3* to *Figure 7-6* with Main effect and Pareto charts for POM and PP. The analysis shows that the polymer melt temperature is the most influential parameter with a positive effect, followed by the injection pressure and mould temperature. Injection velocity has a higher effect than mould temperature, however, with a negative effect. These are shown in both Main effect and Pareto plots. The effects are in agreement with what was obtained in investigation of the effect of process parameters in **Chapter 4**. This shows that for micro channels with similar range of dimensions the behavior of the polymer and its flow remain very close. However, if a different type of polymer is used the behavior is likely to change due to the different structure and flow properties of the polymer. The polymer melt temperature is likely to remain the most influential parameter, however, the order of importance for other polymers and their influence most likely vary.

It must be noted that while the size of the channel is smaller than those previously used (150 µm compared to 212.14, 189.59 and 155.57 µm) the error is reduced. This trend is not in agreement with that obtained in **Chapter 4**. However, this is explained by the fact that the channel used in this pin is made out of a different material (steel) and the process used for its manufacturing is different (wire EDM). As a result the surface roughness of the channel is smaller than that of the brass channels (0.252 µm for the steel channel compared to 0.27, 1.286 and 1.967 µm for the Brass channels). This results in better flow of the polymer melt, hence the better dimensional

accuracy. Furthermore, and more importantly, stainless steel has a thermal conductivity of 16 w/mk compared to 110 w/mk for Brass. This means the polymer melt retains considerably more of its temperature when it comes in contact with the mould. This stops it from freezing and ensures that the polymer flows easier in the micro channels, which results in better dimensional accuracy. It must also be mentioned that in investigation of the effect of process parameter on the dimensional accuracy the size of the channels and their range was one of the assumptions. If the size of the micro channels on the mould changes drastically, i.e. become much smaller (e.g. 10 µm or smaller) polymer flow behavior will change. In that case, correct adjustment of the mould temperature is likely to have a much higher effect than those seen here. This is because the surface to volume ratio becomes much smaller and therefore the polymer melt will freeze much faster if the mould is not sufficiently warm.

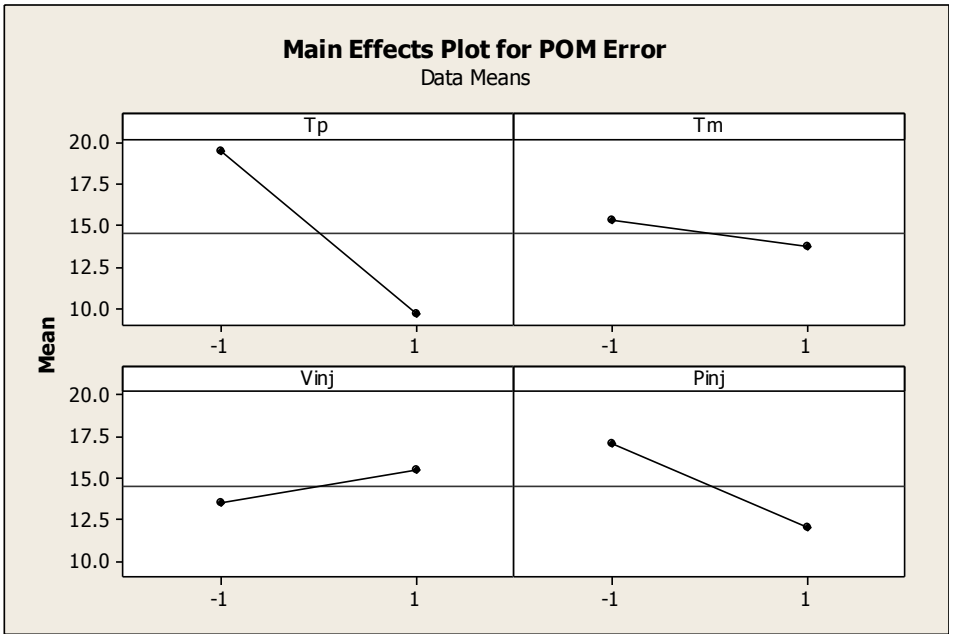


Figure 7-3- Main effect plot for micro wall made out of POM

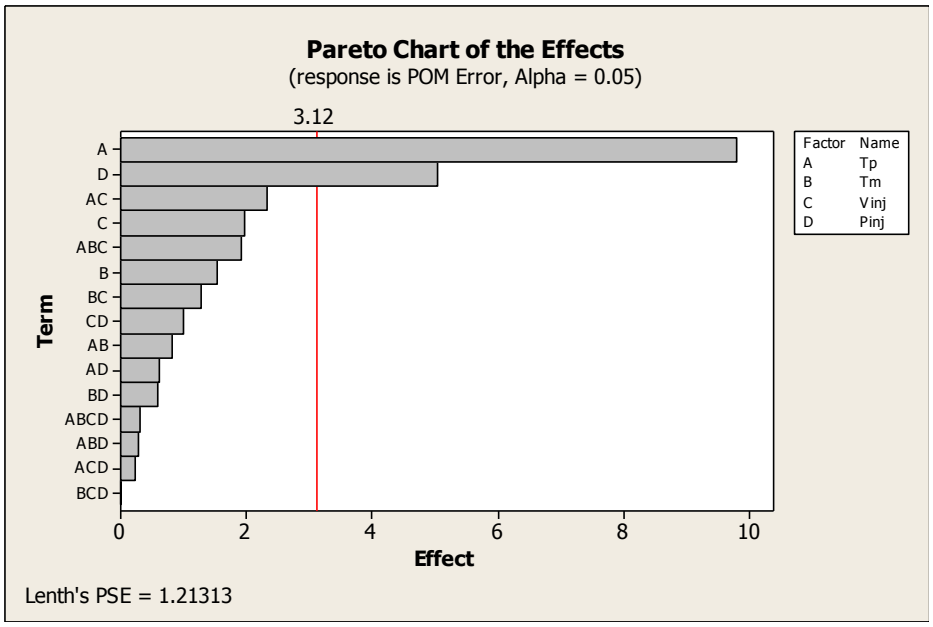


Figure 7-4- Pareto plot for micro wall made out of POM

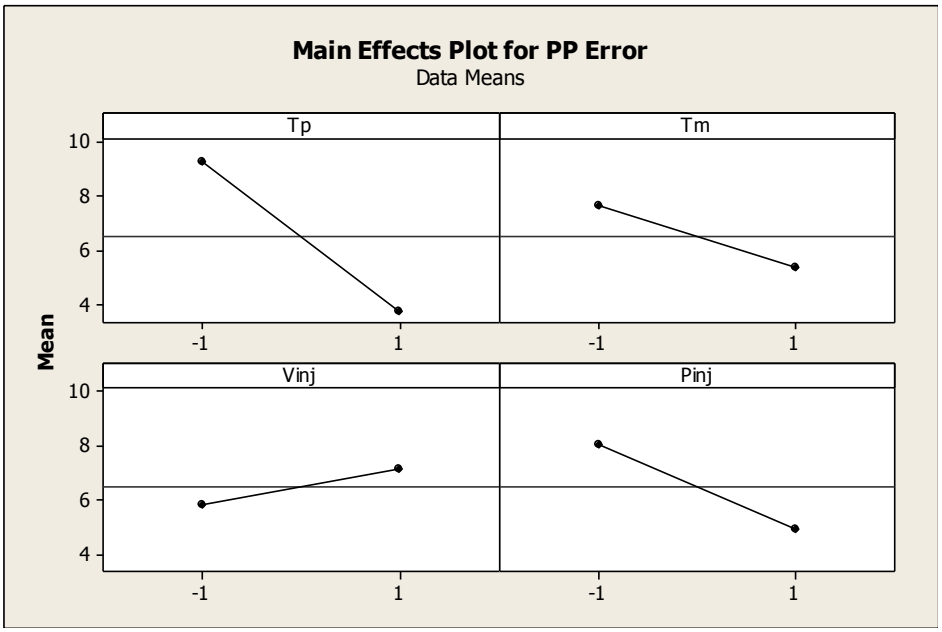


Figure 7-5- Main effect plot for micro wall made out of PP

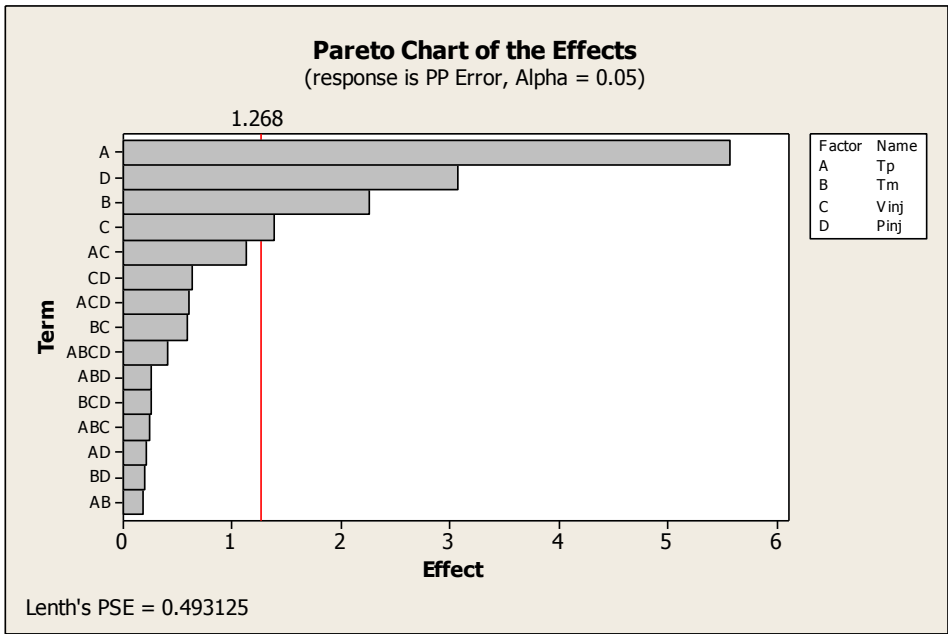


Figure 7-6- Pareto plot for micro wall made out of PP

7.3 Validation of the effect of process parameters on the UTS of µIM parts

This section focuses on the effect of process parameters on the UTS of micro moulded parts. In this scenario, a different mould insert is used to investigate the effects obtained in **Chapter 5**. The aim is to prove that the general trend for the effect of each process parameter remains the same regardless of the change in certain characteristics of the product.

The effect of mould design on the mechanical behaviour of micro moulded parts was explained in **Chapter 5**. Different mould designs result in differences in the flow of the polymer melt. This is specifically important in relation to the direction of the flow, formation of weld lines and stresses applied to the polymer. Each of these factors could result in changes in the morphology of the polymer. For example, a transverse flow of the polymer melt in the channels is likely to reduce the UTS of the micro walls. In addition, while elimination of the weld lines is generally desirable, a comparison between a micro wall with a weld line and one without would not yield any conclusions. This is because the UTS of the part with a weld line is likely to be considerably less than the one without. Taking into account these considerations, the design of the mould is the same as the one used previously.

The mould insert used to conduct these experiments are the same as the previous section. The design and set up of the experiments are the same as those in **Chapter 5**. Two level full factorial design is employed to conduct the experiments. The values for the process parameters are the same as those used in *Table 5-2*.

For each combination ten parts are produced and selected for data collection. These parts are collected after stabilisation of the process.

Once the parts are produced an Instron 5969 machine is used to conduct the tensile testing. Three random parts are selected to conduct the tests. The lowest value obtained from the tests is the selected UTS for the particular combination of process parameters. *Figure 7-7* and *Figure 7-8* show the results obtained for each combination for POM and PP respectively.

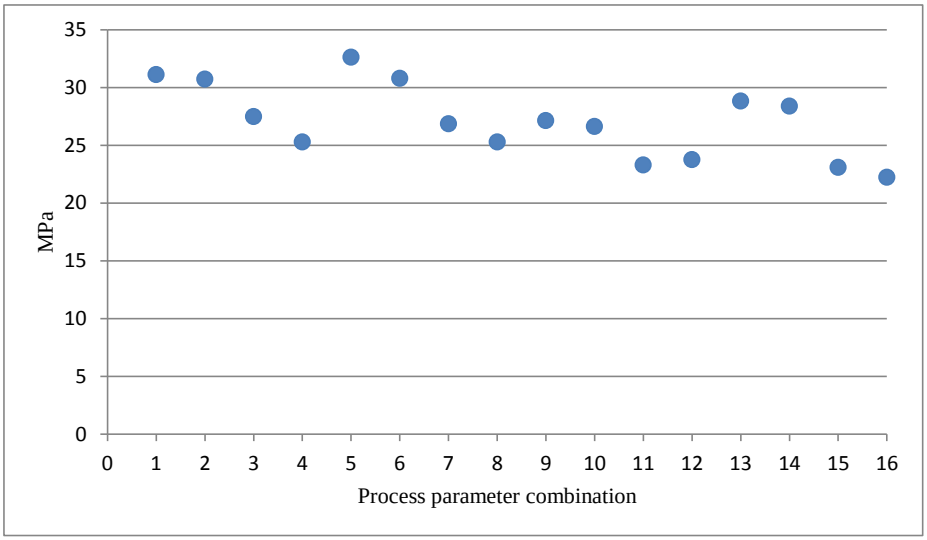


Figure 7-7- UTS for each process parameter combination for POM (MPa)

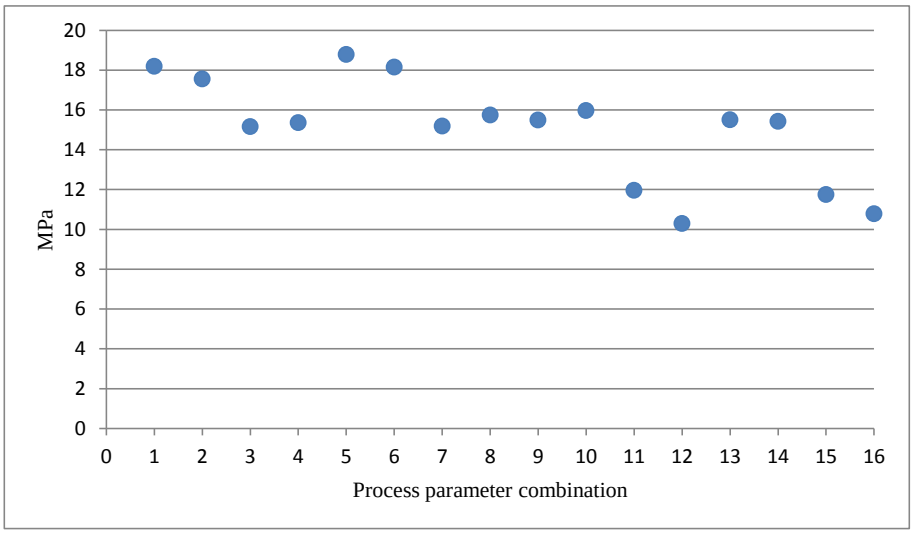


Figure 7-8- UTS for each process parameter combination for PP (MPa)

Statistical analysis of the results is presented in *Figure 7-9* to *Figure 7-12* with Main effect and Pareto charts. The analysis shows that polymer melt temperature has a high negative effect on the UTS of the micro walls. Injection velocity and injection pressure respectively have negative effects on the UTS in that order for POM, and reverse order for PP. This was also seen in the statistical analysis in **Chapter 5**. Mould temperature is the only parameter that shows a positive effect on the UTS for micro walls. This is because it allows for better movement of the polymer melt and formation of a better and stronger weld line. However, it must be noted that the effect on PP was shown to be smaller than POM. Again, this is in agreement with what was found in **Chapter 5**.

It must be noted that the values for the UTS of the 150 µm channel are smaller than those obtained for the brass insert. This is again the result of the lower thermal conductivity of steel. As explained in the previous section and in the literature review, lower thermal conductivity of steel allows the polymer melt to retain its temperature for a longer time, i.e. slower cooling. This means that the molecules have longer time to orientate in any direction which results in formation of large spherolites and crystals; which results in reduction of the UTS. However, this is not the case for PP because this polymer is less susceptible to change in temperature.

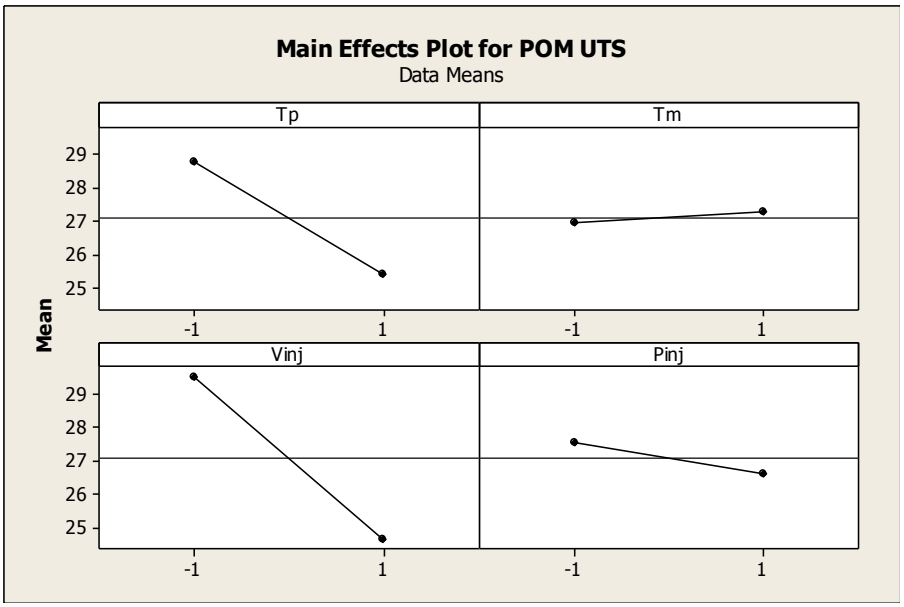


Figure 7-9- Main effect plot for micro wall made out of POM

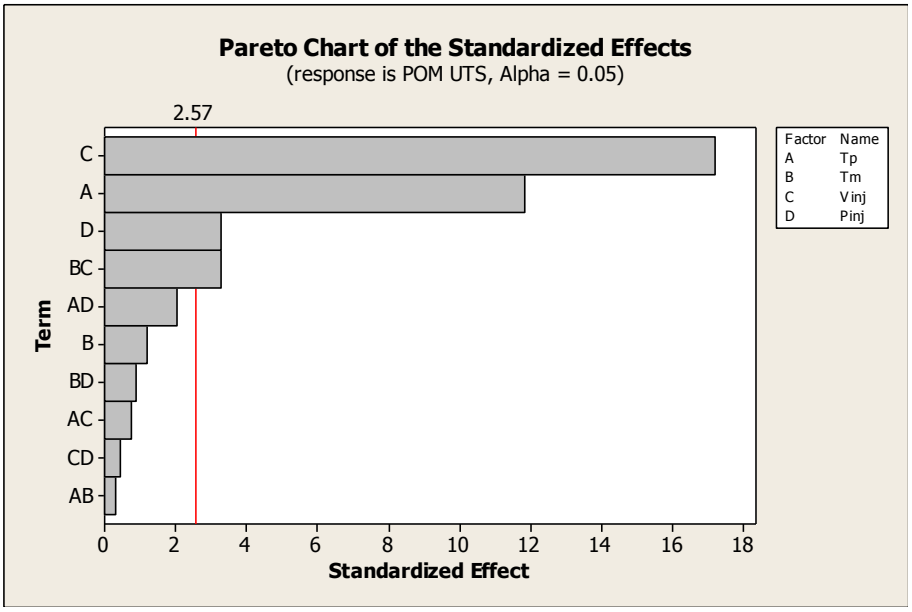


Figure 7-10- Pareto plot for micro wall made out of POM

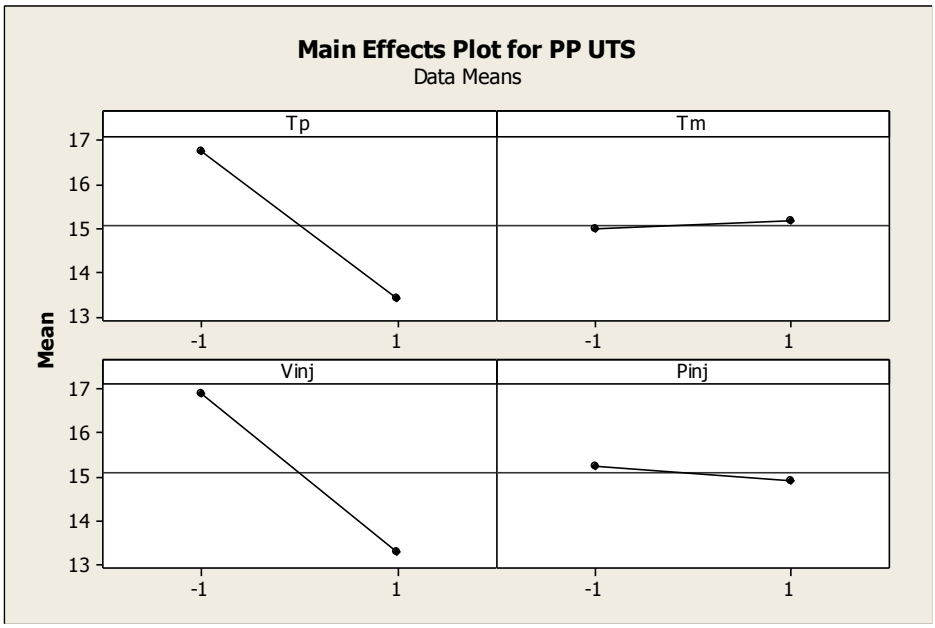


Figure 7-11- Main effect plot for micro wall made out of PP

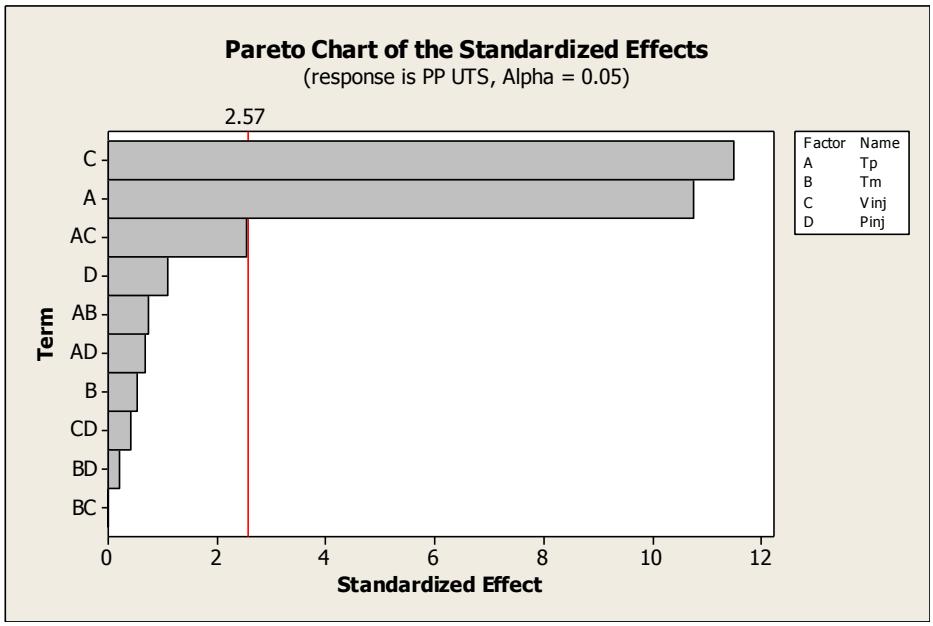


Figure 7-12- Pareto plot for micro wall made out of PP

7.4 Validation of the accuracy and mechanical models

The method for the generation of the accuracy and mechanical models were presented and explained thoroughly in **Chapter 6**. First dimensional analysis was used to form the general models. This showed the relationship between the variables. Then, using empirical data, the relationship between the process parameters with the highest influence and the dimensional accuracy or UTS were investigated. Through this process, constants of the equations were formed. The focus of this section of the

chapter is to show that the final equations are correct and can be used for any micro channels within the proposed mould design. The effect of mould design on the accuracy and UTS of the micro walls was already discussed in the previous two sections.

For the validation of the models, stainless steel inserts with dimensions of 150 µm are used. For each polymer five combinations of variables are selected to investigate the models. In all cases the characteristic of the part (width) will remain the same. The variables for the four process parameters and the characteristics of the polymer change. The mentioned characteristic of the machine (plunger diameter) remains the same throughout the validation. This is because during the period of this study only one machine was available (Battenfeld Microsystem 50 with plunger diameter of 5 mm).

To validate the models, the values for process parameters and polymers' constants are entered in the equations and dimensional accuracy and UTS are calculated. Additionally, the micro walls on the new inserts are formed with the polymers and parameter combinations. Then measurements and tensile testing are performed to measure the experimental values. The calculated and experimental results are then compared. *Table 7-1* and *Table 7-2* show the four parameter combinations and the calculated and experimental values of dimensional accuracy and UTS for each polymer.

As it can be seen from *Table 7-1* the calculated dimensional errors from the models and measurements from the experiments are in good agreements. However, the difference between the model and experimental values for POM are higher than those obtained from the brass insert (*Table 6-3*). This is due to the use of an insert with a different material (stainless steel). Steel has a considerably lower thermal conductivity and therefore, the polymer retains its temperature for longer, which results in better filling of the micro channels and reduction of dimensional error. Mould insert material was not a parameter in the original model. This is the source of error between the model calculations and the experimental values. The difference for PP is considerably less. This is because PP has a large range of melting temperature and therefore is less susceptible to variation in the polymer melt temperature.

Therefore, the mould insert is not likely to have very large effect on its flow. Furthermore, the surface roughness of the micro channels in the brass and steel micro channels is different; and lower for the steel insert. This is another factor that affects the polymer flow and was not considered in the models.

Table 7-1- Comparison of calculated and experimental dimensional error for POM and PP

Polymer & Process combination	***Error (µm)***		***Difference (µm)***
	Model	***Experimental***	
POM (T_p, T_m, V_{inj}, P_{inj})			
200, 120, 350, 600	21.27	18.88	2.39
200, 120, 350, 800	14.71	13.95	0.76
225, 120, 350, 600	11.48	10.05	1.43
225, 120, 350, 800	8.17	5.67	2.5
PP (T_p, T_m, V_{inj}, P_{inj})			
190, 90, 350, 600	8.95	8.92	0.03
190, 90, 350, 800	6.89	5.87	1.02
220, 90, 350, 600	3.90	3.89	0.01
220, 90, 350, 800	1.28	1.17	0.11

Table 7-2 shows a comparison of the calculated UTS from the models and those obtained from the experiments. The difference shown in numbers is the result of using the steel insert. It was explained that the lower thermal conductivity of the mould insert results in lower UTS of the micro parts. Mould material was not considered in the models and the models are generated based on the brass inserts. This is the source of the difference between the experimental and calculated UTS for the steel insert. However, because PP is less affected by change in temperature, the results have much smaller error than those of POM.

Table 7-2-Comparison of calculated and experimental UTS for POM and PP

Polymer & Process combination	***UTS (MPa)***		***Difference (MPa)***
	Model	***Experimental***	
POM (T_p, T_m, V_{inj}, P_{inj})			
215, 120, 400, 700	39.52	32.62	6.9
215, 120, 650, 700	28.03	26.86	1.17
225, 120, 400, 700	34.88	28.82	6.06
225, 120, 650, 700	23.19	23.09	0.1
PP (T_p, T_m, V_{inj}, P_{inj})			
210, 95, 400, 700	19.04	18.79	0.25
210, 95, 600, 700	14.46	15.18	0.72
220, 95, 400, 700	14.27	15.50	1.23
220, 95, 600, 700	9.98	11.75	1.77

7.5 Chapter summary

This chapter was intended to validate all the three contributions, the experimental results and the empirical models obtained for dimensional accuracy and UTS. For this purpose a set of experiments were designed. These experiments are intended to validate the trends and calculations obtains in the previous three chapters.

To do a comprehensive validation, a new steel mould insert was used with micro channels that have different but close dimension to those used in the brass insert. Once the results were obtained they were compared with those from the previous chapters and any differences and discrepancies were examined and explained.

Chapter 8

Chapter 8 Conclusions & Future work

8.1 Thesis summary

The work has delivered a new method for modeling of the effect of process parameters on the dimensional accuracy and ultimate tensile strength (UTS) of micro parts. These models support the aim of optimizing the process of manufacturing micro parts by enabling the estimation of these two important quality criteria. The models are achieved as a result of using several methods that are employed in the field and also developed in this project. These address specific knowledge gaps identified in the literature. The models and methods were developed empirically with the help of experiments designed specifically for this purpose. The main experimental work consists of manufacturing micro walls with different dimensions in micro range, using the Battenfeld Microsystem 50 micro moulding machine. Two polymers were used in the development of the models, POM and PP. This work was supported by visualization and measurements performed on a scanning electron microscopy (SEM) and tensile strength analysis using an Instron 5969 pull test machine. The acquired data was analysed using a variety of software such as Excel, MATLAB and Minitab.

The models were developed with assumptions and limitations in mind. First of all, the design of the mould remains the same throughout the study to ensure similar flow of polymer melt for all analysis. Secondly, the dimensions of the features are kept within a certain range and do not change drastically. This is again to ensure that the behavior of the polymer melt does not vary heavily. Thirdly, the developed models can only be employed for semi crystalline polymers. Use of amorphous polymers will most likely change the flow properties and so may vary considerably from the results predicted by the models developed in the study. All equipment used in this study is commercially available and used in industrial applications. All the good practice, guides and recommendations are followed strictly to ensure the realisation of high quality parts.

The developed models and methods in this thesis were experimentally validated for different dimensions of the features used in this work. Since the proposed models address a field that is both vast and complex it would have been beyond the scope of

this study to validate them for all polymers and features. In addition, the high cost of mould design and manufacture also prevented the specific models from been validated for other mould designs.

The key findings and results from this thesis are presented in the following sections.

8.2 Knowledge contributions

The research guided by the originally defined aim and objectives has delivered several main contributions to knowledge, which are summarised below.

8.2.1 Effect of process parameters on the dimensional accuracy of micro moulded micro parts

The effect of the process parameters on dimensional accuracy of micro parts was investigated to understand the behavior of the polymers in response to variation in four process parameters. These four parameters are polymer melt temperature, mould temperature, injection velocity and injection pressure. The width of the micro walls was varied to investigate the behavior of the polymer melt in different sizes of channels. Statistical analysis showed that polymer melt temperature is the most influential parameter in enhancing the dimensional accuracy of the parts. This was followed by injection pressure and mould temperature. Increase in these three parameters was shown to have a positive effect on the dimensional accuracy. However, increase in injection velocity was shown to reduce the dimensional accuracy. Nevertheless, this effect was small (5% at most). The choice of polymers also had a significant effect on the dimensional accuracy. Use of PP caused the range of error to fall about 50% in most cases compared to POM.

Overall, the chapter provides a methodology for obtaining empirical data that can be used for the development of a model to relate the process parameters to dimensional accuracy of the micro parts. Furthermore, a process window was established for optimisation of the process based on empirical data. The process window shows the range of these four parameters where the smallest error can be achieved.

8.2.2 Effect of process parameters on the ultimate tensile strength (UTS) of micro moulded micro parts

The effect of process parameters on the strength of weld lines was investigated. The same four process parameters (polymer melt temperature, mould temperature, injection velocity and injection pressure) were used. This was done to be able to compare and investigate whether variation in the parameters would have a similar or the opposite effect on the strength of the micro parts. Statistical analysis showed polymer melt temperature has the highest effect on the strength of the weld lines. This is followed by injection velocity and mould temperature and injection pressure in most cases (in one case, the second micro wall made by PP, injection pressure was shown to have a higher influence than mould temperature). However, the effect of mould temperature and injection pressure was below the statistical threshold in all cases. Furthermore, increase in all process parameters showed a negative effect, except mould temperature which showed a minor positive effect. The polymers were shown to have a significant influence on the UTS. POM was shown to have two times the UTS compared to PP under the same processing conditions.

In summary, the chapter provides a method for obtaining empirical data that can be used for developing a model for estimating the UTS of the micro walls.

8.2.3 Empirical modeling of dimensional accuracy and the ultimate tensile strength (UTS)

Two models were developed for estimation of dimensional error and UTS of micro walls. The models were generated based on a combination of dimensional analysis and empirical data. A link was established between specific polymer properties and some process parameters to estimate the dimensional error and UTS of the micro walls. The investigated polymer properties were density, specific heat capacity and thermal conductivity; and they were linked to polymer melt and mould temperature, and injection pressure and velocity. The accuracy of the PP at pressure of 800 bar showed to have a different behavior to pressures of 400 and 600 bar. Therefore, a separate model was developed for this case. The threshold pressure at which the behavior changes requires further investigation.

All models were validated experimentally, using a different mould with a different channel dimension. A comparison of the experimental values and those generated through calculations with the accuracy model showed very good agreement for the brass pin. However, use of a steel insert resulted in higher error between the calculated and experimental results; which is the result of change in the mould material.

8.2.4 Concluding remarks

In respect to the first two contributions it must be noted that, with the exception of mould temperature, the other process parameters have the opposite effect on the two quality criteria investigated in this work. This requires a careful consideration of the process parameters and their values when making the parts. This is especially crucial in the case of the polymer melt temperature and injection velocity, which were both shown to have a considerable effect on the dimensional accuracy and the UTS.

The use of polymers also presents a similar case. The micro walls made by PP proved to have considerably smaller dimensional error, however, they also had a significantly lower UTS. While the use of a specific polymer is likely a requirement of the customer, the application needs to be considered. Employment of the parts in different applications and definition of the most important criterion must dictate the settings on the machine and selection of the values of the process parameters. Mould material also showed a similar case and resulted in significant effect on both dimensional accuracy and the UTS of the micro parts.

8.3 Future work

The research presented in this thesis has been completed and the proposed models and methods have been validated experimentally, thus achieving the projects' aim and objectives. The research has also identified new opportunities for further investigation that could build on the results of this work.

Investigation of the effect of process parameters is an area that is being pursued by many researchers. Further investigation of other polymers will assist in understanding the effect of process parameters on the flow of the polymers. In this

instance, there are several other parameters that can be investigated. The list includes parameters such as holding pressure, holding time, ejection force and ejection temperature. Also realisation of other features with considerably smaller dimensions in the micro range is of interest.

In respect to the effect of process parameters on the UTS of micro parts, further parameters can be investigated. Most studies have focused on the investigation of PP, POM and HDPE. Further polymers can also be investigated. Furthermore, the ejection stage of the process is a part that requires further investigation.

In regards to the two proposed models, further enhancement is possible by the developments mentioned earlier in this section. The proposed models do not include several factors such as mould design, properties of the mould inserts, other features, sizes and polymers due to restriction of time and resources.

Investigation of the effect of mould design on part properties, their formalisation and inclusion in the models can enhance the performance of the models considerably. Also, further characterisation of the process in terms of polymer melt flow, flash formation, air evacuation, ejection phase, shrinkage and wrapage, and their addition to the models will make them more comprehensive. Other types of polymers, namely amorphous polymers and those reinforced by other materials such as glass and fibre, need to be investigated and included in the models.

To conclude on this section, all the above mentioned future work would further expand the proposed models, and enhance their performance, resulting in better and more accurate prediction of the properties of the micro parts. Consequently, this ensures a more optimised process in the manufacture of high quality parts in a repeatable and reliable manner. The ultimate goal would be to develop a comprehensive and integrated software tool which can predict the optimised values for a combination of process parameters in accordance with the product specification.

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Appendices

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Appendix A POM & PP Datasheets

Figure A-1 and *Figure A-2* show the datasheets for specific grades of PP and POM used in this study. Since the information regarding PP's physical data is not available online, it was obtained over a phone conversation with the manufacturer.

CARMEL OLEFINS

Technical Data Sheet

CAPILENE® SW 75 AV

Polypropylene Impact Copolymer

Description

CAPILENE® SW 75 AV is a high melt flow rate controlled rheology impact copolymer for injection molding. **CAPILENE® SW 75 AV** is nucleated with antistatic additivation. It is characterized by good stiffness and impact resistance as well as low shrinkage and low warpage.

Applications

CAPILENE® SW 75 AV is suitable for high speed injection molding of thin walled packaging containers and household articles.

Quality, Environment and Safety Regulations

Material Safety Data Sheet and Product Safety declarations are available on our web site http://www.caol.co.il

Properties		Method	Typical Value*	Unit
Physical				
Melt Flow Rate	(230°C/2.16Kg)	ASTM D 1238	65	g/10min
Mechanical				
Tensile Stress at Yield	(50mm/min)	ASTM D 638	24	MPa
Tensile Strain at Yield	(50mm/min)	ASTM D 638	8	%
Flexural Modulus		ASTM D 790	1200	MPa
Izod Impact Strength, notched	(+23°C)	ASTM D 256	75	J/m
Izod Impact Strength, notched	(-20°C)	ASTM D 256	45	J/m
Thermal				
Vicat Softening Temperature	(10N)	ASTM D 1525	147	°C
Heat Deflection Temperature	(0.45MPa)	ASTM D 648	95	°C

Figure A-1-PP datasheet

Ticona
Engineering Polymers

HOSTAFORM® C 27021 | POM | Unfilled

Physical properties	Value	Unit	Test Standard
Density	1410	kg/m³	ISO 1183
Melt volume rate (MVR)	24	cm³/10min	ISO 1133
MVR test temperature	190	°C	ISO 1133
MVR test load	2.16	kg	ISO 1133
Mold shrinkage - parallel	1.9	%	ISO 294-4
Mold shrinkage - normal	1.8	%	ISO 294-4
Water absorption (23°C-sat)	0.65	%	ISO 62
Humidity absorption (23°C/50%RH)	0.2	%	ISO 62

Mechanical properties	Value	Unit	Test Standard
Tensile modulus (1mm/min)	2900	MPa	ISO 527-2/1A
Tensile stress at yield (50mm/min)	65	MPa	ISO 527-2/1A
Tensile strain at yield (50mm/min)	7.5	%	ISO 527-2/1A
Nominal strain at break (50mm/min)	17	%	ISO 527-2/1A
Tensile creep modulus (1h)	2500	MPa	ISO 899-1
Tensile creep modulus (1000h)	1300	MPa	ISO 899-1
Charpy impact strength @ 23°C	120	kJ/m²	ISO 179/1eU
Charpy impact strength @ -30°C	120	kJ/m²	ISO 179/1eU
Charpy notched impact strength @ 23°C	6	kJ/m²	ISO 179/1eA
Charpy notched impact strength @ -30°C	4.5	kJ/m²	ISO 179/1eA

Test specimen production	Value	Unit	Test Standard
Processing conditions acc. ISO	9988	-	Internal
Injection molding melt temperature	195	°C	ISO 294
Injection molding mold temperature	85	°C	ISO 294
Injection molding flow front velocity	200	mm/s	ISO 294
Injection molding hold pressure	90	MPa	ISO 294

Rheological Calculation properties	Value	Unit	Test Standard
Density of melt	1200	kg/m³	Internal
Thermal conductivity of melt	0.155	W/(m K)	Internal
Specific heat capacity of melt	2210	J/(kg K)	Internal
Ejection temperature	165	°C	Internal

Figure A-2- POM datasheet

Appendix B Battenfeld operating procedure

Battenfeld Microsystem 50 was used to conduct all the experiments in this study. *Figure B-1* to *Figure B-3* show the panels used for control of the machine. The operating procedure and the order of actions followed are detailed below:

1. Turn on the main switch.
2. Operate the safety doors (open and close) (*Figure B-3*).
3. Operate the emergency stops (activate and release) (*Figure B-3*).
4. Enter "log in" details
5. Remove drier from the hopper.
6. Insert polymer pallets.
7. Screw the drier back on the hopper.
8. Turn on the motor (*Figure B-3*).
9. Turn on the heaters (*Figure B-3*).
10. Set the desired temperature values in the temperature setting interface (*Figure B-2*).
11. Set other processing parameters in their respective setting interface (injection velocity, injection pressure, volume, holding pressure, holding time, injection time) (*Figure B-2*).
12. Once the desired temperatures are achieved, machine can be operated.
13. Put the robot arm in home position (*Figure B-3*).
14. Pull ejectors back (*Figure B-3*).
15. Ensure mould cavity is aligned (*Figure B-3*).
16. Empty degraded polymer from the injection chamber by purging some of the polymer (*Figure B-3*).
17. Use the injection piston to empty the injection chamber (*Figure B-3*).
18. Once the chamber is empty of any polymer, push the piston in forward position (*Figure B-3*).
19. Pull polymer melt in the dosing chamber by operating the dosing piston (*Figure B-3*).
20. Put the machine in automatic mode (*Figure B-3*).
21. Push the mould forward to start the production cycle (*Figure B-3*).
22. Process parameters can be changed during the operation.

23. Each time a new set of parameters are entered, discard the first 10 parts.
24. Use the following 10 parts for analysis and data gathering.
25. Once experiments are finished, stop the automatic operation by selecting the manual mode.
26. Polymer can be changed by performing step 4 and further experiments can be conducted following the operating procedure.
27. Once the experiments are fully completed remove the polymer pallets from the hopper.
28. Empty the injection chamber by purging the remaining polymer melt.
29. Preferably use a purging agent or PP to ensure the chamber is empty of sensitive engineering polymers such as POM as they can degrade quickly and burn.
30. Turn off the heaters (*Figure B-3*).
31. Turn off the motor (*Figure B-3*).
32. Log out of the account.
33. Turn the machine off from the main.

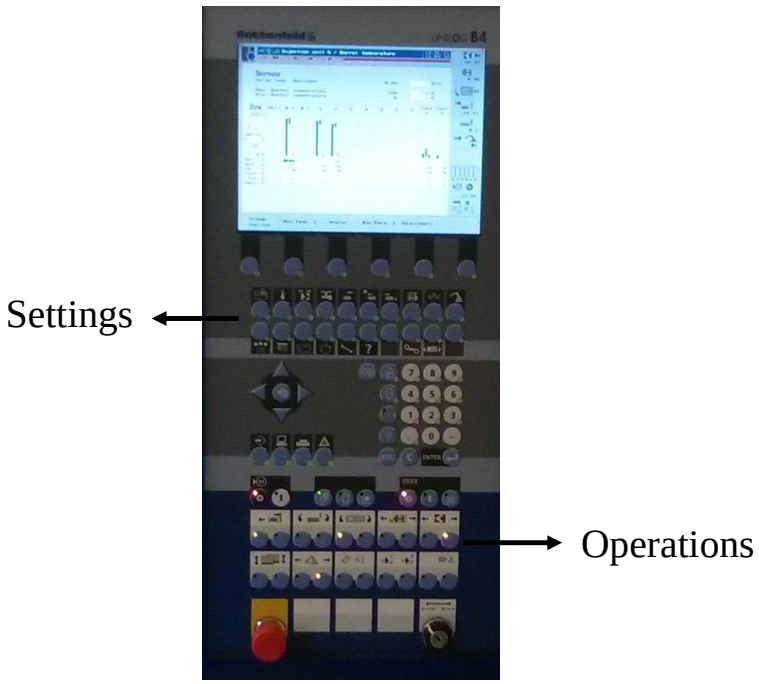

Figure B-1- Microsystem 50's overall control panel

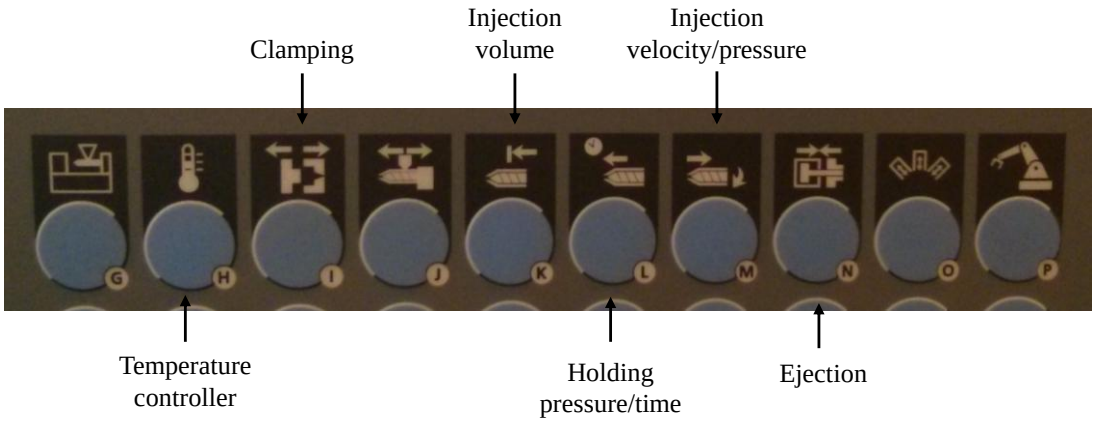

Figure B-2- Microsystem 50's settings panel

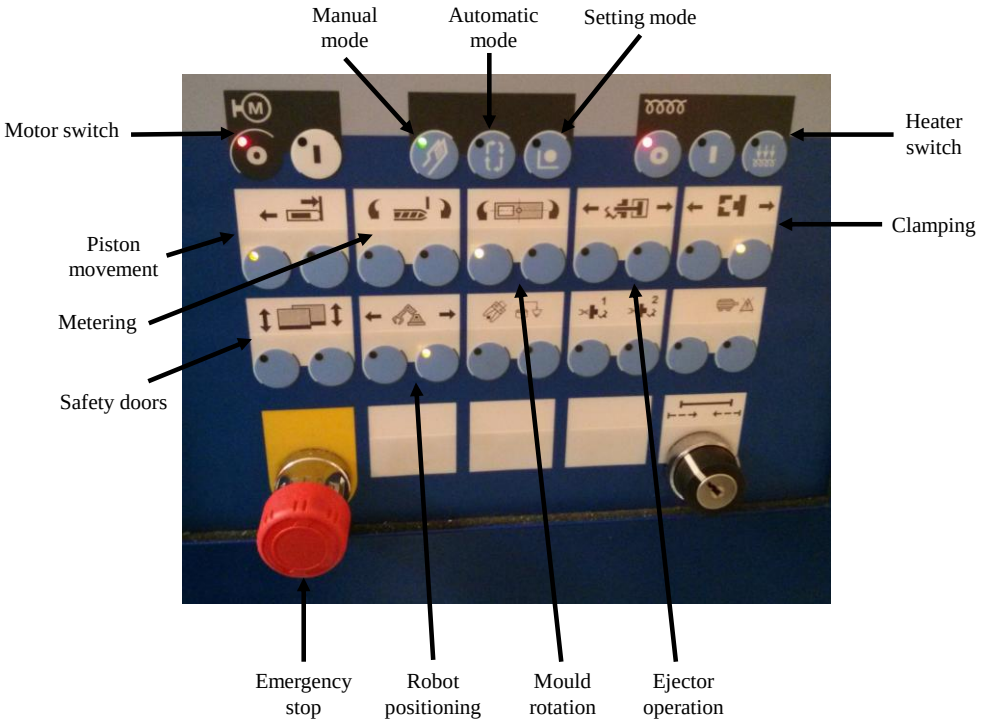

Figure B-3- Microsystem 50's operations panel

Appendix C Surface roughness measurements

This section provides the analysis done on a surface roughness measurement machine "Veeco". For each channel three locations are measured, left, middle and right side of the channels. This is done for all the three micro channels used in this study and the one used for validation on the steel pin. The average of the three measurements is considered the surface roughness of that micro channel. Results are presented below in *Table C-1*.

Table C-1- Surface roughness measurements for each micro channel

Pin/ Channel	***S_a left (µm)***	***S_a middle (µm)***	***S_a right (µm)***	***S_a average (µm)***
Brass, Channel 1	0.656	0.343	2.862	1.286
Brass, Channel 2	0.251	0.205	0.352	0.270
Brass, Channel 3	1.305	1.460	3.136	1.967
Steel	0.335	0.213	0.209	0.252

Appendix D Instron 5969 operating procedure

Instron 5969 was used to conduct the pull tests in this study. The operating procedure and the actions followed are listed below:

1. Turn on the machine and the computer.
2. Enter details of the specimens for the test (dimensions of the width and depth).
3. Select a load and the maximum load (50 N) and the rate of elongation (1mm/s in this study).
4. Put the part in the fixture.
5. Cut the edges.
6. Ensure that initial elongation and force are set to zero.
7. Start the test.
8. After the test is done, open the fixture and remove the part.
9. To conduct a pull test on the next specimen, repeat from Step 4.

Appendix E Calculation of the accuracy model for POM & PP

Calculations for POM:

The general shape of the equations is $\pi_1 = aEXP(b\pi_7))$, where each micro channel has different values for "a" and "b". However, "a" and "b" are different due to change in temperature (π_8). To reduce the error of the calculations, the "a" and "b" are considered for all equations (still as a function of π_8). To make a general model for all the micro channels, a constant "c" is defined which is the function of π_8 and $l = {D_c}/{D_p}$. To achieve each of these constants, the values for each micro channels are plotted against π_8 and the function with the least error is calculated through the curve fitting function in MATLAB. The results are shown below:

Calculation of "a", "b" and "c"

a: Linear model Poly2:

$a = -1.783\text{e} + 007\pi_8^2 + 2.546\text{e} + 005\pi_8 - 767.9$

Goodness of fit:

SSE: 1.682e-024

R-square: 1

****

b: Linear model Poly2:

$b = 2.465\pi_8^2 - 0.03267\pi_8 + 2.723\text{e-}005$

Goodness of fit:

SSE: 2.613e-038

R-square: 1

****

c: $c = q_1\pi_8^2 + q_2\pi_8 + q_3$

where the constants are calculated as 2nd order functions of *l*:

q_1: Linear model Poly2:

$q_1 = -1.562\text{e} + 007l^2 + 1.214\text{e} + 006l - 2.337\text{e} + 004$

Goodness of fit:

SSE: 2.404e-022

R-square: 1

****

q_2: Linear model Poly2:

$q_2 = 2.609\text{e} + 005l^2 - 2.04\text{e} + 004l + 395.8$

Goodness of fit:

SSE: 4.097e-027

R-square: 1

****

q_3: Linear model Poly2:

$q_3 = -963.6l^2 + 73.59l - 1.388$

Goodness of fit:

SSE: 1.595e-031

R-square: 1

****

Replacing the constants gives the following final equation:

$$\pi_1 = (-1.783 \times 10^7 \pi_8^2 + 2.546 \times 10^5 \pi_8 - 767.9) EXP((2.465\pi_8^2 - 0.03267\pi_8 + (2.723 \times 10^{-5}))\pi_7) + \left((-1.562 \times 10^7 l^2 + 1.214 \times 10^6 l - 2.337 \times 10^4)\pi_8^2 + (2.609 \times 10^5 l^2 - 2.04 \times 10^4 l + 395.8)\pi_8 + (-963.6l^2 + 73.59l - 1.388)\right)$$

Calculations for PP:

Calculations for P_{inj} of 400 and 600 bar

Figure E-1, *Figure E-2* and *Figure E-3* show the functions with the smallest error for micro walls 1, 2 and 3.

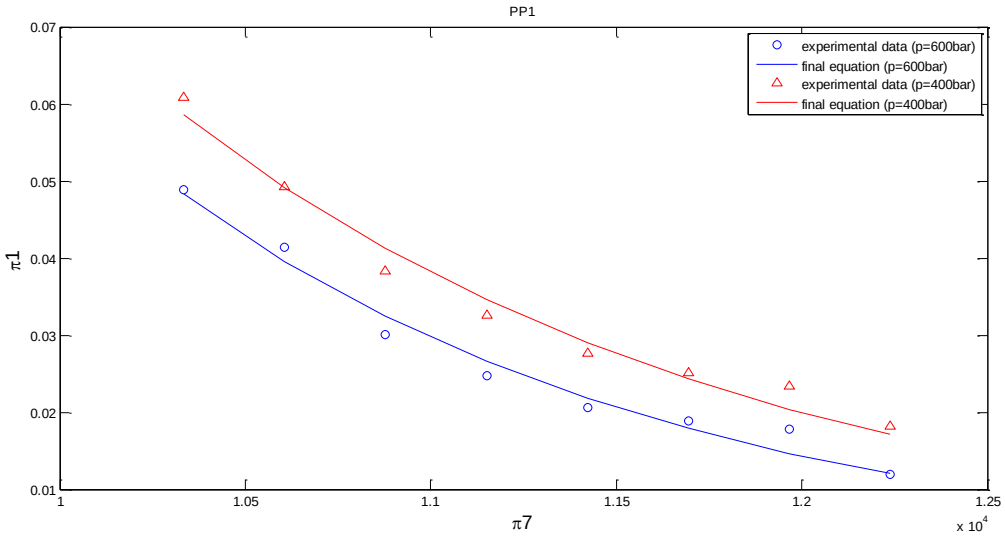

Figure E-1- Best fit for micro wall 1 accuracy data for PP (Pinj of 400 and 600 bar)

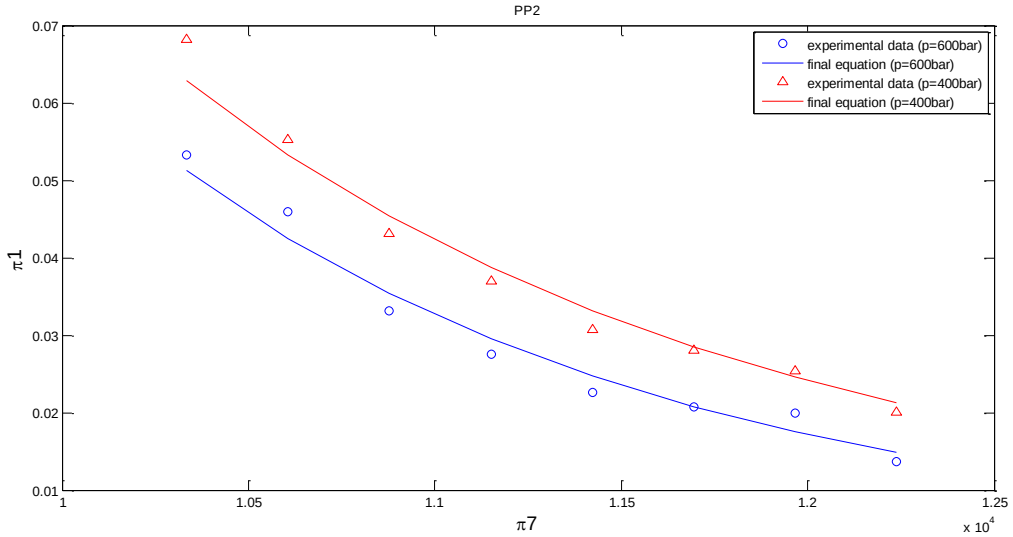

Figure E-2- Best fit for micro wall 2 accuracy data for PP (Pinj of 400 and 600 bar)

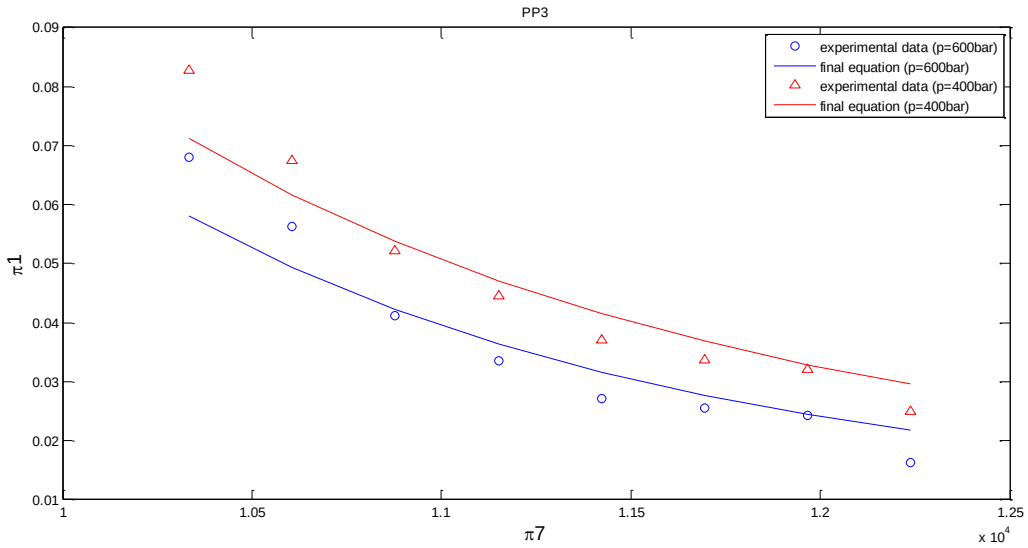

Figure E-3- Best fit for micro wall 3 accuracy data for PP (Pinj of 400 and 600 bar)

Calculation of "a", "b" and "c"

a: Linear model Poly1:

$a - 2.514\text{e} + 004\pi_8 + 180.6$

Goodness of fit:

SSE: 8.583e-028

R-square: 1

****

b: Linear model Poly1:

$b = 0.04693\pi_8 - 0.0008964$

Goodness of fit:

SSE: 1.175e-038

R-square: 1

****

c: $c = q_1\pi_8 + q_2$

where the constants are calculated as 2nd order functions of *l*:

q_1: Linear model Poly2:

$q_1 = -3403l^2 + 114.1l + 1.279$

Goodness of fit:

SSE: 6.903e-031

R-square: 1

****

q_2: Linear model Poly2:

$q_2 = 43.78l^2 - 3.62l + 0.07476$

Goodness of fit:

SSE: 6.372e-034

R-square: 1

****

Replacing the constants gives the following final equation:

$$\pi_1 = (-2.514 \times 10^4 \pi_8 + 180.6) EXP((0.04693\pi_8 - 0.8964 \times 10^{-3})\pi_7) + \left(-3403\left(\frac{D_c}{D_p}\right)^2 + 114.1\left(\frac{D_c}{D_p}\right) + 1.2789\right)\pi_8 + \left(43.78\left(\frac{D_c}{D_p}\right)^2 - 3.62\left(\frac{D_c}{D_p}\right) + 0.07476\right)$$

Calculations for P_{inj} of 800 bar

The same method is used to find an equation for the pressure of 800 bar for PP. As explained previously in this section, PP behaves differently at this temperature and therefore, requires a model with different constants. *Figure E-4* below shows that the form of the equation is the same as before (exponential). However, the constants for the equation are different.

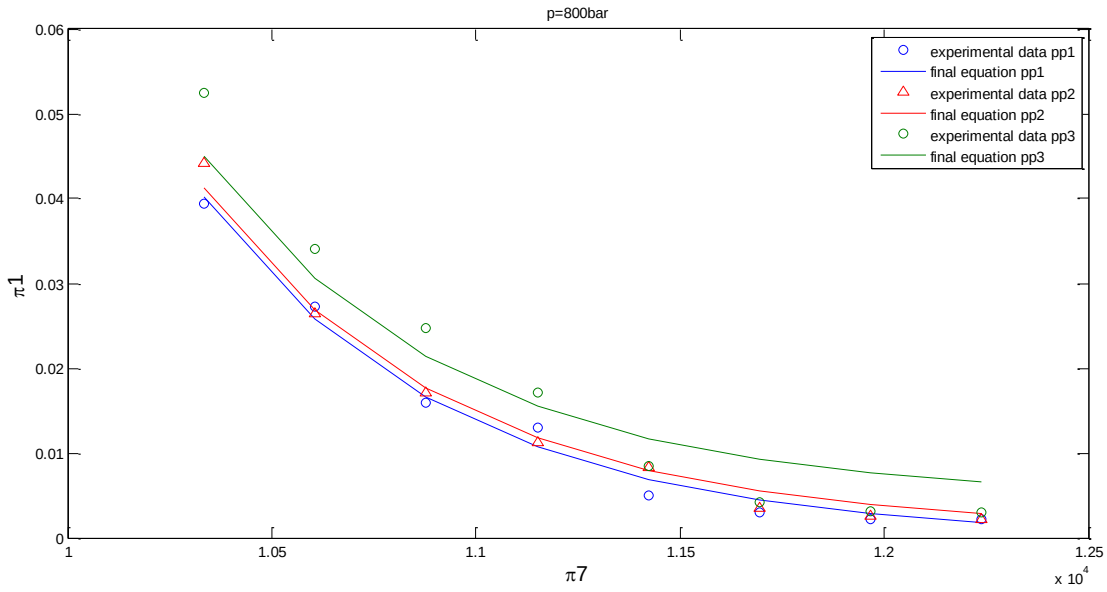

Figure E-4- Best fit equations for all three micro walls made out of PP (Pinj of 800 bar)

Calculation of "a", "b" and "c"

The general form of the equations is:

$\pi_1 = aEXP(b\pi_7) + c$

Where "a" and "b" for micro channel 1 are:

General model Exp1:

$\pi_1 = 7.984\text{e} + 005EXP(-0.001626\pi_7)$

Goodness of fit:

SSE: 1.5e-005

R-square: 0.9885

****

Since the pressure is at a constant value of 800 bar, the constant "c" is a function of *l*.

Linear model Poly2:

$c = 27.17l^2 - 2.429l + 0.05415$

Goodness of fit:

SSE: 1.585e-035

R-square: 1

****

Replacing the constants gives the following final equation:

$$\pi_1 = (7.984 \times 10^5)EXP(-0.001626\pi_7) + (27.17(\frac{D_c}{D_p})^2 - 2.429(\frac{D_c}{D_p}) + 0.05415)$$

Appendix F Calculation of the dimensionless groups for the UTS model

There are eight variables with four basic dimensions (M, L, T and θ). According to Buckingham's π Theorem the number of dimensionless groups is four (8-4=4) which are π_1, π_2, π_3, π_4 and π_5. Due to the fact that Buckingham's π Theorem may not result in correct value for "r", one must validate the number of dimensionless groups by formation of the dimensional matrix. This is shown below in *Figure F-1*.

	σ_{UTS}	T_p	T_m	Q	P	ρ	k	C_p
L	-1	0	0	3	-1	-3	1	2
M	1	0	0	0	1	1	1	0
T	-2	0	0	-1	-2	0	-3	-2
θ	0	1	1	0	0	0	-1	-1

Figure F-1- Dimensions of the variables in μIM mechanical model

The dimensional matrix is then

$$\begin{bmatrix} -1 & 0 & 0 & 3 & -1 & -3 & 1 & 2 \\ 1 & 0 & 0 & 0 & 1 & 1 & 1 & 0 \\ -2 & 0 & 0 & -1 & -2 & 0 & -3 & -2 \\ 0 & 1 & 1 & 0 & 0 & 0 & -1 & -1 \end{bmatrix}$$

Following the method introduced previously, the least number of columns and rows that result in a determinant of a number other than zero is clearly four (e.g. last four columns). Therefore, the rank of the dimensional matrix, and the value of *r*, is four. So four dimensionless groups (*n*-*r*=8-4=4) are required to form the mathematical equation that predicts the UTS as a function of the other seven variables. This confirms that Buckingham's π theorem was also correct in this case.

Once the number of dimensionless groups is identified one can form them by dimensional analysis. The four dimensionless groups require four non-repeatable variables. These are UTS T_p, T_m and K (as a polymer characteristic). Therefore, there are four repeatable variables; Q, C_p, P and ρ. Each of the non-repeatable variables exists in one dimensionless group, with the four repeatable ones. Therefore, π_1 is calculated as:

$$\pi_1 = \sigma_{UTS} P^a \rho^b C_p^c Q^d \equiv (ML^{-1}T^{-2})\,(ML^{-1}T^{-2})^a\ (ML^{-3})^b\ (L^2T^{-2}\theta^{-1})^c (L^3T^{-1})^d \quad \textit{Equation F.1}$$

Since π_1 is a dimensionless number, the sum of the powers for M, L, T and θ should be zero. Therefore,

$$\text{L: } -1 - a - 3b + 2c + 3d = 0 \quad \textit{Equation F.2}$$

$$\text{M: } 1 + a + b = 0 \quad \textit{Equation F.3}$$

$$\text{T: } -2 - 2a - 2c - d = 0 \quad \textit{Equation F.4}$$

$$\theta\text{: } -c = 0 \quad \textit{Equation F.5}$$

By solving the above equations, values for d, c, and b are zero and $a = -1$. Therefore,

$$\pi_1 = \sigma_{UTS} P^{-1} \rho^0 C_p^0 Q^0$$

$$\pi_1 = \frac{\sigma_{UTS}}{P} \quad \textit{Equation F.6}$$

π_2 is calculated as:

$$\pi_2 = T_p P^a \rho^b C_p^c Q^d \equiv (\theta)\,(ML^{-1}T^{-2})^a\ (ML^{-3})^b\ (L^2T^{-2}\theta^{-1})^c (L^3T^{-1})^d \quad \textit{Equation F.7}$$

Since π_2 is a dimensionless number, the sum of the powers for M, L, T and θ should be zero. Therefore,

$$\text{L: } -a - 3b + 2c + 3d = 0 \quad \textit{Equation F.8}$$

$$\text{M: } a + b = 0 \quad \textit{Equation F.9}$$

$$\text{T: } -2a - 2c - d = 0 \quad \textit{Equation F.10}$$

$$\theta\text{: } 1 - c = 0 \quad \textit{Equation F.11}$$

By solving the above equations, value for d is zero, $a = -1$ and $= c = 1$. Therefore,

$$\pi_2 = T_p P^{-1} \rho^1 C_p^1 Q^0$$
$$\pi_2 = \frac{T_p \rho C_p}{P} \quad \textit{Equation F.12}$$

π_3 is calculated as:

$$\pi_3 = T_m P^a \rho^b C_p^c Q^d \quad \textit{Equation F.13}$$
$$\equiv (\theta)\ (ML^{-1}T^{-2})^a\ \ (ML^{-3})^b\ (L^2T^{-2}\theta^{-1})^c (L^3T^{-1})^d$$

Since π_3 is a dimensionless number, the sum of the powers for M, L, T and θ should be zero. Therefore,

L: $-a - 3b + 2c + 3d = 0$ *Equation F.14*

M: $a + b = 0$ *Equation F.15*

T: $-2a - 2c - d = 0$ *Equation F.16*

θ: $1 - c = 0$ *Equation F.17*

By solving the above equations, values for d, c, and b are zero and $a = -1$. Therefore,

$$\pi_3 = T_m P^{-1} \rho^1 C_p^1 Q^0$$
$$\pi_3 = \frac{T_m \rho C_p}{P} \quad \textit{Equation F.18}$$

π_4 is calculated as:

$$\pi_4 = K P^a \rho^b C_p^c Q^d \quad \textit{Equation F.19}$$
$$\equiv (MLT^{-3}\theta^{-1})\ (ML^{-1}T^{-2})^a\ \ (ML^{-3})^b\ (L^2T^{-2}\theta^{-1})^c (L^3T^{-1})^d$$

Since π_4 is a dimensionless number, the sum of the powers for M, L, T and θ should be zero. Therefore,

L: $1 - a - 3b + 2c + 3d = 0$ *Equation F.20*

M: $1 + a + b = 0$ *Equation F.21*

T: $-3 - 2a - 2c - d = 0$ *Equation F.22*

$\theta: -1 - c = 0$ *Equation F.23*

By solving the above equations, $a = -{}^{1}/_{4}$, $c = -1$, $d = -{}^{1}/_{2}$ and $b = -{}^{3}/_{4}$. Therefore,

$$\pi_4 = KP^{-{}^{1}/_{4}}\rho^{-{}^{3}/_{4}}C_p^{-1}Q^{-{}^{1}/_{2}}$$
$$\pi_4 = \frac{K}{P^{{}^{1}/_{4}}\rho^{{}^{3}/_{4}}C_pQ^{{}^{1}/_{2}}} \quad \textit{Equation F.24}$$

If the calculations are performed correctly, π_1, π_2, π_3, π_4 and π_5 must have dimensions of one. To validate that the performed equations are correct, dimensions of each of the groups is calculated:

$$\pi_1 = \frac{\sigma_{UTS}}{P} \equiv \frac{ML^{-1}T^{-2}}{ML^{-1}T^{-2}} = 1$$
$$\pi_2 = \frac{T_p\rho C_p}{P} \equiv \theta\frac{M}{L^3}\frac{L^2}{T^2\theta}\frac{M^{-1}}{L^{-1}T^{-2}} = 1$$
$$\pi_3 = \frac{T_m\rho C_p}{P} \equiv \theta\frac{M}{L^3}\frac{L^2}{T^2\theta}\frac{M^{-1}}{L^{-1}T^{-2}} = 1$$
$$\pi_4 = \frac{K}{P^{{}^{1}/_{4}}\rho^{{}^{3}/_{4}}C_pQ^{{}^{1}/_{2}}} \equiv \frac{ML}{T^3\theta}\frac{1}{M^{{}^{1}/_{4}}L^{-{}^{1}/_{4}}T^{-{}^{2}/_{4}}}\frac{1}{M^{{}^{3}/_{4}}L^{-{}^{9}/_{4}}}\frac{1}{L^2T^2\theta}\frac{1}{L^{{}^{3}/_{2}}T^{-{}^{1}/_{2}}} = 1$$

Therefore, all groups are dimensionless.

Based on Buckingham's π Theorem, one of the dimensionless groups is a function of the other four. Since the objective here is to calculate the UTS as a function of the other variables π_1 is the one isolated on the left side of the equation. Therefore,

$\pi_1 = f(\pi_2, \pi_3, \pi_4)$ *Equation F.25*

This means the general mechanical equation is

$$\frac{\sigma_{UTS}}{P} = f\left(\frac{T_p\rho C_p}{P}, \frac{T_m\rho C_p}{P}, \frac{K}{P^{{}^{1}/_{4}}\rho^{{}^{3}/_{4}}C_pQ^{{}^{1}/_{2}}}\right) \quad \textit{Equation F.26}$$

Appendix G Calculation of the UTS models

It was already established in **Chapter 5** that the dimension of the micro walls (or micro channels in the mould cavity) does not affect the UTS of the micro parts. Therefore the size of the micro walls is not a variable in these calculations. To find a general model, dimensional analysis was used to find a general relationship (*Appendix F*). The final expressions were formed in a way to isolate the UTS (π_1), polymer melt temperature (π_2) and injection velocity (π_5). Then a plot of π_1 against π_5 was formed for at different π_2s. The general function was formed through MATLAB's curve fitting function. The function with the smallest statistical error was a 2nd order polynomial function for both POM and PP. The function therefore was:

$$\pi_1 = a\pi_5^2 + b\pi_5 + c$$

Where "a", "b" and "c" are functions of π_2 (polymer melt temperature). To reduce the error of the calculations, a normalisation function *z* was defined where,

$$Z_{POM} = (\pi_5 - 1.0977 \times 10^{-5})/1.1129 \times 10^{-6}$$
$$Z_{PP} = (\pi_5 - 5.1791 \times 10^{-5})/5.2507 \times 10^{-6}$$

Therefore the general function becomes

$$\pi_1 = az^2 + bz + c$$

The figures and calculation of constants for each polymer are shown below.

Calculations for POM:

Figure G-1 shows the functions and the shape of the line for the fitted data for UTS of micro walls made out of POM. The calculation of constants "a", "b" and "c" as functions of π_2 are shown below.

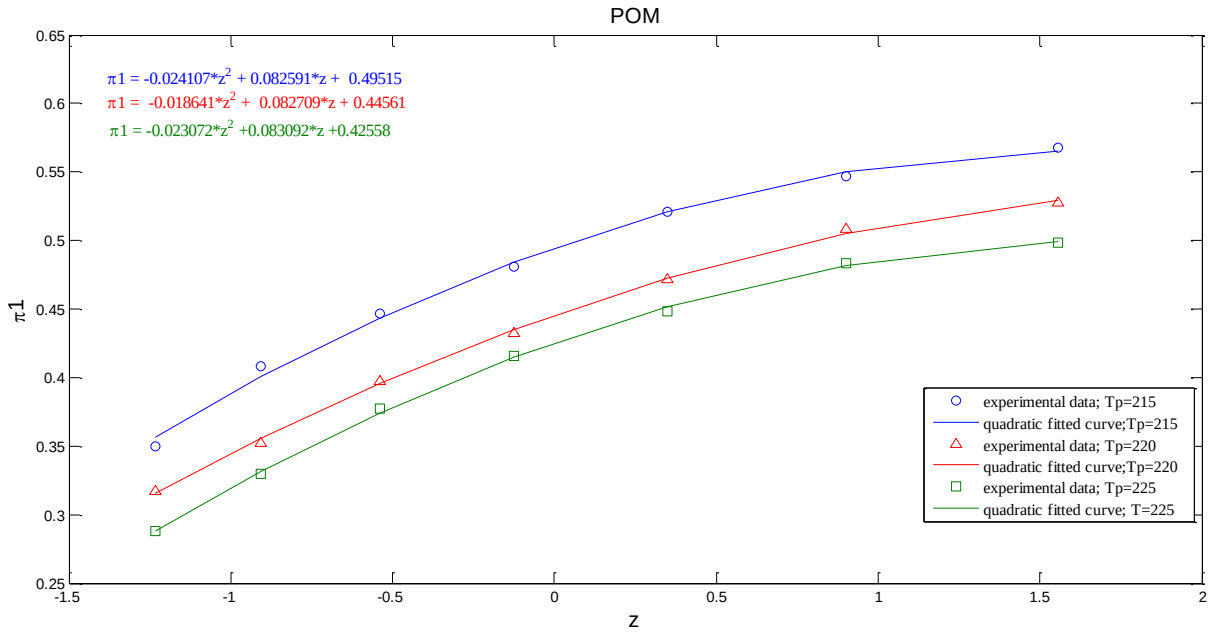

Figure G-1- UTS data fit for micro walls made out of POM

Calculation of "a", "b" and "c"

a: Linear model Poly2:

$a = -92222\pi_2^2 + 1882.1\pi_2 - 9.6217$

****

b: Linear model Poly2:

$b = 2469.3\pi_2^2 - 49.255\pi_2 + 0.32821$

****

c: Linear model Poly2:

$c = 2.7498\text{e} + 005\pi_2^2 - 5755.5\pi_2 + 30.542$

****

Replacing the constants gives the following final equation:

$\pi_1 = (-92222\pi_2^2 + 1882.1\pi_2 - 9.6217)Z_{POM}^2 + (2.469.3\pi_2^2 - 49.255\pi_2 + 0.32821)Z_{POM} + (2.7498\pi_2^2 - 5755.5\pi_2 + 30.542)$

Calculations for PP:

Figure G-2 shows the functions and the shape of the line for the fitted data for UTS of micro walls made out of PP. The calculation of constants "a", "b" and "c" as functions of π_2 are shown below.

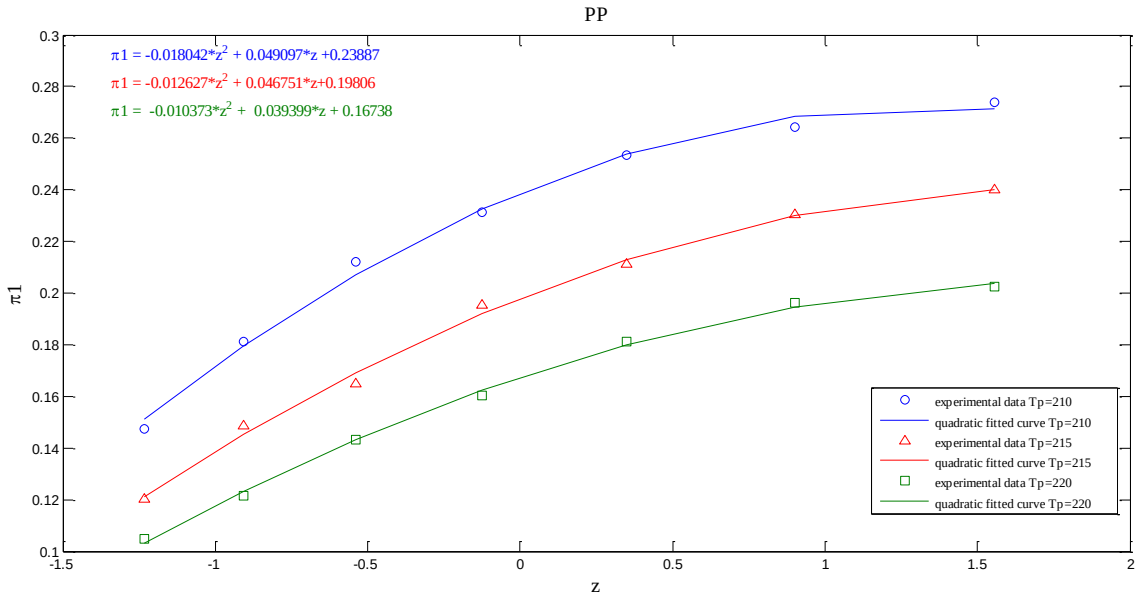

Figure G-2- UTS data fit for micro walls made out of PP

Calculation of "a", "b" and "c"

a: Linear model Poly2:

$$a = -55713\pi_2^2 + 829.77\pi_2 - 3.0998$$

****

b: Linear model Poly2:

$$b = -88233\pi_2^2 + 1249.3\pi_2 - 4.3728$$

****

c: Linear model Poly2:

$$c = 1.7854\text{e}+005\pi_2^2 - 2798.4\pi_2 + 11.1$$

****

Replacing the constants gives the following final equation:

$$\pi_1 = (-55713\pi_2^2 + 829.77\pi_2 - 3.0998)Z_{PP}^2 + (-88233\pi_2^2 + 1249.3\pi_2 - 4.3728)Z_{PP} + (1.7854\pi_2^2 - 2798.4\pi_2 + 11.1)$$