COMPUTER APPLICATION-ELECTRO MECHANICAL SYSTEMS

By

MEFTAH OMAR IBRAHIM

A thesis Submitted in Fulfilment of the requirements for the degree of Master of Engineering (M.Eng)

By research

School of Mechanical and Manufacturing Engineering
Dublin City University

February 2004

Supervisors

Professor. Saleem Hashmi

Dr. Dermot Brabazon

DECLARATION

I hereby certify that this material, which I now submit for assessment on the programme of study leading to the award of Master of Engineering is entirely my own work and has not been taken from the work of others save and to the extent that such work has been cited and acknowledged within the text of my work.

Signed: _____ **ID NO: 51179920**

Meftah Omar Ibrahim **Date: 9-Febrary-2004**

ACKNOWLEDGEMENTS

I am grateful to Professor Saleem Hashim and Dr. Dermot Brabazon for their support and advice through my work. I would also like to extend my gratitude to all academic staff of school who have helped me over the past two years. I would like to thank all the technical staff for their help with the experimental work, especially Michael Tyrrell and Alan Meehan, Liam Domican. I would like to thank the students of school. I would like to thank all my friends I 've met at Dublin City University for making this an interesting time. I would especially like to thank my close friends their support and entertainment. I would especially like to thank my parents for their continued throughout studies.

TABLE OF CONTENTS

List of Tables

List of Figures

Abstract

There are many different Rapid Prototyping (RP) technologies available which have been developed to large-scale use, mainly in the last decade. Today's commercially available rapid prototyping systems work with different techniques using paper, waxes, photocurable resins, polymers and new metal powders. This project is concerned with one type of rapid prototyping technology, namely fused deposition modelling, which was initially commercialised in 1991. A new version of the fused deposition modelling system using wax has been designed and used in this work. The present project describes the basic system design, and the method of wax deposition. The FDM machine builds the part by extruding semi-molten material through a heated nozzle in a prescribed pattern onto a platform. The extrusion jet is mounted on a X-Y table which is controlled by a computer system. In conjunction with the automated control of the plunger mechanism and the depositor position, accurate models were produced. Single layers of wax were built up one on top of the other to produce two-dimensional and three-dimensional objects. The characteristics of the wax were also analysed in order to optimise the model production process. These included wax phase change temperature, wax viscosity and wax droplet shape during processing.

Chapter 1

1. INTRODUCTION

Rapid prototyping (RP) technology is a group of processes that enable the direct physical realization of 3D computer models [1]. RP is relatively new class of technology that can automatically fabricate physical models and prototype parts directly from 3D CAD data. RP machines have the capability to produce solid models from a variety of horizontal cross sections from a computer model in order to construct the physical model layer by layer [2].

Prototyping is one of the important phases in product development. With a prototyped product the designer can examine its aesthetic aspect, measure the physical dimensions of an assembly, accomplish functionality tests, validate its performance and so on. If the prototype fails to reach the standard requirements, the designer will have to redesign the product and prototyping will be needed again to re-check the product properties. Prototyping is a process of building pre-production models of a product to test various aspects of its design. RP techniques are methods that allow designs to quickly produce physical prototypes with the important benefit to reduce the time to market. By using of these techniques prototypes can be built only requiring the skill of individual craftsmen only for finishing the part. Furthermore, the resulting design cost will be considerably decreased. Many different RP technologies have been developed for large scale use over the last decade each has its own unique set of competencies and limitations. In some RP technologies the prototype part is produced by adding materials rather than removing materials. This simplifies the 3D part producing processes to a 2D layer adding processes so that a part can be produced directly from its computer model [3]. There are several different machines available from Stratasys Ltd., the main developer of Fused Deposition Modeling technology since 1991.

Fused Deposition Modeling (FDM) is one method to develop a rapid prototyped part. The FDM machine builds the part by extruding a semi-molten material through a heated nozzle in a prescribed pattern onto a platform. It entails the control of the deposition of wax or plastic droplets and the movement of an X-Y receiving table to produce the prototype. Single layers are bulit up, one on top of the other, to produce the final part shape.

Some additive RP technologies include stereolithography (SLA), Fused Deposition Modeling (FDM), selective laser sintering (SLS) and others. The focus of the research into these RP technologies is to minimise the prototyping time which increasing the accuracy and complexity of shapes that can be produced.

This thesis has been carried out to experimentally develop a fused depositon modeling (FDM) system using wax as the model material. The effect of depositon pressure on the viscosity and hence processability of the wax was investigated. Models produced with this system were for analysed dimensional accuracy under various processing condition. The measurements were conducted at 75, 78, up to 90 °C and with depositon pressure from 1 psi up to 30 psi. At these temperatures and pressures, the viscosities were observed to be in the range from (1.41 Pa.s to 0.143 Pa.s). The viscosity decreased with increasing pressure.

Chapter one presents an introduction and literature review of rapid prototyping, Chapter two provides the detail of the experimental system and procedures, and the results and discussion are presented in Chapter three and Chapter four respectively. The conclusion and recommendations based on this study are summarized in chapter five.

1.1 Rapid Prototyping Overview

Prototyping has become a necessary means to test and physically examine design, which are otherwise viewed with difficulty from either two dimension or three dimension schematic formats [4]. These three dimensional RP machines allow designers to quickly create tangible prototypes of their designs, rather than just two dimensional pictures. Rapid prototypes also bring benefits of reduced costs and improved product quality and hence its use within industry is expanding rapidly [5].

Rapid Prototyping systems work with different materials such as paper, polymers and waxes [6]. Rapid prototyping include enhanced visualization capability, decreases in cost and cycle time associated with fabrication of prototype parts [7], increased ability to calculate mass properties and detect design flaws before hardware fabrication, and increased part optimisation – development prior to prototyping [8]. RP for creation of concept models greatly reduces design cycle time. Engineers, designers, technicians, and managers can now examine a prototype more thoroughly before it goes into production. The part can also be used for fit and functional testing, but this depends on the mechanical properties of the material used

to build the prototype. Some rapid prototyping techniques enable the building of snap together mating parts. Rapidly prototyped parts can also be tested for aerodynamic properties. The field of rapid prototyping has seen the recent introduction of automated systems which can convert a computer solid model into a three-dimensional artifact. RP also called desktop manufacturing or free-form fabrication was developed in the mid-1980s [9]. This thesis will describe research into a new rapid prototyping process called Fused Deposition Modeling (FDM).

1.2 Benefits of Rapid Prototyping

Rapid prototyping can be achieved operating with additive or subtractive fabrication. The subtractive or "sculpturing" like technologies belong to the family of numerical control (CN) machining. The subtractive prototyping processes are widely used to produce prototype parts quickly. A subtractive prototyping process involves carving a solid block of material to reveal the shape of the desired object [10]. In comparison additive processes are more common and are characterized by the following features:

1.2.1Unlimited geometrical complexity

Complex structures that would require re-fixturing, tool changes and multi-axis tool paths to be machined can be more readily produced.

1.2.2 Engineered millistructure

Along with the ability to make arbitrary external shapes, additive fabricators offer the radical new possibility of designing the internal structure of fabricated objects. The advantages this offers in customizing material properties are beginning to be explored.

1.2.3 Unattended operation

The methodical lay down of section after section of material, or layer upon layer, is easy to automate. In contrast, the full automation of milling and other subtractive processes is more difficult if not impossible for some geometries to accomplish.

1.2.4 Waste-less fabrication

A subtractive process always wastes the entire "negative space" of the object being built. Most additive systems eliminate this waste with one exception being the LOM process, which generates the same amount of waste as any fully subtractive system [11].

1.3 Methodology of Rapid Prototyping

The basic methodology for all current rapid prototyping techniques can be summarized as follows:

1. Design: Create a 3D CAD solid model of the design
2. Converting: Convert the CAD model to STL format
3. Pre-Process: Slice the STL file into thin cross-sectional layers (generated by a dedicated software)
4. Building process: Construct the model one layer at a time
5. Post-process: Clean and finish the model

1- An STL file consists of x, y, z coordinates, which represent triangles. The file is built using a Computer-Aided Design (CAD) software package. Solid modelers, such as Pro/Engineer AutoCAD, and Solid works, can create STL files. The various CAD packages use a number of different algorithms to represent solid objects. The STL format (Stereolithography - the first RP technique) has been adopted as the standard of the rapid prototyping industry [2,12].

2- The second step is to convert the CAD file into STL format. This format represents a three-dimensional surface as an assembly of planar triangles. The file contains the coordinates of the vertices and the direction of the outward normal of each triangle. Because STL files use planar elements, it cannot represent curved surfaces exactly. Increasing the number of triangles improves the approximation, but at the cost of bigger file size. So the designer must balance accuracy with manageability to produce a useful STL file.

3- In the third step, a pre-processing program prepares the STL file to be built. Several programs are available, and most allow the user to adjust the size, location and orientation of the model. Build orientation is important for several reasons. First, properties of rapid prototypes vary from one coordinate direction to another. For example, prototypes are usually weaker and less accurate in the z (vertical) direction than in the x-y plane. Excessive support material for overheating sections was also be needed if the wrong build direction is choosen.

4- The fourth step is the actual construction of the part. Using one of several techniques, RP machines build one layer at a time from materials such as polymer, as paper, wax or powdered metal. Most machines are fairly autonomous and need little human intervention.

5- The fifth step is post-processing. This involves removing the prototype from the machine and detaching any supports. Some photosensitive materials such as those used in the Stereolithography process need to be fully cured before use. Prototypes may also require minor cleaning and a surface smoothing treatment. Sanding, impregnating, sealing, or painting the model will improve its appearance and durability.

1.3.1 Chemical and physical Principles For Additive Rapid Prototyping

Actual prototypes can be obtained using polymers (both thermoplastic and thermosetting) waxes, metals and mainly alloys with low melting points. Development of materials, suitable for rapid prototyping with ceramics, is still a matter of research [11,13]. A critical point of rapid prototyping material is related to the fact that the material is often different from that used for series production.

This means that although the prototype can be considered a "functional prototype", if a different material is used it will, perform in a different manner, in terms of material properties, compared to the production component.

The fabrication processes are associated with different types of material transformations. A rough division can be attempted between methods based on a chemical process, such as solidification of an organic resin or use of adhesives, and methods based on physical transformation of the materials, such as melting and solidification or sintering. RP routes in the first group include:

- Photopolymerization
  - Stereolithography
  - Solid ground curing
- Cutting and bonding
  - Laminated object manufacturing
- Adhesive bonding of powders
  - 3D Printing

RP routes in the second group include:

- Solidification of a polymer or a wax
  - Fused deposition modeling
  - InkJet modeling
- Sintering of polymers or metals
  - Selective laser sintering

An alterative grouping that is sometimes used for RP processes is the discussion into those that use liquid and those that use solid feedstock.

1.4 Detail of Rapid Prototyping Processes

Those processes that use liquids are divided into two categories, those that melt the solid material into a liquid form and then solidify it (Fused Deposition Modelling) and those that use liquid photosensitive resins (sterolithography) [14]. This thesis will describe research into a rapid prototyping process called Fused Deposition Modelling.

The sterolithography (SLA), selective laser sintering (SLS), fused deposition modeling (FDM), laminated object manufacturing (LOM), solid ground curing (SGC), and 3D printing, RP processes are described below. [15].

1.4.1 Stereolithography (SLA)

This additive prototyping system was called sterolithography and was patented by Charles Hul [16]. In 1987, the first commercial unit was developed. Sterolithography (SLA) is one of the most widely used additive prototyping systems in the market [17]. The materials used are liquid photo-curable epoxy-based polymers. The process builds three-dimensional models from photosensitive liquids that solidify when exposed to ultraviolet light. The SLA technique is illustrated in Figure 1.1 [18], the model is built upon a platform positioned just below the surface in a vat of liquid epoxy or acrylate resin. A computer controlled UV laser traces out the first layer, solidifying the models cross-section whilst leaving the remainder of polymer liquid.

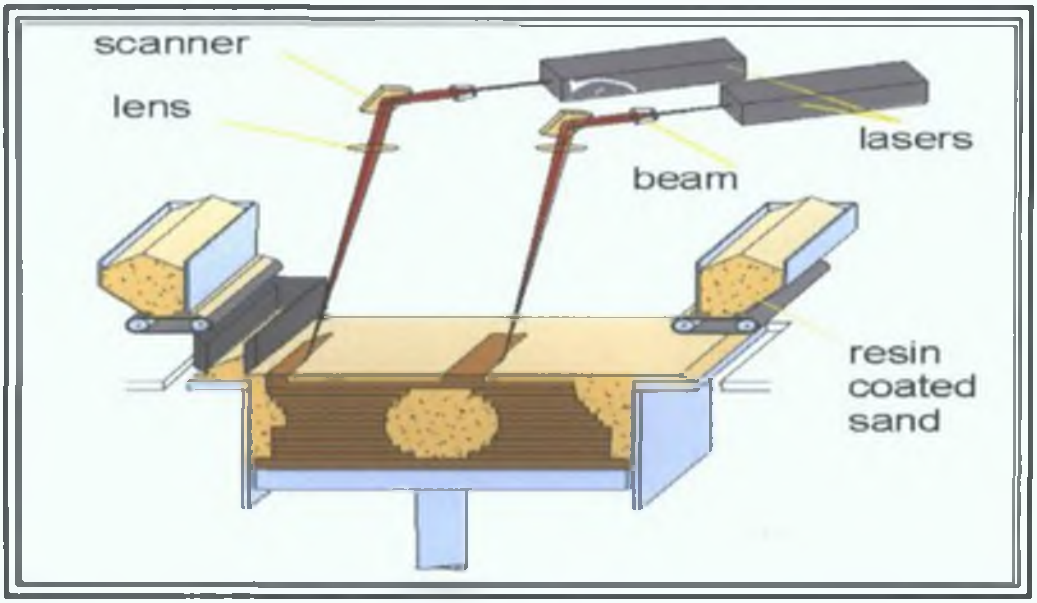


Figure 1.1: Sterolithography machine [17]

After a layer is built, the elevator drops an user-specified distance and a new coating of liquid resin covers the solidified layer, and the laser traces the next layer directly on top of the previous one. This is repeated until the part is finally finished [1]. Afterwards, the solid part is removed from the vat and rinsed clean of excess liquid polymer and placed in an UV oven for complete curing. Supports are broken off and the model is then placed in an ultraviolet oven for complete curing. "It has been suggested that SLA machines made by 3D Systems are currently the most accurate machines among the RP systems [2]." A brief overview of the main feature of sterolithography is reported in Table 1.1 [19, 20].

Table 1.1: Overview of the Stereolithography process

Stereolithography	
Process	SLS uses an ultraviolet laser moved at the surface of a vat of liquid polymer to produce a single layer of solidified resin - the first slice of the object under construction. The initial layer is then lowered incrementally by the height of the next slice, whereupon the layer is recoated with resin and another layer is traced on top of it. This procedure is repeated until the entire part is fabricated.
Materials	Photo-curable polymer or resin
Accuracy	± 0.05 – 0.1 mm
Layer-thickness	0.1 - 0.5 mm
Max. dimension	600 mm x 600 mm x 400 mm
Comment	Often used for small, filigree, and sharp contours.
Advantages	Very good model accuracy, smooth surface finishes Good quality solid 3D prototype Lowers developmental costs and improves parts quality, produces physical models for market research
Disadvantages	Limited range of materials that can be used. Accuracy not in the range of mechanical part manufacturing. Restricted areas of application due to given material properties. Risks of curl and warping. Relatively high costs compared to other RP methods.
Applications	Stereolithography is used by designers to quickly translate CAD files 3D object. Medical models, form-fit functions for assembly tests.

1.4.2 Selective Laser Sintering (SLS)

Carl Deckard and Joe Beaman jointly developed the selective laser sintering technique in 1986 [21]. SLS uses a laser to sinter powder based materials together, layer-by-layer, to form a solid model. The process is based on the principle of using an infrared laser beam to fuse selectively a powdered thermoplastic material into a 3D object [22]. The system consists of a laser, part chamber, and control system. A schematic of this process is shown in Figure 1.2 [1]. The powder is heated up to a temperature just above or below the melting point of the specific material, which usually takes a couple of hours. Then a roller spreads the powder on the building platform. The laser beam selectively melts the powder and bonds it. As the powder is heated already, the laser needs to elevate the temperature only slightly to causes sintering. The platform moves down incrementally one layer thickness and the process starts again, until the prototype part is finished. After that, the building chamber piston completely moves up and delivers that part. An overview of the process is reported in Table 1.2 [19,20].

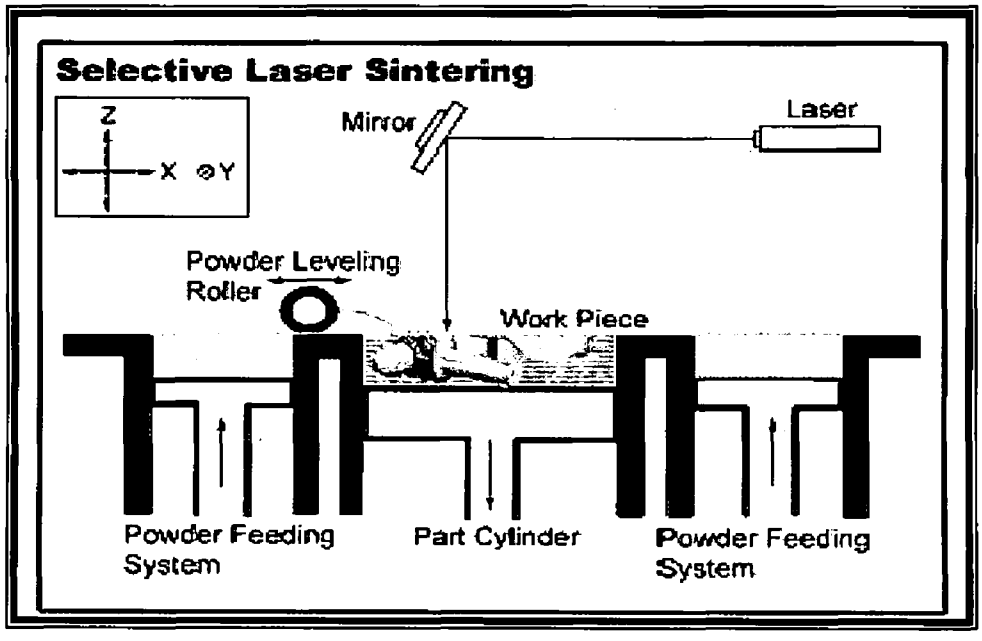


Figure 1.2: Selective laser sintering machine [1]

Table 1.2: Overview of the Selective Laser Sintering

Selective Laser Sintering	
Process	SLS uses a laser to fuse (sinter) a thin layer of powdered material into a solid object
Materials	Wax, metal, ceramic and plastic, powder
Accuracy	± 0.1 - 0.2 mm
Layer-thickness	0.1 - 0.2 mm
Max. dimension	350 x 350 x 600 mm^3
Comments	Process chamber needed for plastics solid parts for casting, e.g. cylinder head
Advantages	A limited number of parts can be produced for testing. Parts do not require any post-curing except when ceramics are used. Left over powder can be reused. Production, from powder to part, is generally a same day process. There is no need to create a structure to support overhanging geometry.
Disadvantages	The energy costs could be high during solidification powder may harden on the borderline. This results in a raw appearance of the part surface. The roughness of surface leads to lowered mechanical properties
Applications	Visual representation and functional tough prototypes. Cast metal parts (by use of wax pattern). Short run and soft tooling. For design, technical, and functional studies. Patterns for vacuum, die, fine and sand casting

1.4.3 Fused Deposition Modeling (FDM)

The Rapid prototyping system 3D modeller developed by Stratasys Inc., constructs parts based by depositon of extruded thermoplastic materials, the layer-by-layer to build a model see Figure 1.3 [23]. A nozzle, controlled by a computer system, is able to move in the x-y direction [24], and the material that is melted by heating. The material is extruded through the nozzle in a liquid form, and hardens on the part. A spool of modeling filament feeds the FDM head and can be easily changed to a different material. Within the building of the desired object the material is extruded and then deposited in ultra thin layers from the FDM process layer-by- layer. A possible modification of this process is achieved using a double extruder head. One nozzle carries the build material the other carries a support wax, which can easily be removed afterward.

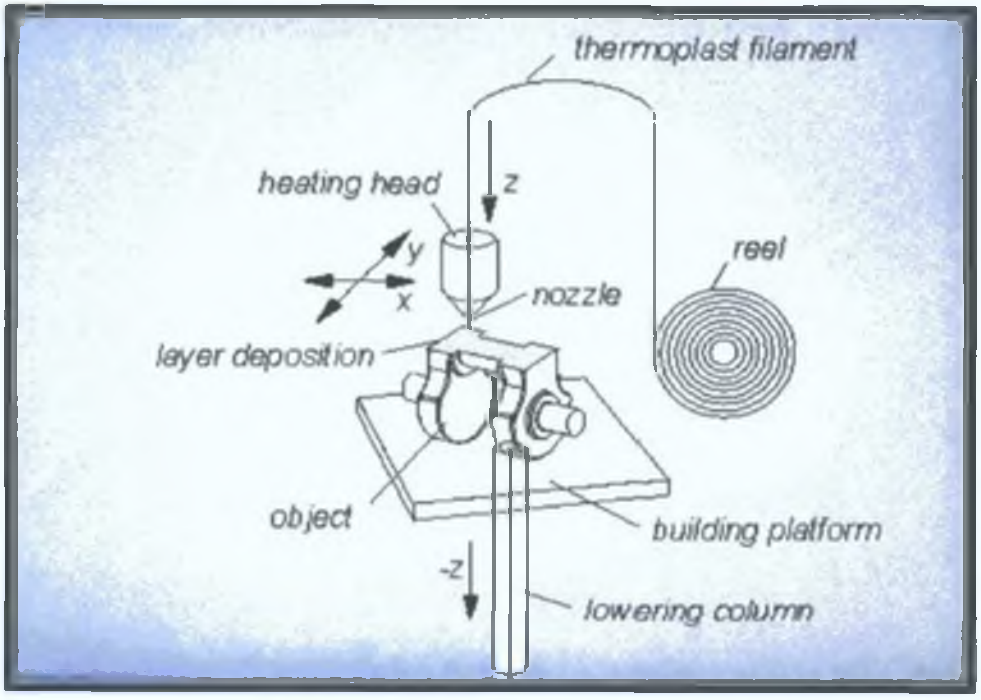


Figure 1.3: Fused deposition modeling machine [23]

This allows parts that are more complex. FDM processes build parts by extruding a bead of thermoplastic polymer. One of the available materials is an investment casting wax. The surface finish of FDM parts is generally better than the SLS process, but the parts can be quite porous and deliver only fair surface finish. An overview of this process is reported in Table 1.3 [19, 20].

Table 1.3: Fused Deposition Modeling

Fused Deposition Modeling	
Process	Melted plastic is deposited through the extrusion nozzle to build up the part.
Materials	Plastic ABS, modeling wax,
Accuracy	± 0.127 mm
Layer-thickness	0.05 - 1.27 mm
Max. dimension	254 x 254 x 254 mm
Advantages	FMD is compatible with many solid modeling packages, the absence of toxic chemicals and liquid polymer bath systems, eliminate waste material during and after producing the model. No clean-up required. Materials can be changed quickly. Low temperatures depending on material between 70°C and 140°C No sensitive laser needed.
Disadvantages	Limited part complexity. Slow when making large cross-sectional areas. Restricted accuracy due to the shape of the material used: wire of 1.27 mm diameter, support structures needed, post-processing for support removal
Applications	Conceptual modeling, fit, form and functional models for further manufacturing procedures such as investment casting, injection molding, vacuum casting, metal injection molding and fine casting

1.4.4 Laminated Object Manufacturing (LOM)

The laminated-object manufacturing (LOM) process was commercialized by Helisys, Inc in 1994 [25]. This process is one of the cheapest and fastest of all the physical prototyping methods [26]. This process requires a laser capable of cutting thin slices of either paper-based or plastic sheets and of course, the material that will make up layers that are bound to each other to the model. The LOM technique is illustrated in Figure 1.4 [27]. These provide support for material which may come on top, and can normally be removed at the end of the process. After the first layer is cut, the platform lowers out of the way and fresh material is advanced by the feeder mechanism. The platform is then raised to slightly below the previous height, the heated roller bonds the second layer to the first, and the laser cuts the second layer.

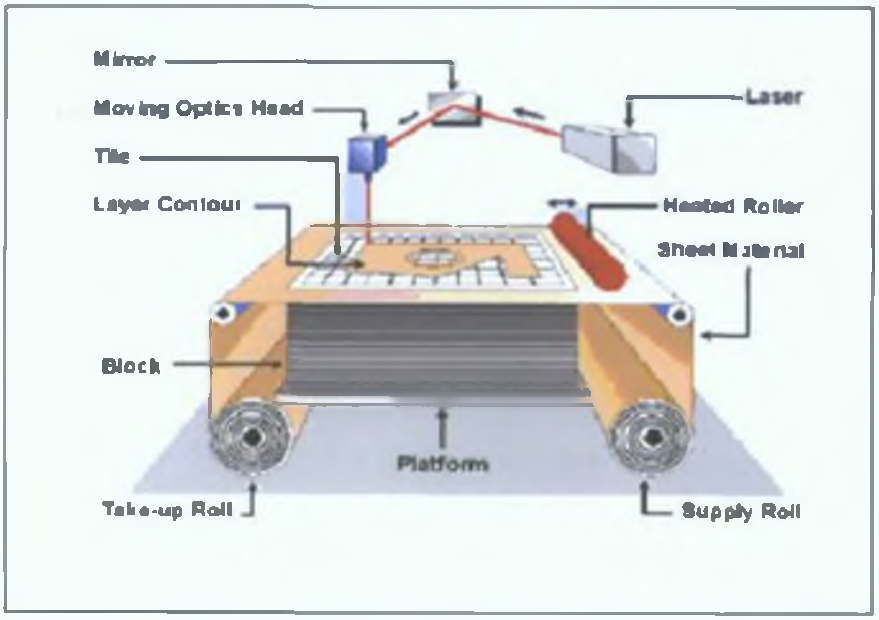


Figure 1.4: Laminated object manufacturing machine [27]

This process is repeated as required to build the part model. As the models are constructed from paper, they must be sealed and finished with paint or varnish to prevent moisture ingress and subsequent damage [2]. An overview of the process is reported in Table 1.4 [19, 20].

Table 1.4: Laminated Object Manufacturing

Laminated Object Manufacturing	
Process	A laser cut material foils in accordance with the model that are layer wise bonded on each other
Materials	Paper foils coated with glue
Accuracy	0.2 mm
Layer-thickness	0.1 mm
Max. dimension	813 x 559 x 508 mm
Comments	Thick walled parts, partly subtractive
Advantages	Fast process and relatively low material cost, largest workspace for parts available on market today. No additional support structure needed. Produces virtually no internal stress and associated undesirable deformation. Complex parts with undercuts
Disadvantages	Excess material is not reusable. Stability of the objects is limited by the bonding strength of the glued layers. Not well suited for manufacturing parts with thin walls in the z-direction. Hollow parts such as bottles cannot be built. Post processing for removal of subtractive part of model required. Finish and accuracy is not as good as other RP methods. Paper must be protected against moisture absorption.
Applications	Visual models for conceptual design, used for large bulky models. As patterns for sand casting patterns, fine casting models for silicon molds, injection molding fabricating of tools

1.4.5 Solid Ground Curing (SGC)

This is a complicated process developed in 1988 by the Cubital Corporation in which thermoset part material is imaged, using an ultraviolet light to form layers of a part [28]. Cubital has its headquarters in Israel with subsidiaries in the United States and Germany. SGC (also known as the Solider process) is illustrated in Figure 1.5 [2]. The solid ground curing techniques also utilise ultraviolet light to selectively harden photosensitive polymer, unlike SLA, SCG cures an entire layer at a time. A photosensitive resin is sprayed onto the build platform, the RP machine develops a photomask of the layer to be constructed. The photomask is then exposed to ultraviolet light, which is only transmitted through the transparent portion of the mask to selectively harden the current layer. When the layer is cured, the RP machine removes the excess liquid polymer by vacuum and sprays wax in its place to support the form during the build. The top surface is milled flat, and process repeated until the model is complete. On completion, the model must be de-waxed by immersing it a solvent [2]. An overview of the process is reported in Table 1.5 [19, 20].

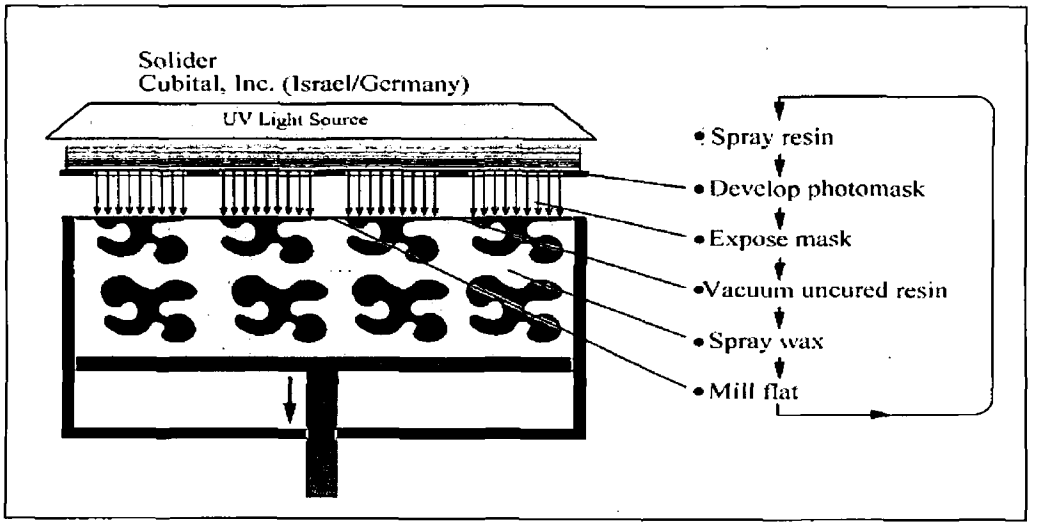


Figure 1.5: Solid ground curing machine [2]

Table 1.5: Solid Ground Curing

Solid Ground Curing	
Process	Layer-wise local curing of a liquid photopolymer by exposing it to an ultraviolet light through a mask (photopolymerization)
Materials	Photopolymers based on acrylic, and epoxy resins
Accuracy	± 0.05 - 0.1 mm
Layer-thickness	0.1 - 0.5 mm
Max. dimension	500 x 350 x 500 mm
Comments	Integral parts with fine and complex structures with many different geometry elements, ribs, guiding, suspensions
Advantages	Good accuracy. Parts with high complexity No additional support structures needed because of wax embedding. High troughput.
Disadvantages	Post processing needed for wax removal. Photopolymers with limited mechanical strength narrows application fields. Risks of curl and warpage. High wax material consumption. High equipment cost.
Applications	Design studies, technical, functional limited strength. Pattern for vacuum, die and fine casting

1.4.6 3-D Printing

Unlike the above techniques, 3-D Printing refers to an entire class of RP machines that employ ink-jet technology. As with other RP techniques, parts are built upon a platform positioned within a powder filled bin. 3D printing was developed at MIT and licensed to Soligen Corporation, Extrude Hone, and others. The process is shown in Figure 1.6. An ink-jet printing head selectively "prints" the binder to fuse the powder together in the selected areas to create the first layer. Unbound powder serves to support the part. The platform is then lowered, more powder added and

levelled, and the printing process repeated. When finished, the part is sintered and removed from the unbound powder. Soligen uses 3-D Printing to produce ceramic moulds and cores for investment casting, while Extrude Hone hopes to make powder metal tools and products.

One type of machine uses two ink-jets, see Figure 1.6. One of these jets dispenses low-melt thermoplastic of which the model is constructed and the other dispenses wax to form supports. After each layer is generated, a machine tool mills the top surface to uniform height. This yields extremely good accuracy, allowing the machines to be used in the jewellery industry. "3D Systems" has also developed a multi-jet based system. The multi-Jet modelling technique, see Figure 1.6, uses an array of 96 separate print heads to rapidly produce thermoplastic models. If the part is narrow enough, the print head can deposit an entire layer in one pass. Otherwise, the head makes several passes [2]. An overview of the process is reported in Table 1.6 [19; 20].

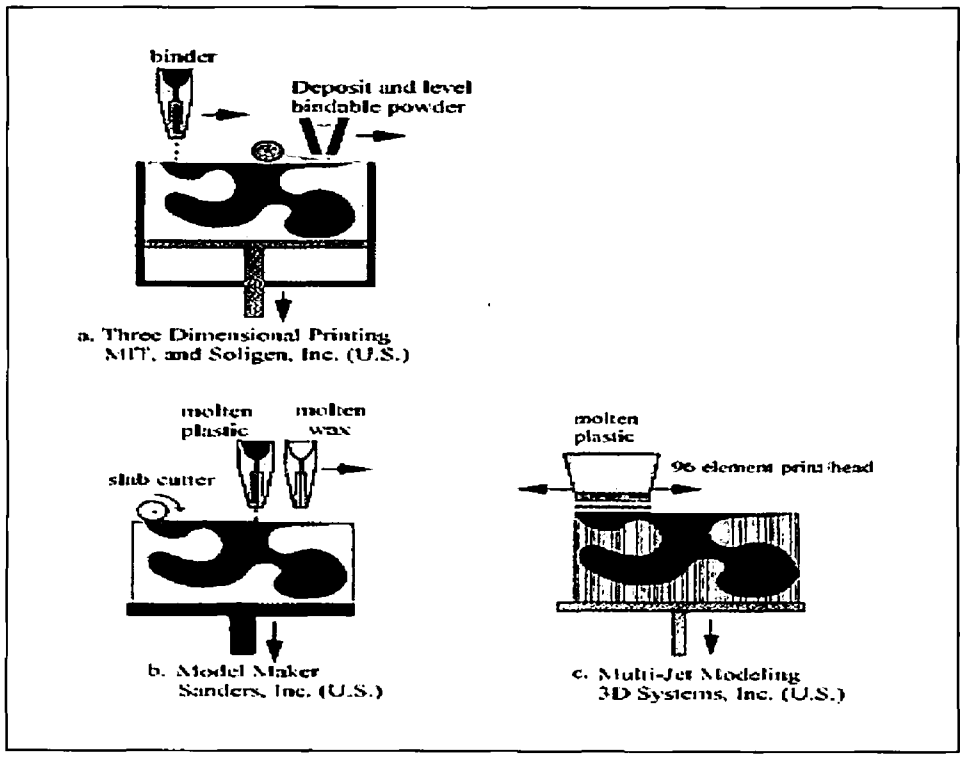


Figure 1.6: 3-D printing machines (a) three dimensional printing MTT. And Soligen, (b) model maker sanders and (c) Multi-jet modeling 3D Systems

Table 1.6: 3-D Printing

3-D Printing	
Process	Desktop modeling technology for computer controlled fabrication of thermoplastic models by using inkjet printer technology
Materials	Thermoplastic, Wax, plaster.
Accuracy	± 0.013 mm over 229 mm in the Z axis and ± 0.025 mm over 76 mm in the X&Y axis
Layer-thickness	0.013 mm to 0.13 mm
Max. dimension	304.8 x 152.4 x 228.6 mm
Comment	Larger parts can be built in segments
Advantages	True desktop use. Up to 10 times more precise than other rapid prototyping systems Non-toxic materials are used. Excellent dimensional tolerance and smooth surface finish. Super fine layer slices thickness. High accuracy.
Disadvantages	Limited size. Limited speed. Build time for large patterns, with thinly sliced layer thickness, increases and becomes more expensive.
Applications	Patterns can be used to build injection molding tooling. Which one wax is ideal for autoclave or burnout for investment casting shells because of the low coefficient of thermal expansion (CTE)

1.5 Application of Rapid Manufacturing

Rapid Manufacturing is the term given to cover Rapid tooling and rapid prototyping technologies. Rapid Tooling involves methods of quickly producing tools. These can be based somehow on RP technologies. The applications for RM is rapidly growing [29]. Rapid prototyping is widely used in the automotive, aerospace, medical, and consumer products industries. Rapid prototyping is also used to produce patterns for investment casting. The investment casting process in this case involves forming a mould completely around an expendable rapid prototyped pattern of the desired part [9].

1.6 Rapid Tooling

Rapid Tooling (RT) is a process that allows a tool for injection molding or die casting to be manufactured quickly and efficiently, so that the resultant part will be representative of the production material [28]. RT is a progression from rapid prototyping. RT is concerned with the automatic fabrication of production quality machine tools using RP techniques [30]. Tooling is one of the most expensive steps in the manufacturing process because of the extremely high quality required. Tools must often have complex geometry, yet be dimensionally accurate to within a hundredth of a millimetre. Additionally, tools must be hard, wear-resistant, and have extremely low surface roughness (about 0.5 micrometers root mean square). Conventional methods of manufacture include CNC machining and electro-discharge machining. The application of RT technologies permits the manufacture of standard machine tools in prototyping lead times. The SLS, RP process is currently the most promising RT technique [30]. RP patterns used in the investment casting process are also useful for RT.

1.6.1 Rapid Patterns for Casting

Traditional casting of metal parts using RP patterns is not always regarded as RT but often as rapid manufacturing or rapid casting. Nevertheless, it is a popular tooling-related use of RP with direct consequences to RT.

Regardless of the casting method, the foundry industry has as its central process the utilization of a physical pattern to produce moulds into which metal can be cast. Although this is true for both the design and production cycles, it is mainly the design stage that will benefit from rapid patterns [31].

The use of RP technologies in the creation of casting patterns allows a foundry to manufacture a metal part without the use of tooling for small quantities. It also helps in optimizing the casting design in terms of process and gating parameters. All of this reduces the cost and time required to produce prototype parts.

1.6.2 Investment Casting

The technique of investment casting is one of the oldest and most advanced of the metallurgical arts [32]. The process most commonly associated with the term precision casting. The development of the process which has evolved into today's manufacturing technology is credited to Austenal Laboratories Inc in the USA. In 1932 the organisation developed the use of hydrolysed ethyl silicate binders to produce moulds [33].

The investment-casting process (also called the lost-wax process) was first used in the application of RP. The pattern is made of wax or plastic such as polystyrene. The sequences involved in investment casting are shown in Figure 1.7 [32].

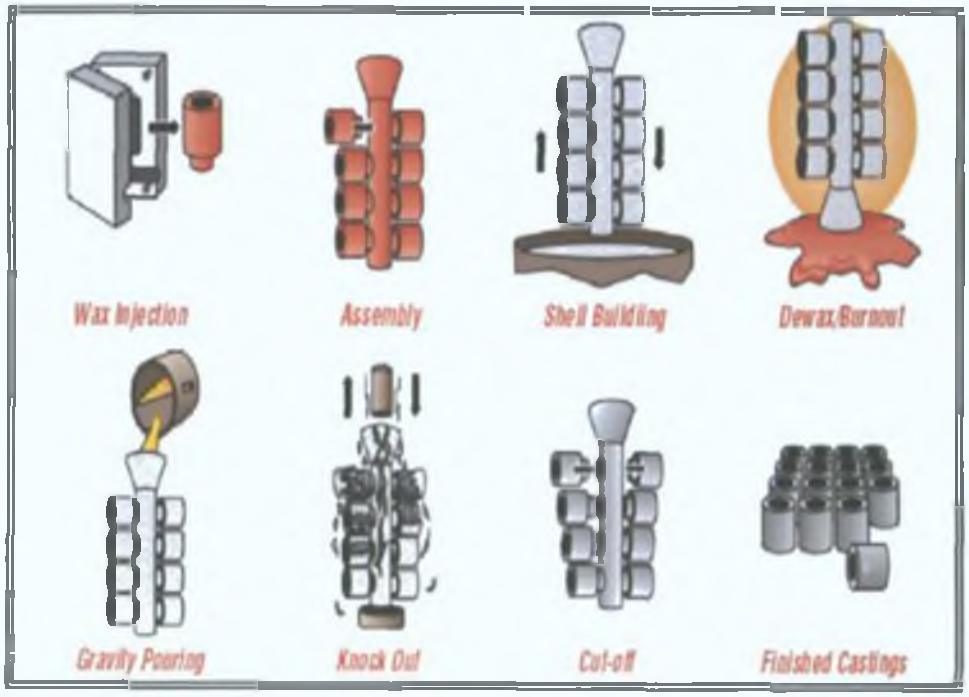


Figure 1.7: Schematic illustration of investment casting (lost-wax process)

The pattern is made by injecting molten wax or plastic into a metal die in the shape of the pattern. A number of patterns can be joined to make one mold, called a tree.

The pattern is then dipped into a slurry and dusted with refractory material, such as very fine silica and binders, including water, ethyl silicate, and acids. After this initial coating has dried, the pattern is coated repeatedly until the desired mould thickness is obtained [31]. The term investment comes from the fact that the pattern is invested with the refractory material. Wax patterns require careful handling because they are not strong enough to withstand the forces involved during mould making. However, unlike plastic patterns, wax can be reused.

The one-piece mold is dried in air and heated to a temperature of (90-175 °C) in an inverted position to melt out the wax. The mold is then fired to (650-1050 °C) for about 4 hours, depending on the metal to be cast, to drive off the water of crystallization (chemically combined water). After the mold has been poured and the metal has solidified, the mold is broken up and the casting is removed [9].

1.7 CAD/CAM Systems

1.7.1 Overview

Rapid prototyping (RP) has been widely used in industry for many years. Using rapid prototyping technologies to improve the manufacturing lead-time has been demonstrated widely in literature. The CAD/CAM RP system transforms a three-dimensional part model into two-dimensional layers. RP fabricates the part model layer by layer and this has the advantage of simplicity for two-dimensional manufacturing instead of the complexity of three-dimensional manufacturing [34].

1.7.2 Computer–Aided Design (CAD)

A description for Computer-Aided Design (CAD) is the effective use of computers in creating, modifying, or documenting engineering design in any design activity [35].

A computer–aided design system includes [36].

1 - The computer and associated peripheral equipment, called hardware.

2 - The computer programs, called software that runs on the hardware.

3 - The data structure, which is created and manipulated by the software.

4 - Human knowledge and activities.

CAD systems often have large and complex computer programs, using specialised computer hardware. Normally the software is comprised of the following elements which process the data stored in the database differently [36].

1- Model Definition: Adding geometric elements to a model, typically in the form of a component.
2- Model Manipulation: Copying, moving, editing, deleting or modifying the design model's elements.
3- Picture Generation: Generation of design model images on a computer screen or on hardcopy devices.
4- User Interaction: Handling user's input commands and presenting output to the user on the operation of the system.
5- Database Management: Management of the files that make up the database.
6- Applications: Generation information of revaluation, analysis or manufacture.
7- Utilities: It is a catch all term for parts of the software that do not directly affect the design model, but modify the operation of the system in some ways such as the selection of line type, display colour, units and so on.

There are four important reasons for using a computer-aided design system to support the engineering design operation [37].

(1) Increasing Designer's Productivity. Designers can reduce time in operations like synthesising, analysing and documenting the design. This is because CAD can help them in conceptualising the product and its components.
(2) Improving Design Quality. Utilising the CAD system with suitable hardware and software capabilities, allows the designer to produce a more complete engineering analysis and to consider a larger quantity and variety of alternatives.
(3) Improving Design Documentation. The graphical output of a CAD system is better than manual drafting in terms of quality of documentation. The engineering drawings are superior, and there is more standardisation of the drawings, fewer drafting errors, and greater legibility.
(4) Creating a Manufacturing Database. A database for manufacturing a product is created in the product design process documentation which includes important manufacturing data like geometric specification of the product.

Roughly 80% of a product's ultimate cost is determined and fixed during the design phase. Typically, companies only allocate about 5% of their resources on design and engineering. Contrasting these patterns of expenditure and commitment of resources over a product's life cycle, one can see that the 5% can have a great effect on competitive advantage [38].

CAD programming languages are the essential part of modern engineering activities. During the last decade, the AutoLISP programming language has been used in a few areas such as a surface-climbing robot simulation [39], geometry simulation in sand mould casting and shape similarity assessment of mechanical parts [40]. AutoLISP is commonly used by educational institutions and by home users that rely on low cost personal computing. It is used to help simulate an additive prototyping process.

1.7.3 Computer–Aided Manufacturing (CAM)

Computer-aided manufacturing (CAM) is defined as the effective use of computer technology in the planning, management, and control of the manufacturing functions [35]. Computer-aided manufacturing links computer graphics, to the physical work that gets done on the factory floor. In 1952 the first numerical control (NC) machine tool was successfully demonstrated at the Massachusetts Institute of Technology (MIT). CAM has played an important role in the manufacturing industry [17].

The application of CAM can be divided into two categories. The two categories represent two different levels of involvement of the computer in plant operations [35].

1- Manufacturing planning. The computer is used indirectly to support the production function, and there is no direct connection between the process and the computer. The computer is used 'off-line' to provide information for the effective planning and management of production actives. Applications of CAM in planning include cost estimating, computer-aided process planning, computer assisted NC part programming, development of work standards, computer-aided line balancing and production and inventory planning.

2- Manufacturing control. The control function in manufacturing includes individual processing and assembly operations regulation and plant- level activity management. Process level control involves the achievement of certain performance objectives by proper manipulation of the inputs to the

process. Plant level control includes effective use of labour, equipmen maintenance, transferring material in the factory, shipping good quality products on schedule, and maintaining the lowest plant operating costs. CAM applications in the manufacturing control aspect are concerned with developing computer systems for managing and controlling the plant's physical operations like quality control, shop floor control, and so on.

Numerical Control

In 1955 a prototyping NC programming system, developed at Massachusetts Institutes of Technology (MIT), was tested on the computer to demonstrate the feasibility of using computers to assist in NC programming. In 1957 a joint effort was initiated by members of the organisation of Aerospace Industries Association to develop a computer program that could assist in preparing NC tapes for all kinds of NC systems.

Numerical Control (NC) is a form of programmable automation in which the machining process is controlled by inserting predefined data in the form of numbers, letters, and symbols. Probably the most universally accepted definition of numerical control is that quoted in [41] Electronics Industries Association (EIA), which defines it as a system in which actions are controlled by the direct insertion of numerical data at some point. The system must automatically interpret at least some portion of this data. There are three elements of an operational numerical control system. These components include Program of Instructions, Controller Unit, and Machine Tool.

Program

The program of instruction is the detailed step by step set of directions which tells the machine tool what to do. It is coded in numerical or symbolic form on some type of input medium that can be interpreted by the controller unit. In a typical NC system, the engineering drawing of the workpart must be interpreted in terms of manufacturing processes to be used. It also lists the machines through which the part must be routed in order to accomplish the sequence of operations. This step in the NC system is referred to as process planning. Secondly, the numerical data, which contains the sequence of machining steps to be performed by NC, for producing a part of the job is maintained on file and is called part programming [41].

The part program is arranged in the form of blocks of information, where each block contains the numerical data required to produce one a segment of the workpiece. The file is moved forward by one block each time the cutting of a segment is completed. The block contains, in coded form all the information needed for processing a segment of the work piece, the segment length, its cutting speed, feed etc. Dimensional information (length width, and radii of circles) and the contour form (linear, circular or other) are taken from an engineering drawing. Dimensions are given separately for each axis of motion. Cutting speed, federate, and auxiliary functions (coolant on and off, spindle direction, clamp, gear changes etc.) are programmed according to the surface finish and tolerance requirements.

Controller Unit

This is the second basic element of the NC system. The operation of the NC machine tool is controlled by an electronic control system which outputs the analogy or digital command signals and receives signals from feedback transducers. The commands necessary to direct the machine operations are on file, which is then fed via a PC data link connection electronic control system [42].

The typical elements of a conventional NC controller unit include the tape reader, a data buffer, signal output channels to the machine tool, feedback channels from the machine tool, control console, and the sequence controls to coordinate the overall operation of the foregoing elements [43]. The data contained on file is read into the data buffer. The purpose of this device is to store the input instructions in logical blocks of information. A block of information usually represents one complete step in the sequence of processing elements. The signal output channels are connected to the servomotors and other controls in the machine tools. Through these channels, the instructions are sent to the machine tool from the controller unit. To make certain that the instructions have been properly executed by the machine, feedback data is sent back to the controller via the feedback channels.

Machine Tool

This is the component of the NC system which performs the useful work. In the most common example of an NC system, one designed to perform machining operations, the machine tool consists of the work table and spindle as well as motors and controls necessary to drive them. It also includes the cutting tools, work fixtures, and other auxiliary equipments needed in the machine operations [43].

There are two basic motion controls of NC system according to the type of the machine known as point to point (PTP) and contour motion [42]. In PTP the objective of the machine tool control system is to move the workpiece to a numerically defined position, and perform the machining operation. After completion of the machining operation the workpiece moves to a new point, and the sequence of actions is repeated, whereas in the contouring system the tool is cutting while axes of motion are moving. All axes of motion might move simultaneously, each at different speeds. When a linear path is required the axial velocity changes. In contour machines the position of the cutting tool at the end of each segment together with the ratio between the axial velocities determines the desired contour of the part, and at the same time the resultant feed also affects the surface finish.

NC machines range in complexity from simple controlled drill presses to highly sophisticated and versatile machining centres. It is a multifunctional machine which incorporates several time saving features into a single automated production unit. A machining centre is capable of performing a variety of different operations, drilling, reaming, tapping, milling, and boring. It also has the capacity to change tool automatically. A variety of machining operations means that a variety of cutting tools are required. The tools are kept in a tool drum or other holding device [43].

1.8 Wax Overview

Waxes may be of animal or plant (paraffin) origin and have complex structures. Compared to greases, waxes are more brittle [44]. Waxes are organic compounds of carbon, hydrogen and oxygen. Waxes are formed when fatty acids and high-molecular-weight alcohols other than glycerol undergo esterification [45]. They are esters of fatty acids and monohydroxylic alcohols. Esters are produced when alcohols react with acids, including organic acids, and loose a molecule of water in the process. Waxes are usually mixtures of esters. Lanolin, the wax from sheep's wool, is a mixture of esters derived from 32 different alcohols and 36 different

carboxylic acids [46]. Waxes are generally harder, more brittle and less greasy to touch than the fats and oils which, together with waxes, are termed lipids. Waxes are thermoplastic in behaviour, which means they can readily be melted and cast into shape [33].

Historically, pattern waxes were based on beeswax, although these were often modified with natural resins (which would harden the wax) or clarified butter (which would soften the wax).

The following summarizes the general features of wax:

1- Solid at ambient temperature.

2- Thermoplastic in nature.

3- Combustible.

4- Liquid at approximately (43 to 93 °C) (110 to 200 °F)

5- Insoluble in water

The term "Wax" is applied to a large number of chemically different materials. Technological advances in the world today have led to an increasing number of commercially available substances of various chemical compositions and properties which have acquired the name "wax". In the most general terms waxes are "naturally" or "synthetically" derived. Waxes can be further categorized by origin as follows [47]

A- Natural Waxes.

- Animal Waxes - Beeswax, Lanolin, Tallow.
- Vegetable Waxes – Carnauba, Candelilla, Soya
- Mineral Waxes
    - Fossil or Earth – Ceresin, Montan.
    - Petroleum - Paraffin, Microcrystalline

B- Synthetic

- Ethylenic polymers e.g. polyethylene
- Chlorinated naphthalenes
- Hydrocarbon type, e.g. Fischer Tropsch

1.8.1 Natural Ester Waxes

Wax esters, consisting of a fatty acid esterified to a fatty alcohol, serve a variety of biological functions [48]. Natural ester waxes are used in small amounts, generally <10%, to increase the hardness of the blend and accelerate the setting process when the wax cools. Being natural products they may have inconsistent properties and they have high ash content. The price of these natural waxes is often very high. Carnauba has a fairly high melting point of 83 °C (182 °F), a low coefficient of thermal expansion and is hard, brittle and non-tacky. Candelilla is anther vegetable wax, obtained from the stems of a weed which grows prolifically in Mexico, which has a relatively low coefficient of thermal expansion. It exhibits less solidification shrinkage than the hydrocarbon waxes and has been used for hardening paraffin waxes and raising their softening point. Beeswax has a melting point of 64 °C (147 °F) and because of its relative softness and high price is rarely used in modern pattern waxes. Commercial waxes have a wide range of applications as lubricants, polishes, plasticizers, coating materials in the medical and food industries, and as raw materials in cosmetic and other chemical industries [49].

1.8.2 Natural Hydrocarbon Waxes

The most commonly used hydrocarbon waxes, are those derived from petroleum crude oils. These can be sub-divided into paraffin waxes, intermediate waxes, and micro-crystalline waxes.

Paraffin waxes. These waxes are usually produced from relatively low boiling point lubricating oil by a vacuum distillation process [50]. They are available in closely controlled grades with melting points varying by 3 °C (5 °F) increments. However, those with melting points in the range from 52 to 68 °C (125 to 155 °F) are most commonly used [51]. The material is fairly translucent when highly refined and exhibits a coarse crystal structure when fractured, and can have a high or low melt viscosity, which accounts for their wide usage. However, applications are limited by their brittleness and high shrinkage. Blends of paraffin and microcrystalline wax are used by themselves or in combination with other additives such as high molecular weight polyethylene and ethylene vinyl acetate copolymers to improve the performance of paper packaging such as paperboard boxes, paper containers, and flexible packaging.

Intermediate Waxes. These waxes can be referred to as semi-micro-crystalline material. They are obtained from the highest boiling point lubricating oil and are also produced by vacuum distillation. These waxes are generally opaque, hard, have a finer crystalline structure than the paraffin waxes, and are less brittle [50].

Micro-Crystalline Waxes. These waxes are obtained from the residues of lubricating oil, the distillation being carried out under high vacuum. They have a very much higher molecular weight than paraffin waxes. These waxes are opaque and have a fine crystalline structure, these waxes are used in many applications including cosmetics, adhesives, coatings and polishes [50].

1.8.3 Synthetic Waxes

These materials are man-made derivatives of either natural ester or natural hydrocarbon waxes. They include Fischer tropsch waxes, polyethylene waxes, polyethylene glycol waxes, derivatives of Montan waxes, oxidised waxes, emulsified waxes, and chlorinated waxes [50]. Waxes are easily blended to suit different requirements. These properties allow waxes to be injected at low temperature and pressures and this, combined with lack of abrasiveness, leads to good tooling casts [51]. Petroleum waxes are hydrocarbons. Petroleum waxes are used in many consumer applications such is cosmetics, polishes, and candles. Unrefined petroleum waxes are often used in fireplace logs [52].

1.8.4 Application of Waxes

Every type of wax is defined by certain parameters such as hardness, melting point, viscosity, colour and many others. These determine the large number of potential uses of the product [53]. Waxes have wide applicability in dentistry and many dental procedures involve wax-containing materials at some stage in the protocol. Examples include bite registration (bite registration wax), the setting-up of artificial teeth (modelling wax), and dental casting procedures (inlay wax, casting wax etc).

Petroleum waxes are used in a variety of commercial products and applications such as candles, chipboards, cosmetics, crayons, polishes, cheese coatings, lubricants, paper and board printing inks, telephone cables, electrical power cables, flexible packaging materials, textiles, lost wax casting and anti-corrosion compounds [54]. An overview of the properties of waxes is reported in table 1. 7 [55].

Definition of Saponification. The term saponification is the name given to the chemical reaction that occurs when a vegetable oil or animal fat is mixed with a strong alkali. In soap making, fat is heated in huge iron kettles with aqueous sodium hydroxide until the fat is completely hydrolysed. Such a reaction is often called saponification [56]. The saponification number is the milligrams of potassium hydroxide, which react with one gram of wax under elevated temperatures, and indicates the amount of free carboxylic acid plus any ester materials, which may be saponified. Both the acid number and saponification numbers are generally provided to give an indication of the free carboxylic acid and ester content of vegetable and insect waxes, and synthetic waxes containing carboxylic acids and or esters. The relation between melting point and saponification number is shown in Table 1.7 All waxes used in current search were of the Candelilla type wax.

Table 1.7: The properties of various waxes

Waxes	**Carnauba wax**	**Montan wax**	**Beeswax**	**Candelilla wax**
Characteristics	Hardest of all vegetable waxes, brittle, non-tacky, colour ranges from pale yellow through greenish brown	Hard fossilized vegetable wax. Dark brown to light yellow color	Slightly tacky. Color varies from yellow to brown.	Hard vegetable wax, lustrous, slightly tacky. Color varies from yellow to tan. Low coefficient of expansion
Melting Point	From 83 to 86 °C	From 84 to 90 °C	65 °C	From 68.5 to 72.5 °C
Acid number	2 to 10	15 to 35	17 to 24	12 to 22
Saponification number	From 78 to 88	From 83 to 102	From 89 to 103	From 43 to 65

1.8.5 Modelling Wax (Baseplate Wax)

A common use of dental modelling wax is the setting up of artificial teeth in the procedure for a full denture. The material is usually coloured pink to simulate the natural mucosa so that a more meaningful visual impression of prosthesis can be obtained. Modelling wax is largely paraffin wax with some additions. The melting point is 58 °C (approximate) and the transition temperature is 50 °C (approximate). Thus, all manipulation of modelling wax should be carried out above the latter temperate to maximise stress relief [57].

1.8.6 Additives

Improvements in the strength and toughness of waxes are usually obtained by the addition of polymers. Polyethylene is the most widely used addition because it is compatible with a wide range of waxes and relatively inexpensive. Other materials which can be used include: ethylene vinyl acetate, ethylene vinyl acrylate, nylon, and ethyl cellulose [51]. The amount of these materials that can be added is limited because they are viscous at the temperature at which the waxes are used. Surface cavitations, or sinking, is a manifestation of solidification shrinkage. The addition of polymers will reduce the amount of shrinkage in proportion to the amount added. However, as the polymer addition is relatively small the effect is also small.

1.8.7 Thermophysical Properties

Physical properties, as the term is being used here, defines the behavior of material in response to physical forces other than mechanical [45]. The thermophysical properties of waxes are usually characterized in terms of a volume expansivity (or volume-temperature relation) and a viscosity [58]. Waxes actually exhibit some non-Newtonian viscoelastic behavior, but this is generally neglected. Their low viscosity allows waxes to be processed easily and facilitates their removal from the completed moulds. Waxes are prototypical thermoplastic materials in the sense that they can be reversibly transformed from a hard solid to a soft solid to a primarily Newtonian fluid by the application of heat. The congealing point is somewhere between the fluid and solid and is usually defined in terms of the viscosity of the material which increases upon temperature reduction. [59].

Melting Waxes

Care should be taken when melting waxes prior to conditioning or injection. Waxes should never be overheated as this may oxidise some of the constituents, embrittle the wax, or affect its injection characteristics and dimensions. Wax should be kept at a temperature between 80 and 90 °C during melting. [33].

Waxes are best melted in a container that is temperature controlled by a reliable thermostat. In addition, a slow speed stirrer should always be used while the wax is in a molten state. This is essential when melting filled waxes. These recommendations will help maintain uniform temperature and prevent localised overheating and damage to the wax.

Waxes are complex mixtures which must be homogeneous before use. To achieve this requirement and optimise viscosity, flow and surface finish, the wax should be held at the injection temperature for several hours before use. Care should be taken to ensure that the wax in the melting tank is at the same temperature as that in the injection machine reservoir [60].

1.9 Viscosity Measurement

The most important physical property of a fluid from the point of view of the study of fluid mechanics is the viscosity. Viscosity is the property that determines the ease with which a fluid will flow [61]. A fluid dose not permanently resist increasing shear stress, it eventually deforms, flows and the velocity of flow increases with increasing shear stress [62]. The viscosity depends on temperature, and pressure. In general as temperature and pressure (or share rate) increase the viscosity decrease. Denser materials also tend to have higher viscosities. In this work the density of the investment wax was 0.95 g/cm^3, the temperature range investigated in most detail was 70 to 90 °C and the pressure range concentrated on was 6,897 to 206,832 Pa.

1.9.1 Capillary Viscometry

Consider measuring the viscosity of fluid, flowing in a cylindrical tube, see Figure 1.8.

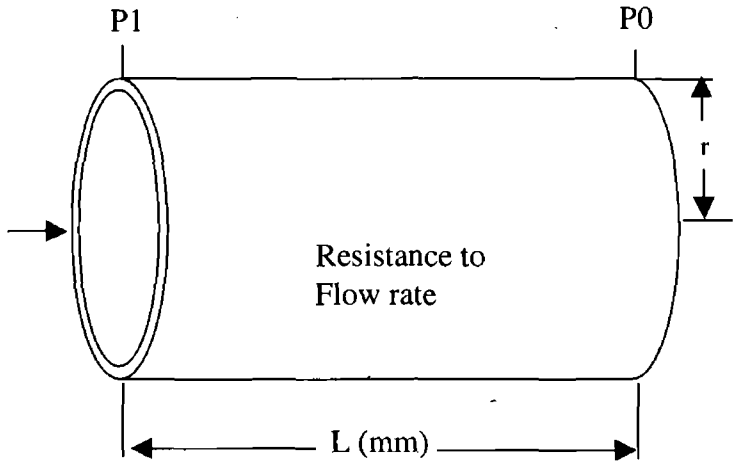


Figure 1.8: Shows schematic of capillary viscometry

To measure the viscosity of the fluid flowing the length of the cylinder. In this case the volume flowrate is proportional to the pressure difference divided by the viscous resistance. This resistance depends linearly upon the viscosity and the cylinder length, but has fourth power dependence upon the tube radius. This relationship is derived below.

The pressure different ΔP, in the tube is sufficient to overcome the shear forces within the liquid and produce flow of a given rate, [62].

Viscosity: $\eta = \frac{\tau}{\gamma} = \frac{F/A}{du/dr}$ (1)

where η = viscosity, τ = the shear stress, and γ = the shear rate, F = force, A = area, u = velocity, r = radius, du/dr is changing in velocity with respect to radius.

$$\eta = \frac{F/2\pi r L}{du/dr}$$

$$= \eta \frac{du}{dr} = \frac{F}{2\pi r L}$$

$$F = \eta(2\pi r\ L)\frac{du}{dr}$$

Pressure Force + Viscous Force = 0 (2)

Therefore $= \Delta P(\pi r^2) + \eta(2\pi rL)\frac{du}{dr} = 0$ (3)

$$\frac{du}{dr} = -\frac{\Delta P \pi r^2}{2\pi r L \eta}$$

$$\frac{du}{dr} = -\frac{\Delta P r}{2 L \eta}$$

$$\int du = \int -\frac{\Delta P r}{2 L \eta}\, dr$$

Velocity, $u = \frac{\Delta P}{2 L \eta} \times \frac{r^2}{2}$

$$= \frac{\Delta P r^2}{4 L \eta} \quad (4)$$

$$u_{ave} = \frac{\Delta P r^2}{4 L \eta} \times \frac{1}{2}$$

$$= \frac{\Delta P r^2}{8 L \eta} \quad (5)$$

Flow rate, $\phi = u_{ave} \times a$

$$= \frac{\Delta P r^2}{8 L \eta} \times \pi r^2$$

$$\phi = \frac{\Delta P \pi r^4}{8 L \eta} \quad (6)$$

Where:

ϕ = Rate of flow of liquid out of nozzle [m^2 / s].

r = Radius of nozzle [m].

Δp = Pressure difference over length of nozzle [kg / $s^2 \cdot$ m].

L = Length of nozzle [m].

η = Viscosity [kg/m $\cdot$ s].

This result is known as Poisseuille's Law and is an expression for the flow rate (in m^3/s) in terms of the viscosity.

The viscosity is directly proportional to the pressure difference between the tube ends.

$\Delta P = P_1 - P_0$

And is inversely proportional to the length 'L' of the nozzle. The viscosity is also proportional to fourth power of the radius 'r'.

This equation has been used extensively by other authors to measure the viscosity of fluids with the capillary viscometer [63].

When pressure is applied on the cylinder (wax chamber), the fluid flows out from the nozzle. The flow rate is affected by many variables, namely the temperature of the fluid, the viscosity of the fluid, the length of the nozzle and the difference between the inside and outside pressure, as shown in Equation (6).

1.10 Plan and Aim of the Present Work

The objective of present work was to build a FDM prototyping machine that could control the X-Y motion and material deposition, to generate two-dimensional and three-dimensional complex shapes. This study focused on the deposition of wax material. The other objective of this work was to find out the properties of the wax materials used in this project in order to enable better control of the FDM process. This study will look at the integration of a computer controlled electro-mechanical system with the traditional FDM additive prototyping process.

1.10.1 Aims of the project

The aim of this work was to design, build, commission and perform preliminary tests of a fused deposition modelling (FDM) machine. Initially, a program was developed for simultaneously controlling both the motion of the precision X-Y stage and the depositor plunger. Next the height of droplet deposition needed to be determined for two different waxes (candle and investment), which were tested. The best wax for temperature processing range and resultant surface finish was chosen. Best processing conditions for model production, viscosity, temperature, pressure, were to be evaluated. Finally, with these processing parameters, the dimensional accuracy of the basic model building block, the wax droplet, and 3-D models produces was statistically analysed.

Chapter 2

2. EXPERIMENTAL SET UP & PROCEDURE

2.1 System Design Overview

The system contains two main sub-systems, the X-Y positioning unit and the deposition unit. The system is shown in Figure 2.1.Two servomotors connected via linear guide and lead screws control the x-y movements of the deposition unit. Another servomotor controls the amount of material deposited from deposition unit. The overall control of the system was implemented by writing sequential control algorithms to manipulate the synchronous movements of each unit in to allow deposition to occur correctly.

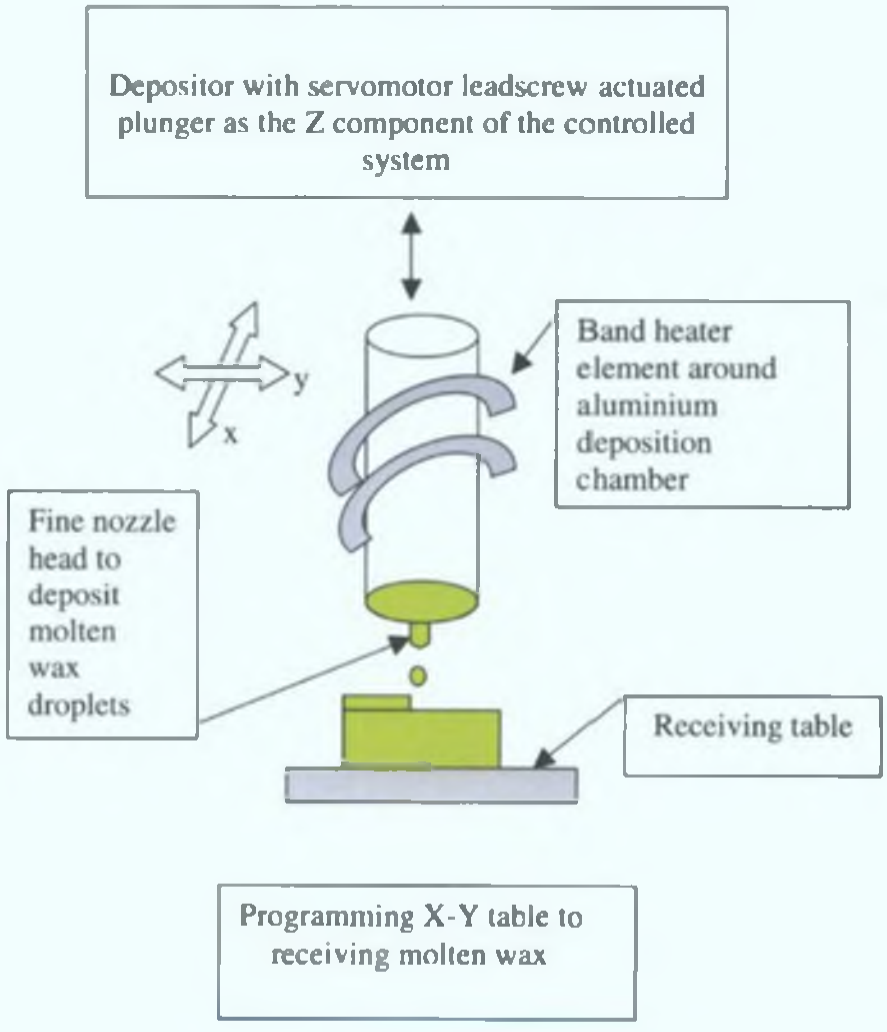


Figure 2.1: Schematic of the fused deposition modeling system developed

The deposition chamber consists of an aluminium nozzle ended cylinder to deposit droplets of wax. The material chosen for the deposition chamber was important to allow conductance from the heating element to occur efficiently and easily so that the wax was fully molten and under tight temperature control.

The experimental equipment used in the current research is shown in Figure 2.2. The apparatus consists of a personal computer, PC-23 indexer, KS-driver, deposition chamber, temperature controller, and thermocouple and pressure gauge.

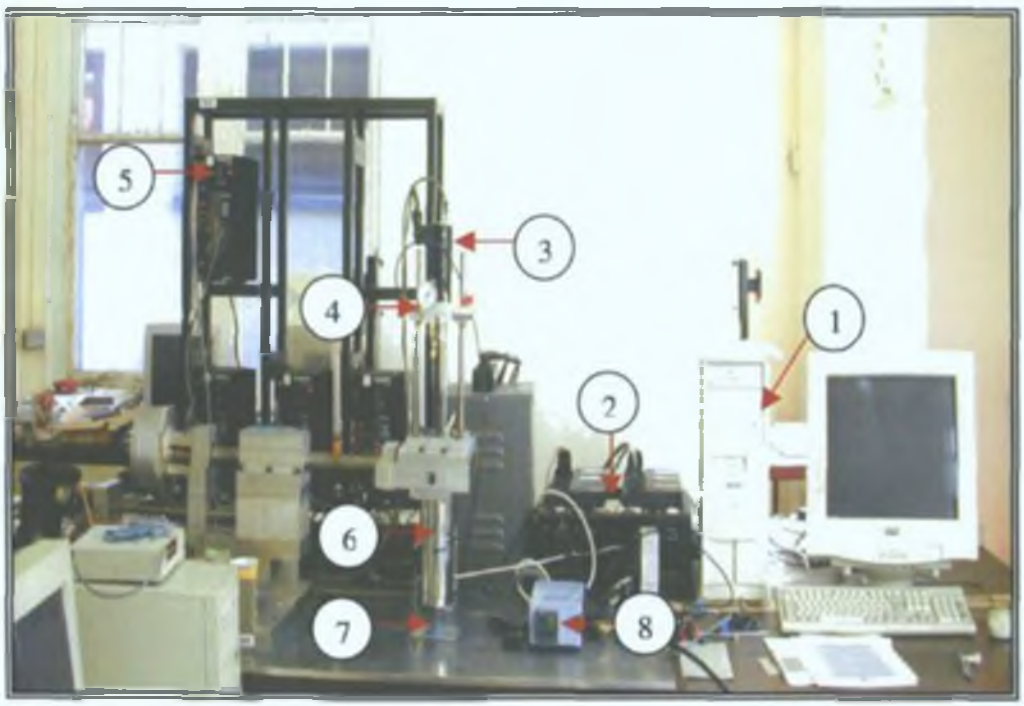


Figure 2.2: Picture of the fused depositon modeling equipment developed

1- Personal computer
2- PC-23 indexer
3- Servomotor
4- Pressure gauge
5- KS-driver
6- Deposition chamber
7- Receiving plate
8- Temperature controller

A personal computer was used to control the system by sending commands and receiving responses from the PC-23 indexer. The indexer in turn communicates with the KS-drive for controlling the a.c. brushless servomotors. The system was used for additive prototyping and to measure the viscosity of the wax material used in this project.

2.2 Deposition Chamber

This is the basis of the deposition rig and therefore holds notable importance. The criteria that were vital for the project were primarily the nozzle dimension and subsequently the size of the rest of the chamber. At the outset a chamber of inner diameter 50mm was chosen, this is the largest possible dimension that could be machined with relative ease. Furthermore this inner dimension allowed for an adequate quantity of wax to be pressured. Te height dimension choosen was 250mm making the chamber a long cylindrical shape, as shown in Figure 2.3.

The nozzle feature itself is protruding from the bottom of the deposition chamber, as shown in Figure 2.3.

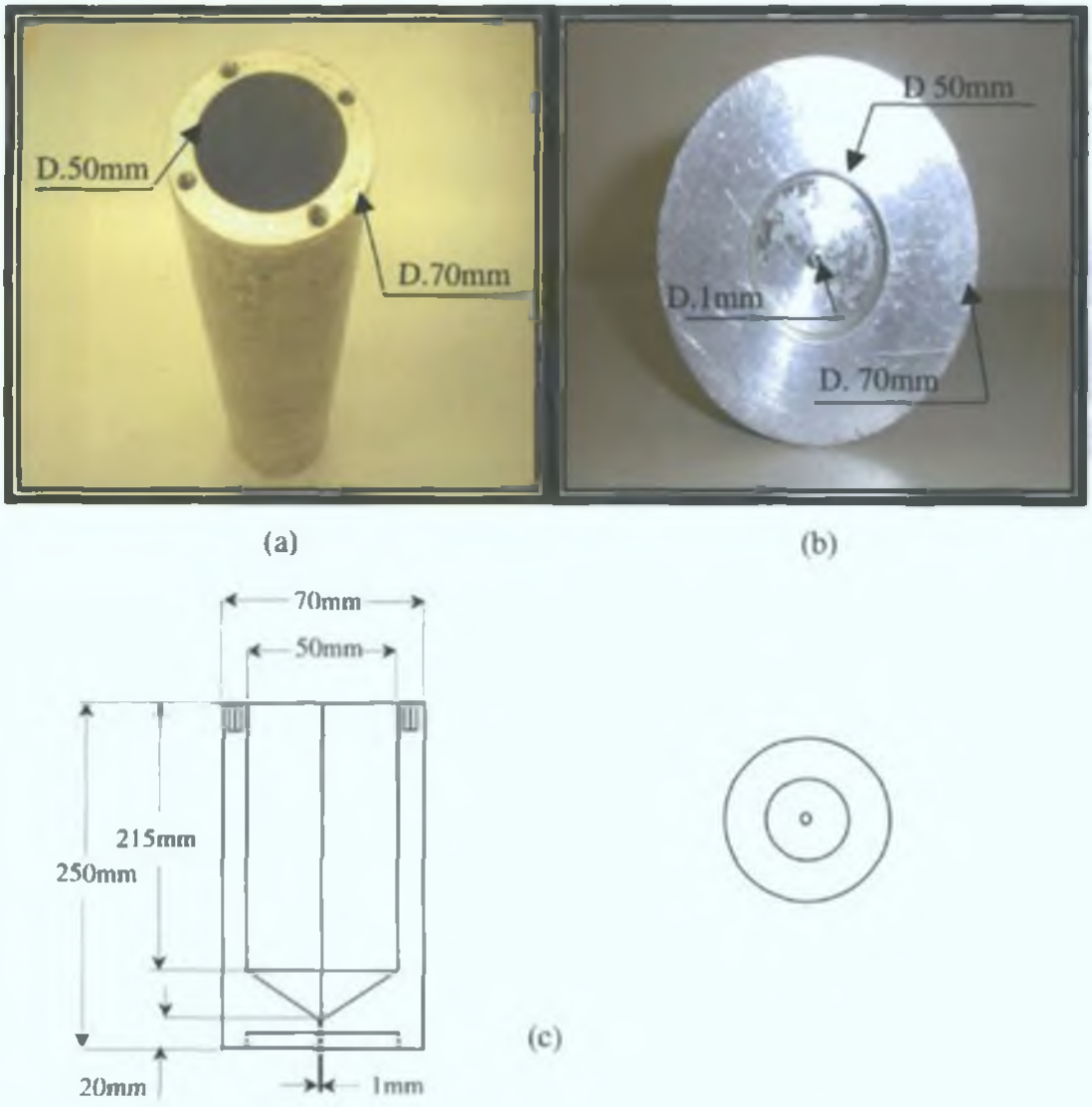


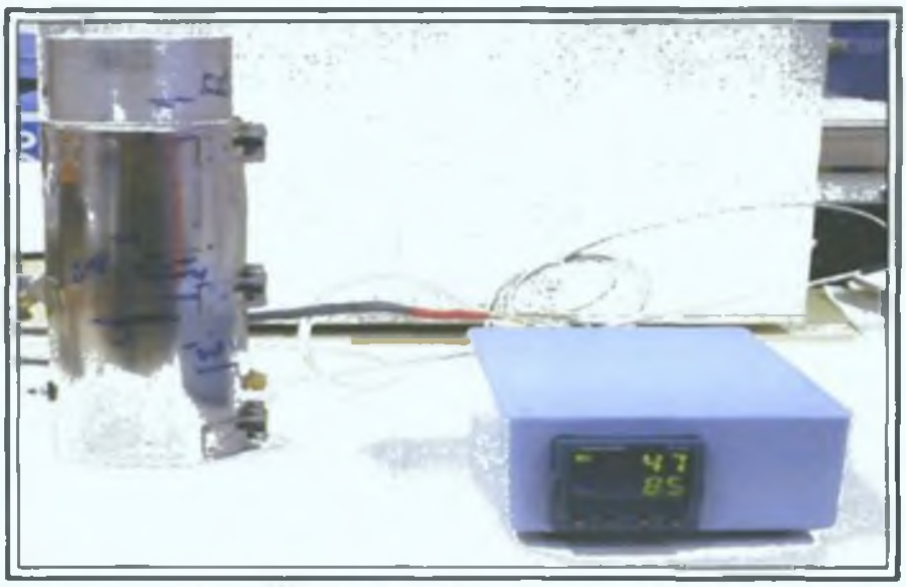
Figure 2.3: (a) Deposition chamber, (b) bottom of deposition chamber showing nozzle feature, (c) cross-section of deposition chamber

2.2.1 Nozzle

The length of the nozzle was 20mm, and its diameter was 1mm Figure 2.3 (c). In this project the nozzle was integrally machined as part of the deposition chamber. The size of the nozzle would have implication for the droplet size and also how well the molten wax would be retained within the chamber. The plungerhead and wax droplets were controlled using the Z-axis servomotor movement. This was the space between the plunger and material. The plunger did not touch the wax inside the cylinder [64]. Based on trial and error, a gap of 40 mm was found to be best and was used in all experimental runs. This extension characteristic allowed droplets that extruded the nozzle to be deposited easily and accurately. A plain flat surface surrounding the deposition opening, which was initially used, caused the wax to flow along the base. Quantity of wax in each experiments was 130g.

2.2.2 Temperature Controller

One of the key functions of this apparatus was to maintain the wax to be deposited at a constant temperature. This was achieved by controlling the temperature within the chamber. The control system is shown in Figure 2.4. The temperature of an electrical mica resistance band heater was controlled by an Eurotherm™ model 2116 PID 48W× 48H, analogue temperature controller [64]. This unit monitored the temperature constantly by means of a K-type thermocouple and compared it to the set point temperature. Appropriate power adjustments to the electric resistance heater are then made by the controller. The band heater was designed to enclose the majority of the deposition chamber, thereby facilitating a more uniform heat input and temperature along the chamber. The accuracy of temperature is ± 1 °C. The element was attached to the deposition chamber with three tightening jubilee screws, as shown in Figure 2.4.



Picture of deposition chamber, bard heater, thermocouple and controller

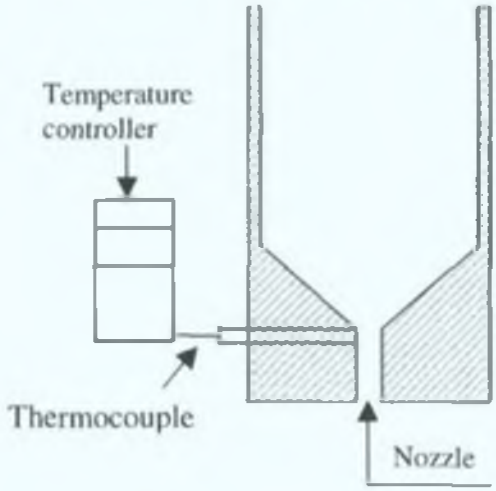


Figure 2.4: Diagram of deposition chamber, thermocouple and controller

2.3 Plunger Assembly

The plunger assembly was designed so that the plungerhead could be moved up and down within the depositon chamber. The frame consists of two precision linear shafts, a motor plate and a base plate. The motor plate supports the motor and traverses up and down two linear shafts with the movement of the leadscrew. The base plate acts as the cap on the depositon chamber and holds two linear shafts in a fixed position. It also holds the thread for the lead screw to rotate on and is fixed with four hexagonal screws in position. The leadscrew hexagonal nut is pressed fit into the base plate, therefore keeping it in a fixed position. This plate also aligns the whole rig therefore the accuracy of the machining for this part was important. The

motor plate holds the servomotor in position, again with four tapped holes. The linear shafts are guided through this plate via two bored brass bashings which were press fitted and glued into the plate. This therefore sustains the motor plates in a linearly vertical position above the centre of the deposition chamber and leadscrew nut, thereby allowing it to traverse relatively freely with the movement of the leadscrew and motor.

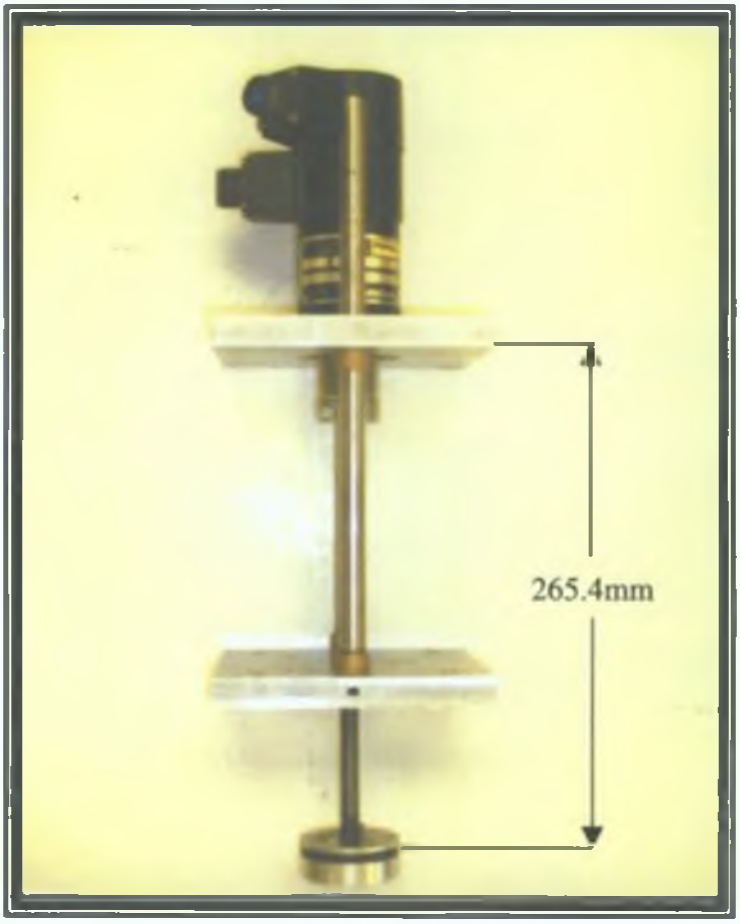


Figure 2.5: Picture of the plunger assembly

Rotating the motor in a clockwise (CW) or counter-clockwise (CCW) direction moves the plungerhead up and down respectively. The plungerhead was also made of aluminium to have a matching expansion coefficient with the depositor chamber and enable a better air tight seal to be obtained. The plungerhead was secured with an 'O' ring seal inserted into a groove in the side of the component. The 'O' ring seal is composed of a nitrile type rubber which can withstand temperature of up to 100°C, sufficient for this work. The position of the seal was important such that no wax was interfering with the compression of the seal with the sides of the chamber, thereby causing air-gaps. Therefore the 'O' ring feature was established 15mm from the base

of the plungerhead. The plunger head also contained a sealable vent to ease experimental set-up. The height of the plungerhead was also important, for it to maintain a horizontal position within the chamber, thereby negating any play between the side of the chamber and the sides of the plungerhead. This was set at 30mm.

2.4 Motion Control System

The control of the X-Y table was fundamental to the success of the developed FDM system. The controller used was is a Compumotor PC-23 which is a microprocessor based indexer within the personal computer. The indexer was written to through the C Borland programming language. The indexer then writes to an external adapter box to control the various motions. This set-up has the ability to control up to three axes. In this application the X-Y movement the depositor and the deposition unit plunger (Z motion) were the three-controlled axis.

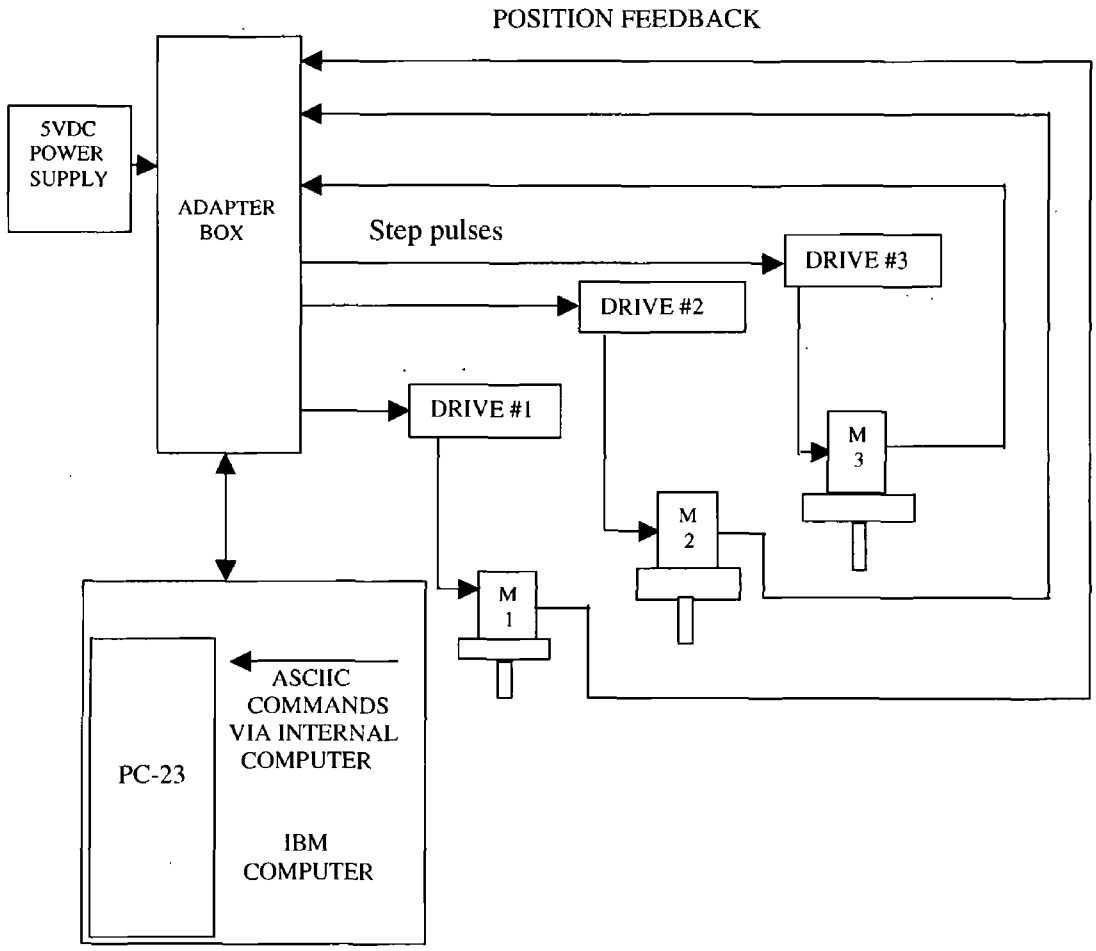


Figure 2.6: Schematic of the FDM control process

The PC-23 uses 16-bit processors with custom circuits to simplify generation of motion profiles and shorten processing time. The PC-23 receives acceleration, velocity, and position information in ASCII (American Standard Code for Information Interchange) characters from the personal computer. In turn the PC-23 uses that information to generate motion profile command signals for the three axes. Move commands are then sent to the external drives in the form of step pulses at a rate of up to 500kHz. The PC-23 gives feedback on the positions of the axis after motion has been completed. Figure 2.6 shows a schematic illustration of the system control process [66].

2.4.1 X-Y control

The movement in the X-Y directions was programmed as simple linear interpolations, which enabled precision movements for the deposition chamber.

An example of the C code for movement in the X-Y direction is shown below.

```
printf ("%s" message);                    /* printing the message string */
message = " LD3 1V5 1D20000 1G 1P "       /* Movement in X DIR */
writecmd (message);
printf ("%s" message);                    /* printing the message string */
message = " LD3 2V5 2D20000 2G 2P "       /* Movement in Y DIR */
writecmd (message);
```

where LD3 is disables limits for axes, 1V5 sets velocity to 5 rps, D is distance, G is go (execute the move) for motor 2, P is pause motor 2.

A more detailed deposition of these commands is shown in Appendix A.

The motion control of the system was implemented through x-y the movement of the depositor. The motor used for X movements was motor one. Similarly the motion of the Y-axis is determined by specifying motion of motor two. The physical motion was set by a specified distance, D, velocity, V, and acceleration, A. The distance was in terms of the pitch of the leadscrew, in the case of the X and Y motion the pitch of the leadscrew was 1.5 mm (5000 steps). This meant for every rotation of the motor shaft, a linear distance of 1.5 mm was moved. The motors on the X-Y table have the ability to move in very precise movements i.e. 1 step, this means it had the capacity to create liner motion in steps of 1.5 / 5000 = 0.0003 mm. The velocity of the movement was specified in revolutions per second RPS, therefore as in the case

above the velocity is set to 5RPS. The motors will rotate 1 revolution in 0.2 sec so the linear velocity was 1.5 / 0.2 = 7.5 mm/sec.

So for different steps, the motors linear produced movement in the X-Y directions could be calculated as below.

$$X = S \times \frac{1.5}{5000}$$

where X is the linear distance in mm and S is the number of motor steps. For example,

$$X_1 = 5000 \times \frac{1.5}{5000} = 1.5 \text{ mm}$$

2.4.2 Z -Control

In this case the movement was in the vertical direction. A downward motion was used to deposit the droplet and then a retraction was used to hold the pressure and the wax within the chamber. The volume of each droplet was calculated at various depositon temperatures, therefore allowing the plunger movement to be such that it compensated for the loss of wax within the chamber. The leadscrew for the plungerhead movement had a pitch of 2 mm. This meant that for every full rotation of the motor shaft, 2 mm was moved by the plungerhead. As with the X-Y movements, each shaft rotation is divided into 5000 steps, therefore the linear movement for one step in this instance is equal to 0.0004 mm. The velocity of movements with the deposition unit is very important. This is due the necessity to hold the pressure differential while depositing a droplet from the chamber. It was found that a gradual plunge movement (V3) is sets velocity 1 rps, and faster retraction movement (V5) is sets velocity 5 rps gave better results.

An example of the C code for movement in the Z direction is shown below.

```
printf ("%s" message);                    /* printing the message string */
message = " LD3  3V3  3D-30000  3G  3P"   /* Plunge command  */
writecmd (message);
message = " LD3  3V5   3D29979  3G 3P"    /* Retract command  */
```

where LD3 is disables limits for axes, 3V5 sets velocity to 5 rps, for motor 3, D is distance, G is go (execute the move) for motor 3, P is pause motor 3.

The distance for each step is calculated below.

$$X = S \times \frac{2}{5000}$$

For example

$$X_1 = 5000 \times \frac{2}{5000} \quad = 2 \text{ mm}$$

2.5 Application of Known Pressure to Cause Wax Flow

The compressor shown in Appendix B was used to supply air to the system. The air was compressed by a 0.34kW electric motor and stored at 79,9999 (8 bar) in a 25 litre storage tank. This was reduced to 19,9999 (2 bar) before entering the system by means of a regulating valve.

Pressure within the chamber was measured by using a pressure gauge. The pressure in the cylinder was supplied by the pressure developed in an air compressor, see below. Tests were performed at pressures ranging from 6897 – 206,922 Pa (1-30 psi) Pressure was held constant for each experiment. The wax flow through the nozzle depended on the pressure drop along the length of the nozzle (L), the radius of the nozzle (R) and the pressure applied from the compressor. The flow rate of the wax also depended on the temperature of wax.

The difference between the applied pressure and the atmospheric pressure at the outlet of the nozzle gave the pressure difference (ΔP), which was measured in the experiment.

$\Delta P = P1 - P0$

Where P1 was the pressure read from the pressure gauge for each experiments, and P0 is atmospheric pressure.

2.6 Transition and Melting Temperature of Wax

In order to determine the temperature at which the wax should be pressured the effect of temperature on the consistency of the wax was investigated. Some substances such as wax melt more easily than others. The temperature where the solid melts is called the melting point. The transition temperature is where the material begins to significantly soften. Waxes and plastic often are characterised with such a temperature (also from as the glass transition temperature).

A test tube, timer, 600-ml beaker, volume of wax 10 – 15g, thermometer, and hot plate were used in this test, Figure 2.7.

Test Procedure

1- Obtained a test tube containing an unknown sample of solid (wax) to be tested. Filled 600-ml beaker with water.

2- Placed the test tube containing the sample in the hot water and place a thermometer in the hot water.

3- Heated up the wax until it melts and recorded the temperature as the liquid cools and recorded time,

4- After the wax melted, decreased the temperature slowly and re-read the temperature against time.

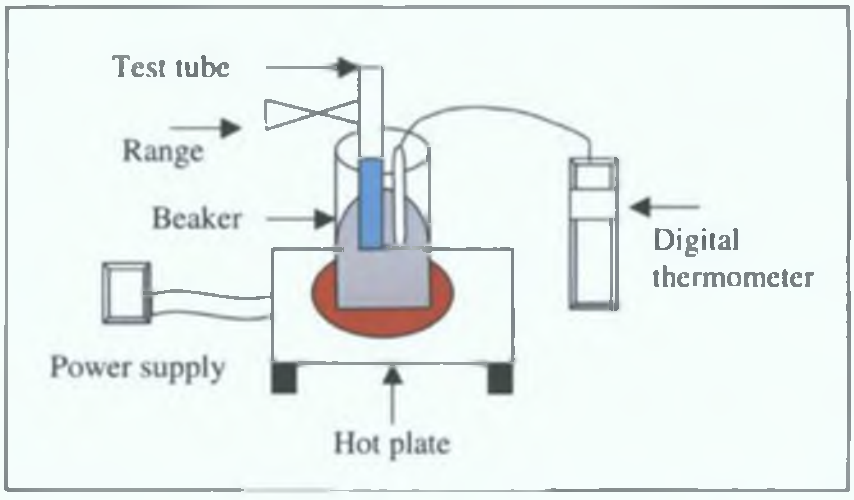


Figure 2.7: Schematic of the equipment used for assessing the temperature dependence of wax

A glass stirrer was kept in the water and used to regularly check the consistency of the wax. The temperature and condition of the sample (wax) in the test tube was at one minute intervals. It was noted when melting started, and when melting was complete. The wax was then allowed to solidify by turning off the hot plate. The solid was then reheated gradually, temperature, time and consistency reading again recorded were this enabled a check on the consistency of the results. The transition temperature for the choosen wax was 57 °C (± 1 °C)

Knowledge of the variance of the viscosity of with temperature and pressure would allow for optimum setting of these parameters in the FDM process. The data table is shown in Appendix D.

2.7 Viscosity Measurement Experimental Procedures

The viscosity of wax can be measured by a variety of techniques. In this work the viscosity is measured with the wax depositor presented in Section 2.2. The pressure drop associated with a forced flow rate through the small nozzle was used to calculated the viscosity, such a viscometer is known as a capillary viscometer

The volume of the wax placed in the depositor in this experiment was 130g, and the density of the wax used was 0.95 g/cm^3. The wax used was Hoben wax 120 (Royal) and was supplied by Hoben International. This wax is commonly used for the investment casting process.

The temperature range used in this experiment was from 75 °C to 90 °C (as found in result section), the wax was melted in the cylinder and stabilised at the required temperature before each experiment. This typically took four to five hours for each of temperature chosen.

For each temperature chosen, the pressure ranged between 1 and 30 psi in each set of experiments.

During the tests the pressure was applied from the compressor and then time for to flow the wax through the nozzle was calculated using a stop watch (generally a few seconds). The mass of the wax deposited was also measured.

In this experiment, the volume of the wax that flows through the nozzle can be calculated using the following equation:

$$\rho = \frac{m}{v} \qquad (1)$$

$$v = \frac{m}{\rho} \qquad (2)$$

Where v is the volume

m is the mass

ρ is the density

After the volume of the wax has been calculated, the flow rate can be obtained using the following equation:

$$\phi = \frac{v}{t} \qquad (3)$$

Where: ϕ is the flow rate

v is the volume

t is the time (sec)

And finally, the viscosity can be calculated, using the following equation:

$$\phi = \frac{\Delta P \pi r^4}{8 L \eta} \qquad (4)$$

where r is the radius of the nozzle (0,5 mm), L is the length of the nozzle (20 mm) and η is the measured viscosity. Re-arranging equation 4:

$$\eta = \frac{\pi \Delta P r^4}{8 L \phi} \qquad (5)$$

So by increasing the temperature and repeating the experiment several times with different pressure values, different values of viscosity were obtained. The correlation between the pressure, temperature and viscosity could then be examined.

2.8 FDM Process

Fused Deposition Modeling is a Rapid Prototyping (RP) technique. Its basic principle is to build 3D physical models, layer by layer, directly driven by the computer system. The material is heated within a heating chamber and extruded through the nozzle, which moves in the X and Y direction [67]. The computer controls the motion and the material deposition out of the nozzle. The droplets fall onto a platform and stack up a 3D object layer by layer, see Figure 2.8.

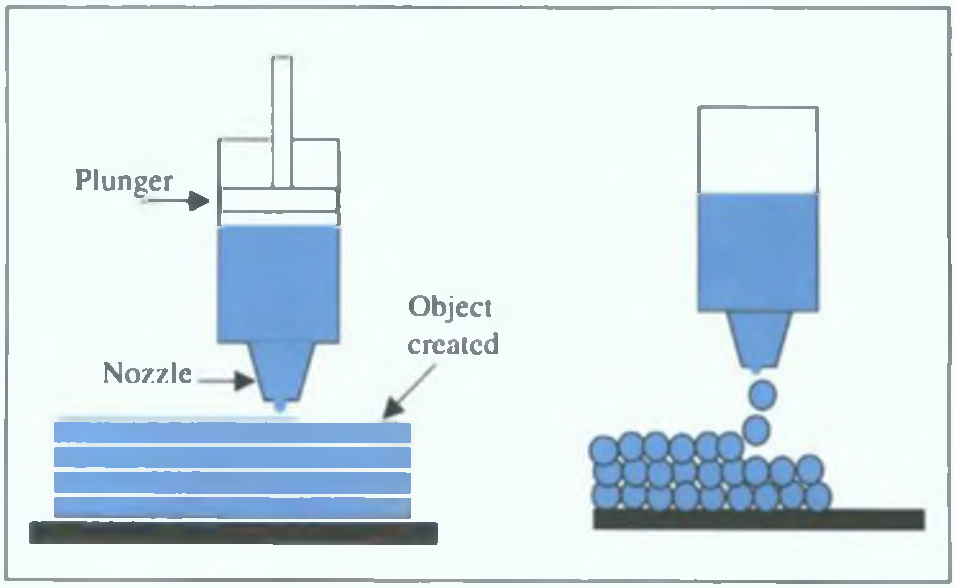
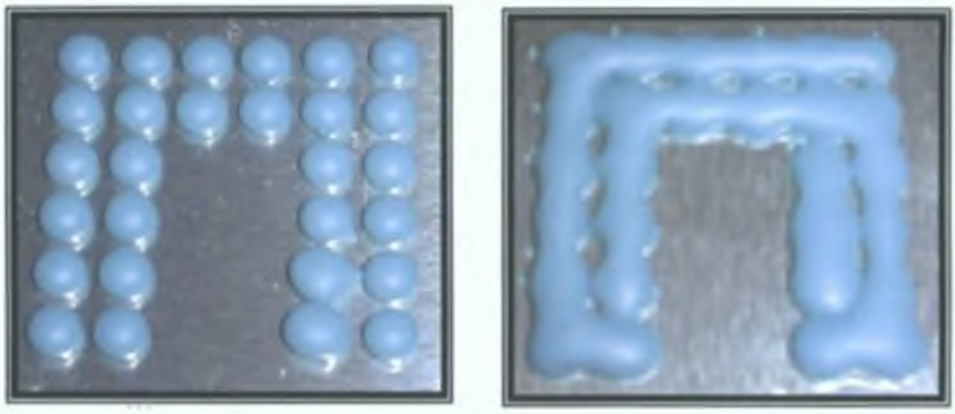


Figure 2.8: Schematic illustration of the FDM process

The FDM technology builds models, layer by layer directly from three-dimensional digital models.



(a) (b)

Figure 2.9: Schematic illustration of built pattern for various deposition temperatures

In the Figure 2.9(a) the temperature was 84 °C increased the temperature at 88 °C resulted in a different pattern as shown in Figure 2.9 (b). With appropriate selection of temperature and pressure repeatable dimension of the droplet can be obtained, see Figure 2.9 (a).

2.9 Procedures for RP Shapes Production

The apparatus used to obtain required shapes was shown in Figure 2.1. The procedures followed to build various shapes are discussed below. Some parameters used are shown in Table 2.1. Six millimetres was left between each drop deposited.

Table 2.1: Parameters used in the rapid prototyping experiments

Parameters	Temperature °C	Pressure (psi)	Distance (mm) X dir / Y dir	
A	80	2	30	54
B	85	3	30	54
C	80	2	30	54
D	84	3	30	60
E	84	3	30	60
F	85	3	30	30
G	90	6	0	0

Parameter A

The geometry deposited for parameter A setting is shown in Figure 2.10.

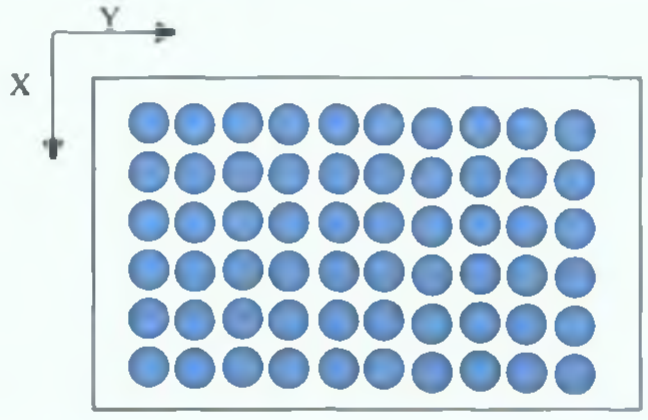


Figure 2.10: geometry deposited for parameter (A) settings

The wax needed was placed in the cylinder and then heated up to 80 °C for 4 hours to stabilise the temperature. The wax was then checked to ensure the condition (semi-liquid at this temperature). The temperature was kept constant at this level during the experiment. After checking the wax condition, the plunger was moved down in the Z direction (12mm) in order to drop the first droplet as shown in Figure 2.11. After that the plunger was moved back up (11.9mm) and then motor 1 was moved (6mm) in the X direction, see Figure 2.11, to drop the second droplet, and so on. Those steps were repeated until the required shape was obtained. Figure 2.11 shows the droplets location as well as the nozzle path. The result obtained is presented in Chapter 3, see Figure 3.18.

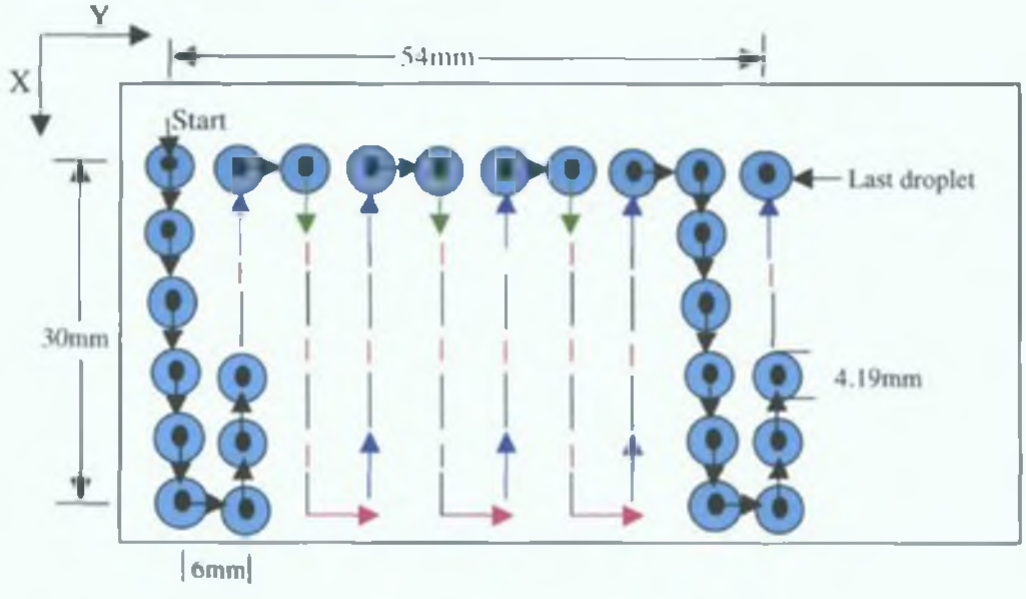


Figure 2.11: X-Y nozzle path in the for parameter for (A) geometry

Parameter B. The same procedures as above were used to build parameter B, however the temperature was increased to 85 °C. The diameter of droplets was larger compared with parameter A as shown in Section 3.5, Figure 3.19.

Parameter C

Parameter C geometry is shown in Figure 2.12.

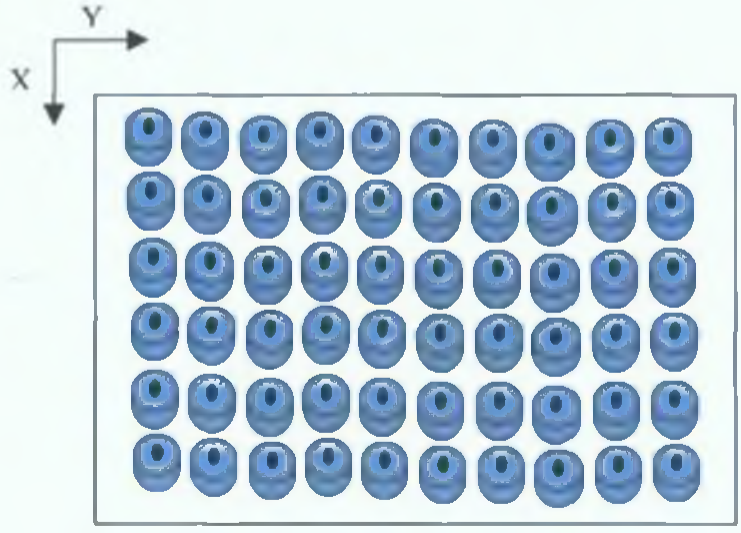


Figure 2.12: Illustrated a geometry of parameter C

The system was moved in the same was as for the parameter A geometry, but two layers. Were produced. The second was built on the top of the first to create the model as shown in Figure 2.13. The result is presented in Section 3.5, Figure 3.20.

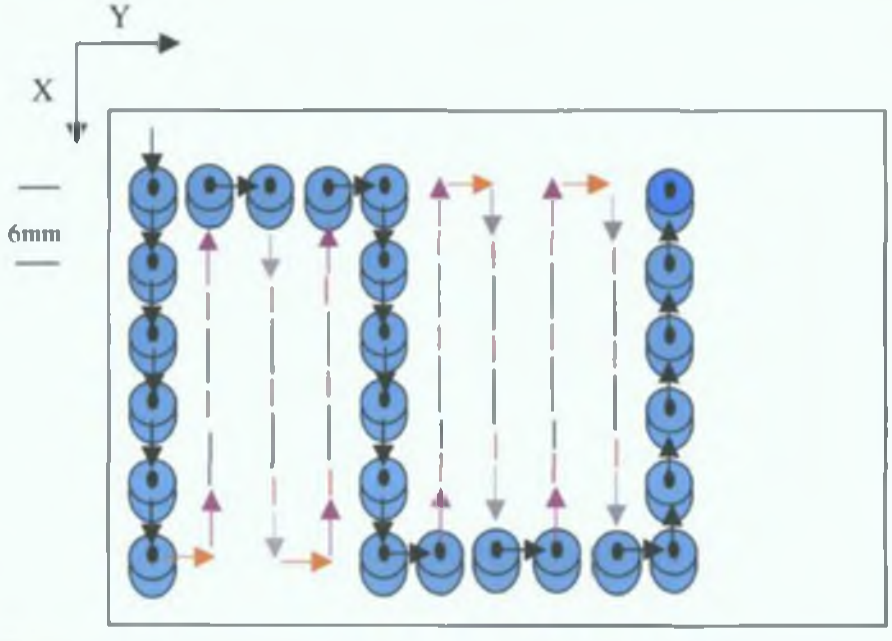


Figure 2.13: Schematic of path for multi-layer deposition with parameter C setting

Parameter D

The geometry produced for parameter D is shown in Figure 2.14.

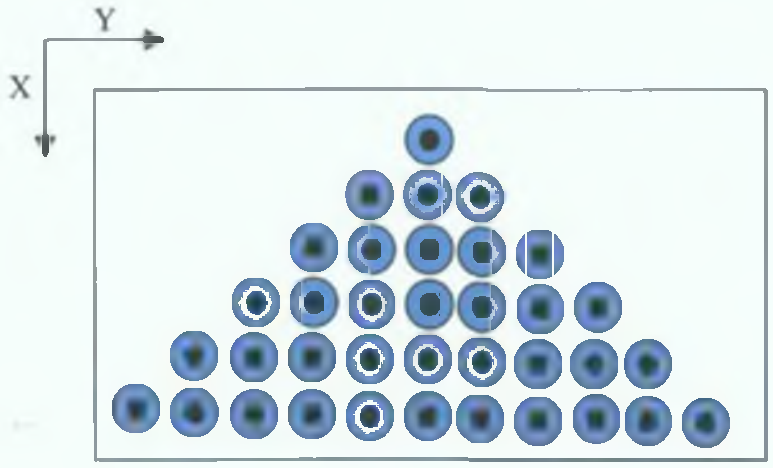


Figure 2.14: Schematic of the geometry produced with Parameter D setting

The temperature was set at 84 ℃ in this experiment. The system was moved to deposit droplets of 30 mm diameter in the X direction also the system was moved 60 mm in the Y direction to deposited droplet. These steps are repeated until required form was obtained see Figure 2.15. The result presented in Section 3.5 in Figure 3.22.

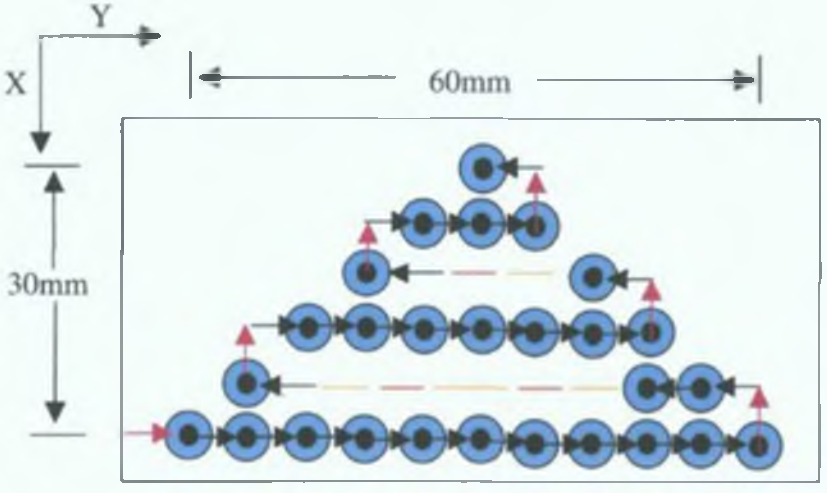


Figure 2.15: X-Y deposition points and path Parameter D geometry

Parameter E

The same experiment was repeated to deposited layer up to the other layer to bulit different models. The shape was obtained as shown in result chapter see Section 3.5, Figure 3.23.

Parameter F

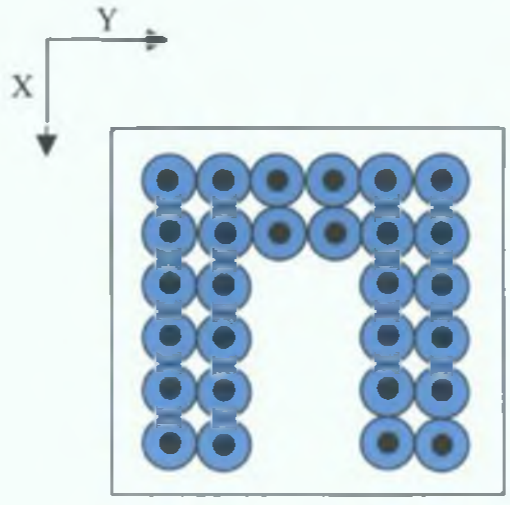


Figure 2.16: Schematic of the geometry produced for parameter F settings

The parameter F geometry was created at a temperature of 85 °C. The system was moved 30mm in the -X direction to deposits the first row, the nozzle was then moved 30mm in the Y direction to deposit the first column, and then the system was moved as shown in Figure 2.17 until the required shape was obtained. The shape produced is presented in the results chapter, Section 3.5, Figure 3.24.

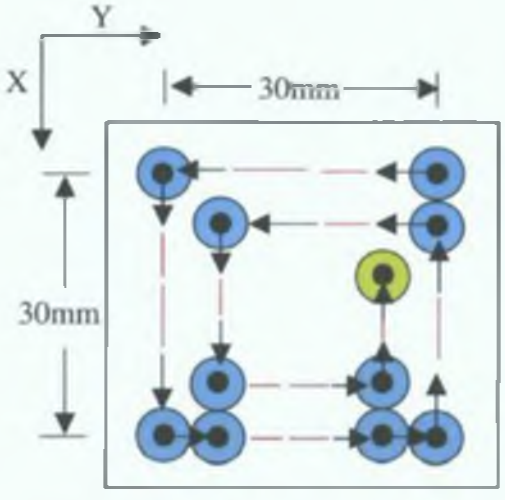


Figure 2.17: X-Y motions for parameter F geometry

Parameter G. This experiment was used to produces patterns of wax. The moulds were obtained without using the X-Y movement. In this experiment the wax was melted at 90 °C in the deposition chamber. The pressure was constant at 6 psi. A container to recive the wax extruded through the nozzle was put in place until the container was filled. The container was then removed to allowed the mould to cool. These steps were repeated in such a way until the required pattern was obtained as shown in the results chapter, Section 3.5 Figures 3. 25, 3. 26.

3-D Objects

In these experiments, various 3D models were produced. The x-y movement of the depositor defined the placement of each wax droplet. This imparted on the dimensional accuracy of the layer being deposited as the distance between each drop affects how well each droplet bonds with the next and previous. Tests were also conducted to find out the affect on droplet size that the height that they are dropped from has. The results showed that optimal bonding was obtained when the distance between deposited drops was the radius of the droplet. The affect of the plate material (polystyrene and aluminium) was also tested. To produced the 3D objects using a polystyrene plate. The results are shown in Section 3.5 Figure 3.28. This experiment was carried out to produced 3D objects, the system was moved in the x, y direction to deposited layer upon layer to bulit different models.

I-Beam. This experimenemt was carried out to produce I-beam model, the temperature was 83 °C, the system was moved in x-y direction to deposit three layers in each direction the flange length is 12 dopes, and width is 3 drops, the flange thickness is 3 drops. The web is 5 drops in length and 2 drops in width and 3 drops thickness.

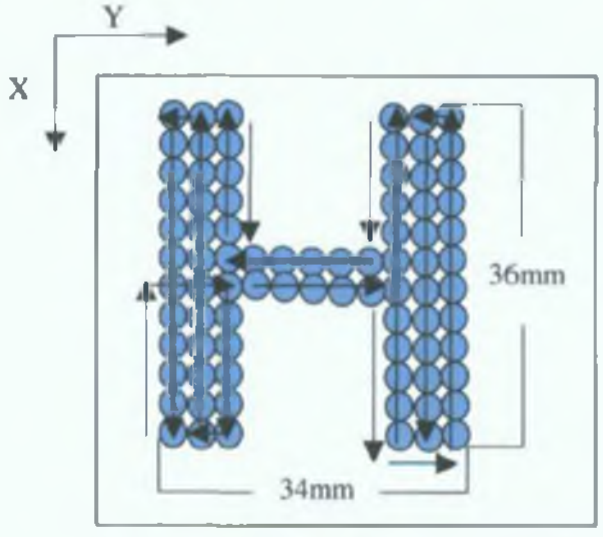


Figure 2.18: Shows I-beam geometry

This experiment was carried out to produce impeller model, the temperature was 83 °C, the system was moved in the x-y direction to deposit three layers in each direction and deposit eight layers high with built the shaft blade three drops wide and eight drops long. The models are shown in results chapter, Section 3.5 see Figure 3.28.

The experiment developed a model of an impeller Figure 2.19 shows the x-y direction of the deposited three layers, the system was moved 27 mm in the x direction and was moved 9 mm in the y direction and the deposited layer up on layer to produce impeller shape with shaft, the shaft was deposited three drops wide and eight drops high, the central shaft a square three drops side length with the final shapes was shown in the results chapter.

Other experiments were carried out with the same setting parameters but using airflow to cool the droplet. The result showed that optimal bonding was obtained between deposited drops. The model is shown in result chapter see figure 3.33

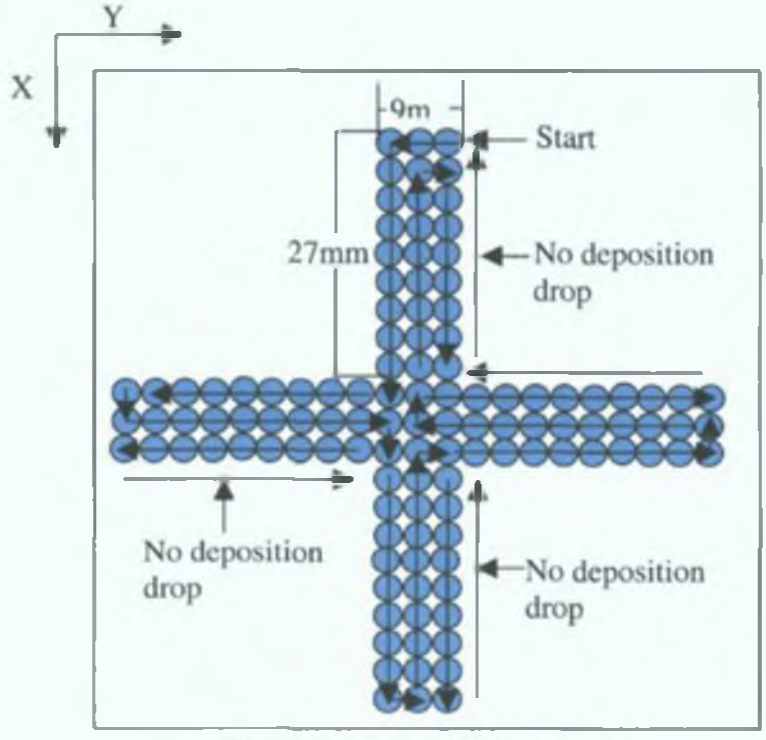


Figure 2.19: Impeller geometry

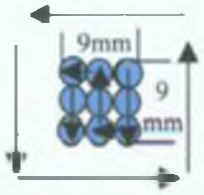


Figure 2.20. Shows the shaft of impeller

The geometry impeller shape can be seen in Figure 2.21.

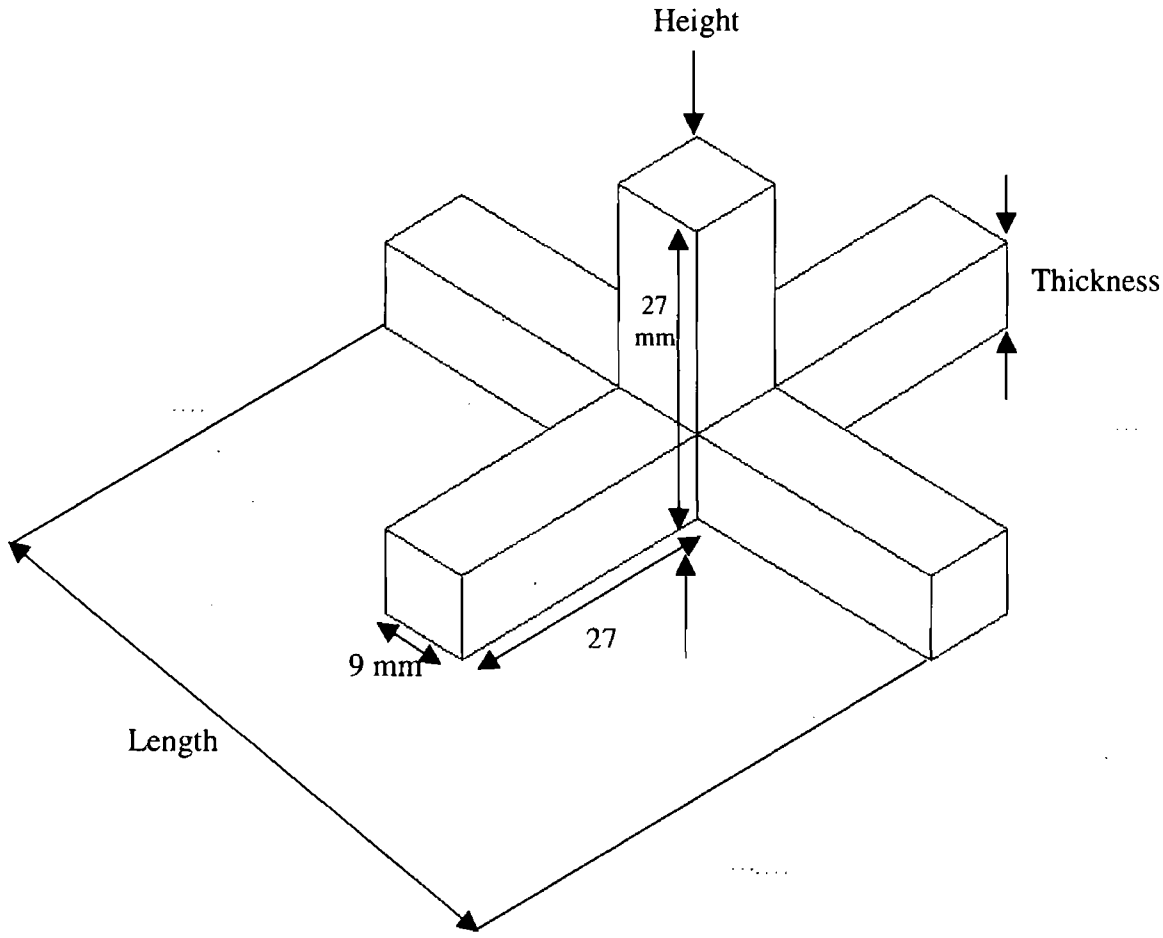


Figure 2.21: Schematic of the geometry of impeller shape

2.10 Analysis of the Droplet and Impeller Sizes

The mean diameter and height of ten drops produced under processing temperatures in the range of 77 to 90 °C was determined along with the standard deviation and the confidence interval. The length, thickness and height of at least five impellers produced with air-flow and without air-flow was also statistically evaluated. A review of the statistics used is presented in Appendix F.

Chapter 3

3. RESULTS AND DISCUSSION

3.1 Height for Deposition

Initial tests were performed with the nozzle at different heights. It was found that for deposition heights much below or above 40 mm that too wide a diameter droplet resulted. It is thought that for deposition distances below 40 mm the drop was too fluid when it hit the deposition plate and that for distance above 40 mm there was too much droplet momentum. The distance between the nozzle and receiving plate was therefore set at 40mm in all experiments. In the depositon experiments, the droplets were deposited onto a receiving plate which was placed 40 mm below the nozzle to allow the droplets to have an adequate time to be partially solidified.

3.2 X-Y-Z Control

The motion in X-Y direction was controlled as simple linear interpolation, which enabled precision movements for deposition chamber. A graph of the number of motor steps against the distance travelled is shown in Figure 3.1.

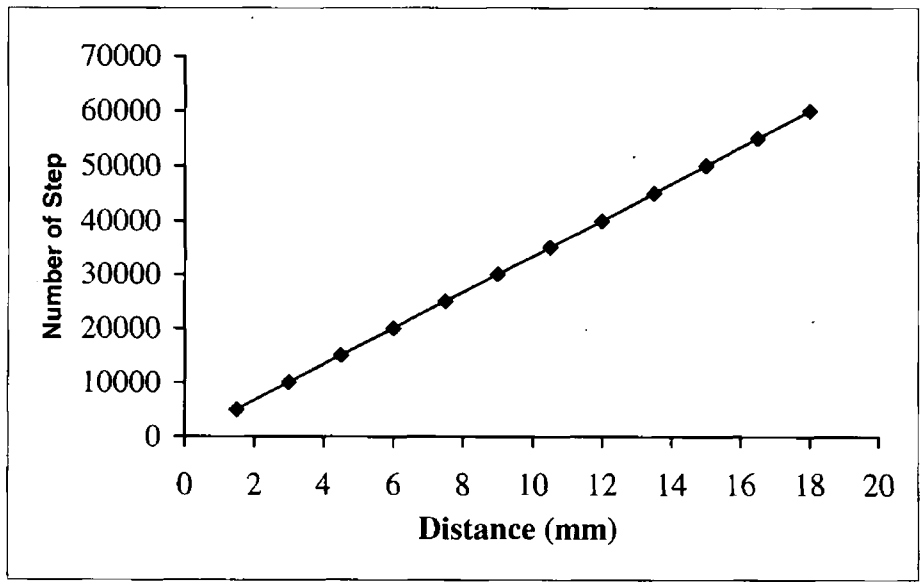


Figure 3.1: Graph the distance moved in the x or y direction versus the number of steps

The Z control the motion was in the vertical direction. A movement was used to deposit the droplet. Figure 3.2 shows the number motor of steps against the distance moved for the Z direction

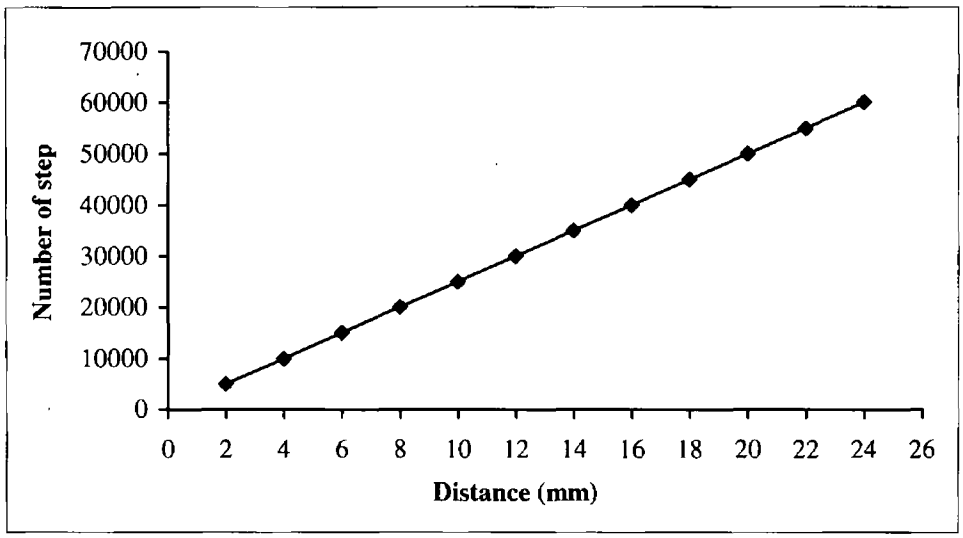


Figure 3.2: Graph of the distance in the z direction against the number of steps

3.3 Transition and Melting Temperature of Wax

Figure 3.3 shows the temperature against time of the investment wax for this experiment. Above 58°C the wax was liquid and below 56 °C completely solid. The full data for this test and for the candle wax is shown in Appendix D. This information allowed appropriate setting of the temperature parameters to be investigated for the rest of the experiments. Initial deposition tests for temperatures in the range of 58 to 70 °C however prove very difficult to process. It is believed that this was due to the larger temperature fluctuations that would be expected to occur in the larger test vessel of the deposition chamber.

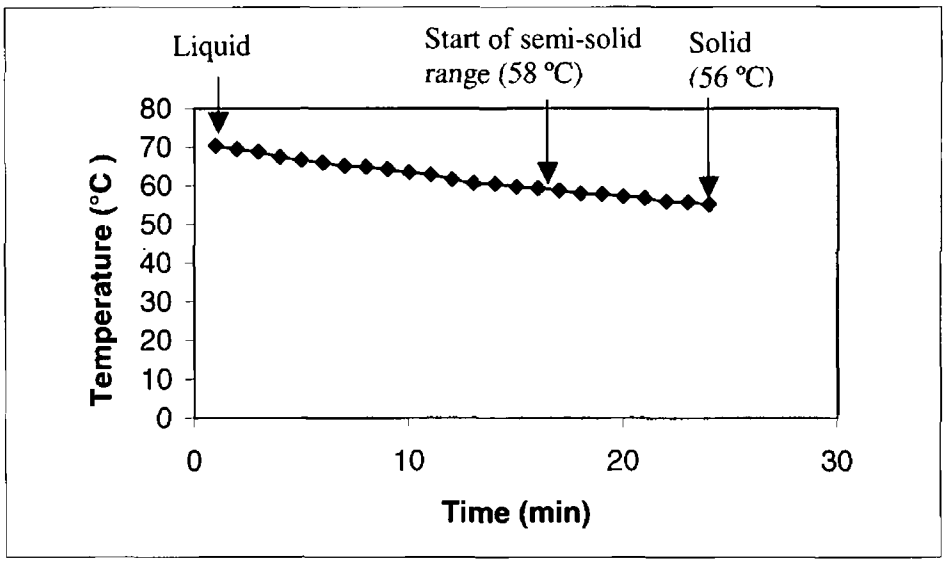


Figure 3.3: Graph of temperature versus time for the cooling wax

3.4 Viscosity Measurement

From the capillary viscometer viscosity equation presented in the last chapter, it can be seen that flow rate of the wax for a specified pressure difference needed to be determined for each experiment. With the temperature set at 75 °C and the pressure at 34,487 Pa the first value of viscosity recorded is seen on the left of Figure 3.4. The experiment was repeated at constant temperature but for figure levels of pressure producing the graph in Figure 3.4. In this experiment the viscosity was observed to decrease when the pressure increased. The viscosity decreased markedly with increasing the pressure until a point. After this a lower decrease in pressure was noted.

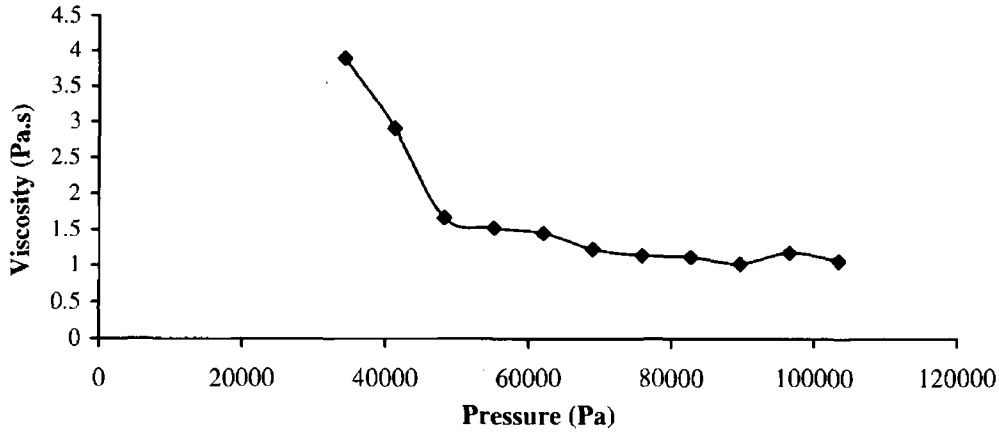


Figure 3.4: Relation between the pressure, from 34,473 Pa to 103,421 Pa (5 to 15 psi), and viscosity, with a constant temperature of 75 °C

The same experiment was repeated with temperature of 75 °C but the pressure range was changed to 34,487 to 144,845 Pa. The results for this test followed a similar pattern, as shown in Figure 3.5.

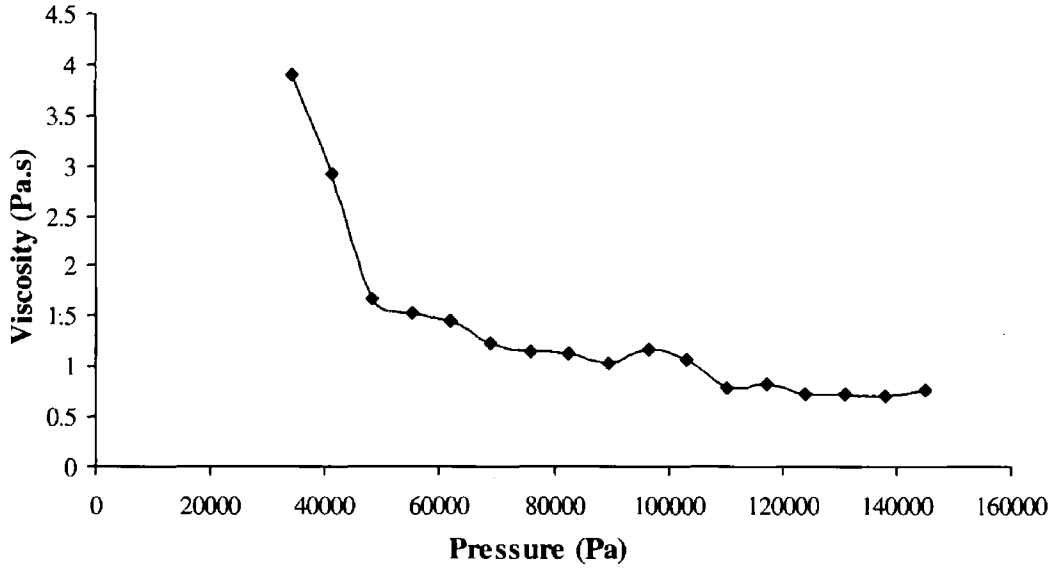


Figure 3.5: Relation between the pressure, from 34,487 to 144,845 Pa (5 to 21 psi), and viscosity, with a constant temperature of 75 °C

The experiment was repeated at 78 °C with pressure range from 34,487 to 103,461 Pa and then again with same temperature but an increased pressure range from 34,487 to 206,922 Pa. These results can be seen in Figure 3.6 and 3.7 respectively.

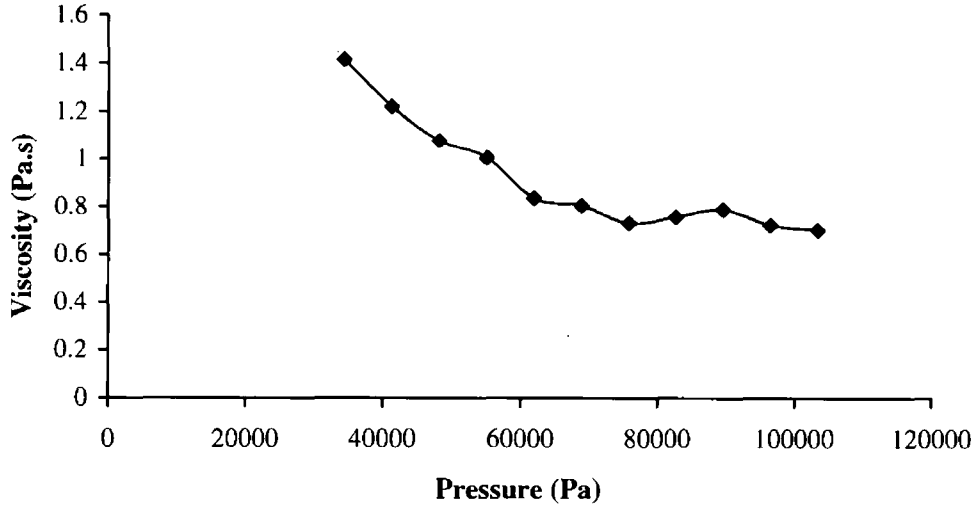


Figure 3.6: Relation between the pressure, from 34,487 to 103,461 Pa (5 to 15 psi), and viscosity with a constant temperature of 78 °C

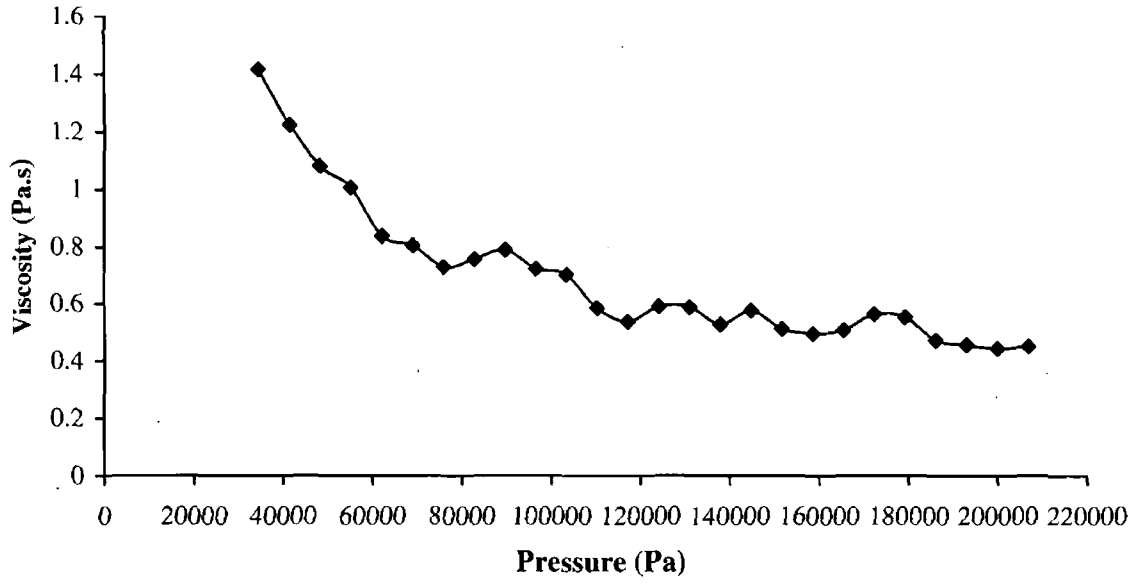


Figure 3.7: Relation between the pressure from 103,461 Pa to 206,842.71 Pa (5 to 30 psi), and viscosity at temperature 78 °C

In this experiment the temperature was set at 80 °C the condition of material as liquid. The pressure was set at 6,897 Pa (1 psi) and raised in increments of 7 psi for each experimental run until 15 psi was reached. Again, the viscosity decreased when the pressure was increased. The influence of pressure on the viscosity for this experimental run is shown in Figure 3.8. For the pressure from 62,076 – 103,461 Pa (9 psi to 15 psi) the values of the viscosity were almost constant. For experiment at this temperature and above the wax was completely liquid throughout the depositor. Temperatures below 80 °C resulted in a solid annular section in the depositor. These results suggest to keep the temperature at 80 °C or above and also leave the pressure at 34,473 Pa (5 psi) or above.

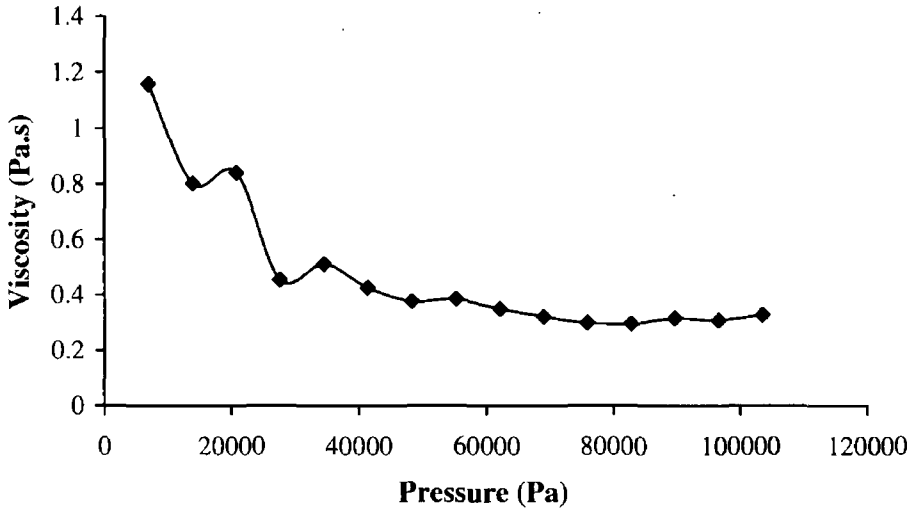


Figure 3.8: Relation between the pressure, from 6,897 to 103,461 Pa (1 to 15 psi), on the viscosity at temperature 80 °C

The experiment was repeated again, this time at 82 °C and with a pressure range of 20692 to 103.461 Pa (3-15 psi). A second experiment at this temperature was performed but with a pressure range from 20,692 to 206,922 Pa. The result of these two tests run be seen in Figure 3.9 and 3.10 respectively. The viscosity was seen to gradually decline with increasing pressure for both cases.

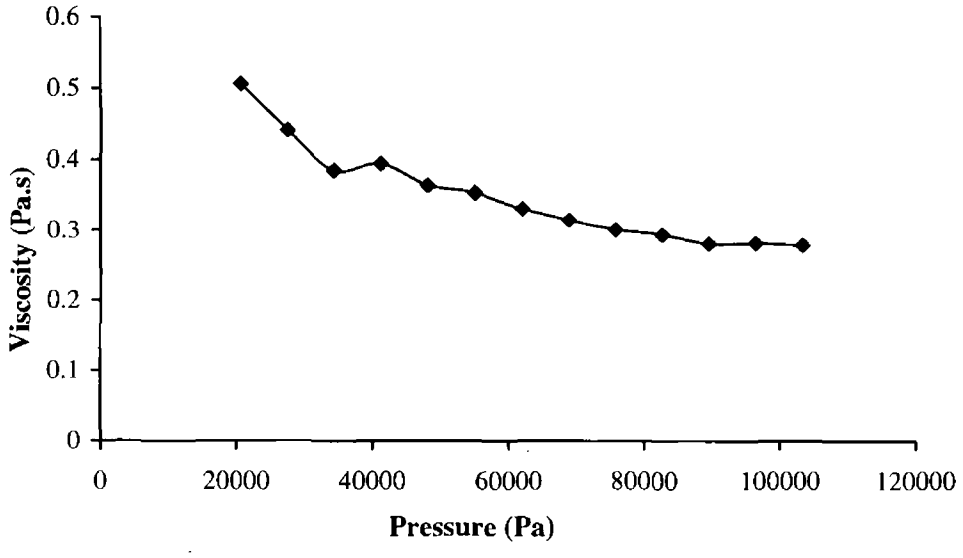


Figure 3.9: Relation between the pressure, from 20,692 to 103,461 Pa (3 to 15 psi), and viscosity at temperature 82 °C

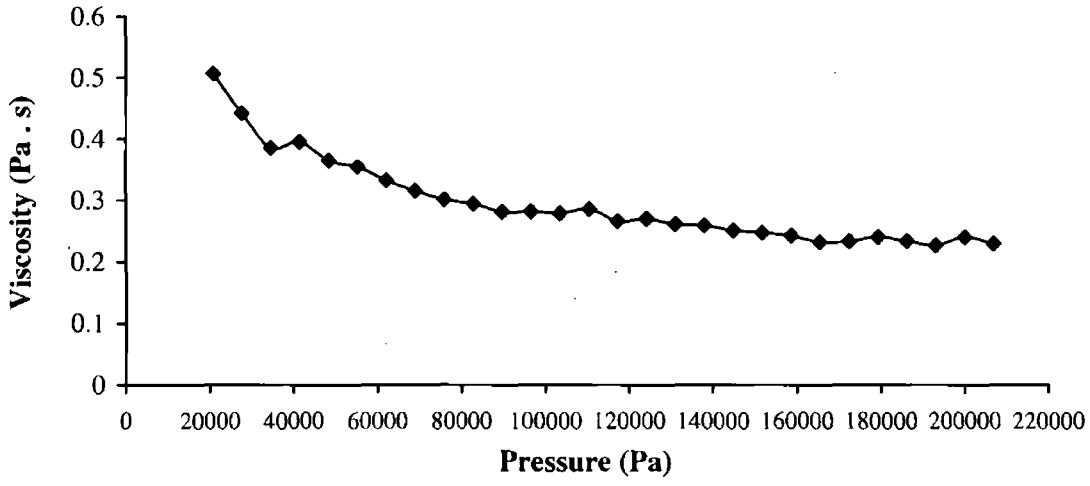


Figure 3.10: Illustrated influence the pressure from, 20,692 to 206,842 Pa (3 to 30 psi), on the viscosity at temperature 82 °C

The Figure 3.11 shows the relation between the pressures and viscosity, for a temperature of 85 °C. The values of the viscosity gradually decreased with increasing pressure.

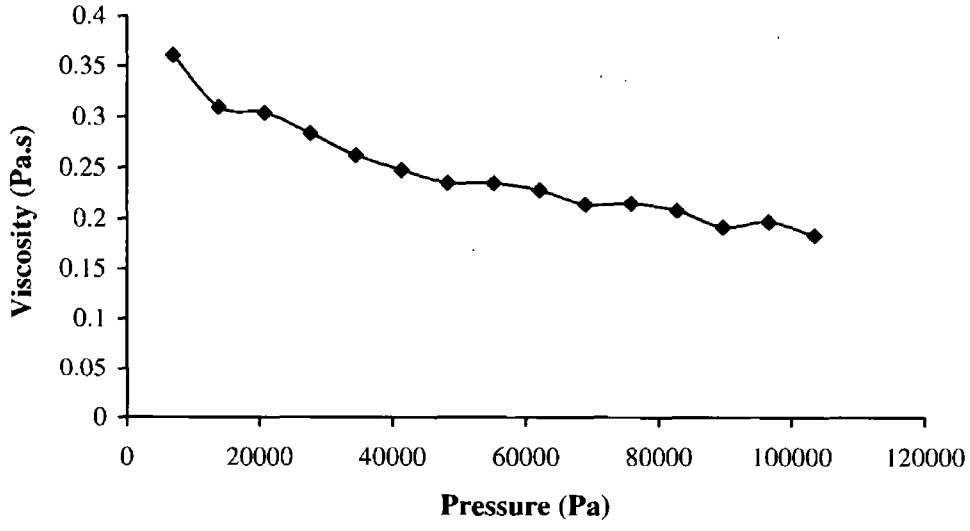


Figure 3.11: Illustrated influence the pressure, from 6,897 to 103,461 Pa (1 to 15 psi), on the viscosity at temperature 85 °C

Figure 3.12 shows the viscosity of the wax in relation to pressure again with a constant temperature at 85 °C but this time with the pressure applied from 6,897 to 103,461 Pa (1 psi to 21 psi) The relation was found to be almost the same as the curve above. The viscosity decreased, as the pressure was increased.

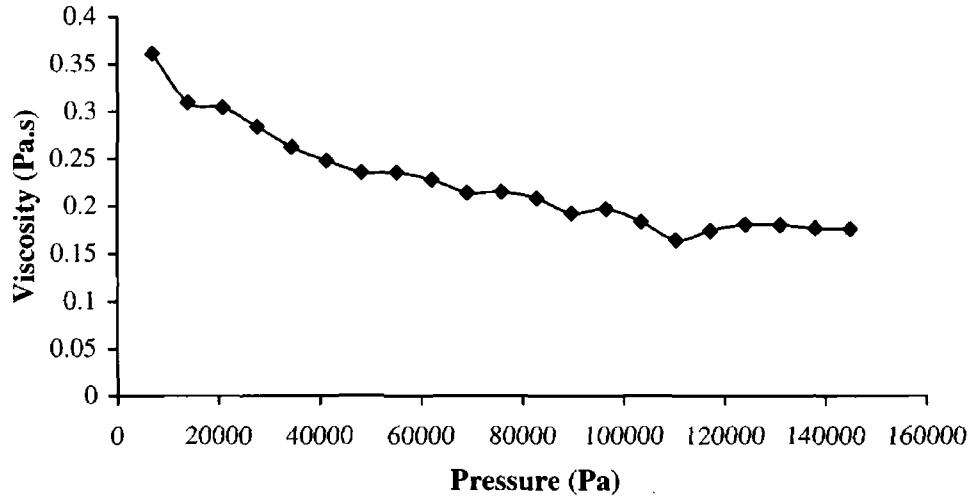


Figure 3.12: Illustrated influence the pressure, from 6,897 to 144,845 Pa (1 to 21 psi), on the viscosity at temperature 85 °C

Two experiments were repeated at 88 °C one with a pressure range from 13,795 to 103,461 Pa and other from 13,795 to 158,640 Pa. Results from these tests are presented in Figure 3.13 and 3.14 respectively. A sharp decrease in the viscosity is noted until 27,590 Pa and then a more gradual decrease in the viscosity was found with increasing pressure.

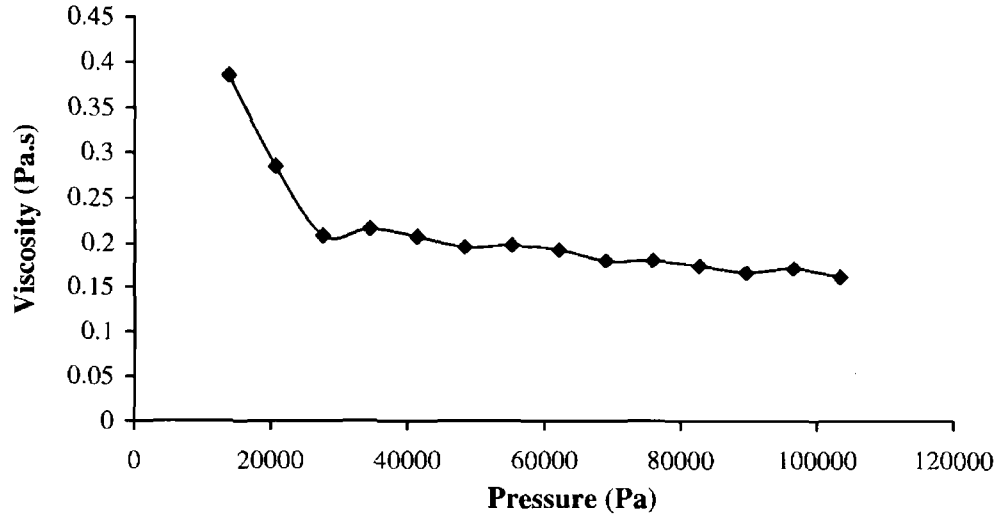


Figure 3.13: Illustrated influence the pressure, from 13,795 to 103,461 Pa (2 to 15 psi), on the viscosity at temperature 88 °C

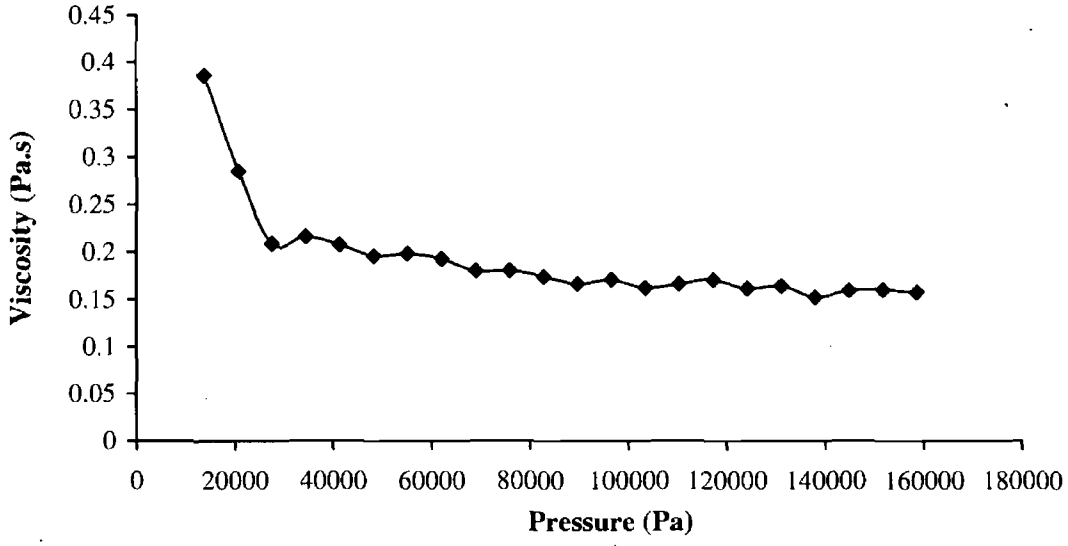


Figure 3.14: Illustrated influence the pressure, from 13,795 to 158,640 Pa (2 to 23 psi), on the viscosity at temperature 88 °C

In the next experiment the same procedure was repeated but with the temperature at 90 °C and a pressure range from 13,795 to 103,461 Pa initially Figure 3.15, and then 13,795 to 172,435 Pa, Figure 3.16 the values of viscosity showed only small reduction while the pressure was increased.

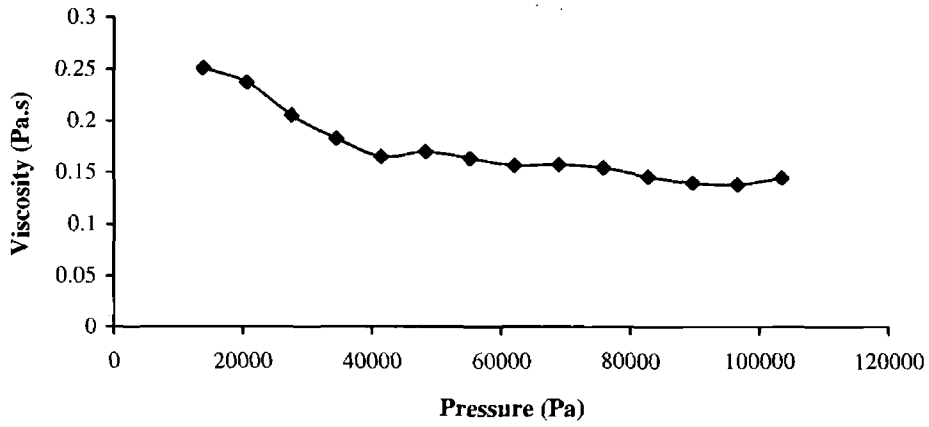


Figure 3.15: Illustrated influence the pressure, from 13,795 to 103,461 Pa (2 to 15 psi), on the viscosity at temperature 90 °C

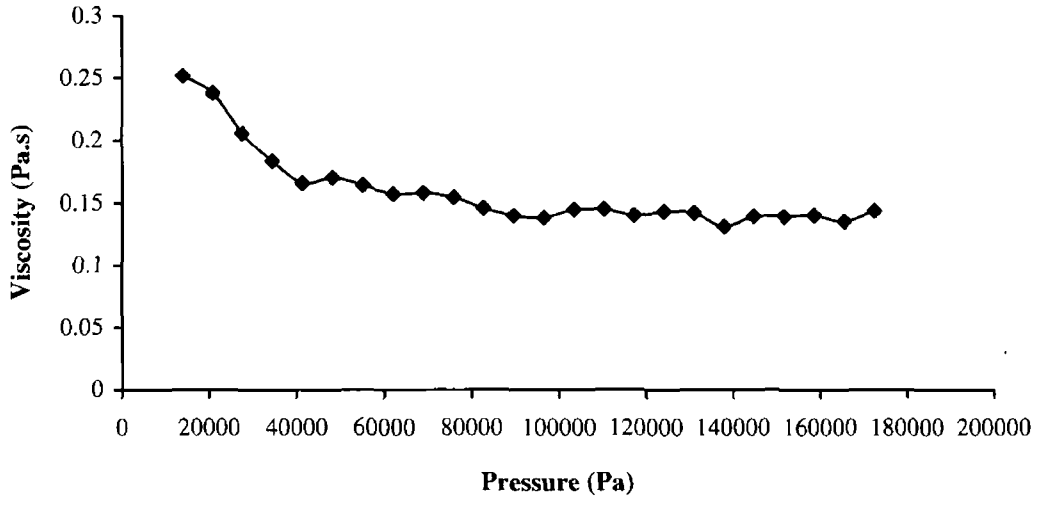


Figure 3.16: Illustrated influence the pressure, from 13789.51 to 172,368.92 Pa (2 to 25 psi), on the viscosity at temperature 90 °C

The results refer to (Figure 3.4 to Figure 3.16) the relationship between viscosity and pressures for a given wax melt at the required temperature. All viscosity measurements were conducted at a temperature between 75 and 90 °C, with pressure ranging from 1 psi up to 30 psi. The viscosities recorded ranged from 1.41 Pa.s to 0.143 Pa.s. The viscosity decreased with increasing pressure.

The viscosity reduced to between 0.175 to 0.15 Pa.s for pressure of 172,368.92 Pa (25 psi) at 90 °C Figure 3.16. The wax was too fluid however above 85 °C and would pour out of the depositor if the exit was not blocked. A temperature range of 82-85 °C would therefore be recommended for processing this wax. This corresponds to a viscosity range from 0.39 to 0.22 Pa.s for a pressure range from 34,487 to 68,974 Pa (5 to 10 psi). A limit of 10 psi is suggested for the pressure due to the overly rapid exit speed of the wax above this pressure. This viscosity processing range is readily visible for the various pressures tested, see Figure 3.17.

3.4.1 Viscosity Determined for Wax at Different Temperatures

The viscosity was sensitive to temperature. At low temperature, the viscosity was high. And at the high temperature the viscosity was low. Figure 3 .17 below is a collation of the results presented in the last section. The figure below shows the influence of temperature on the viscosity. The decrease in the viscosity with increasing temperature was most apparent for the lower deposition pressures.

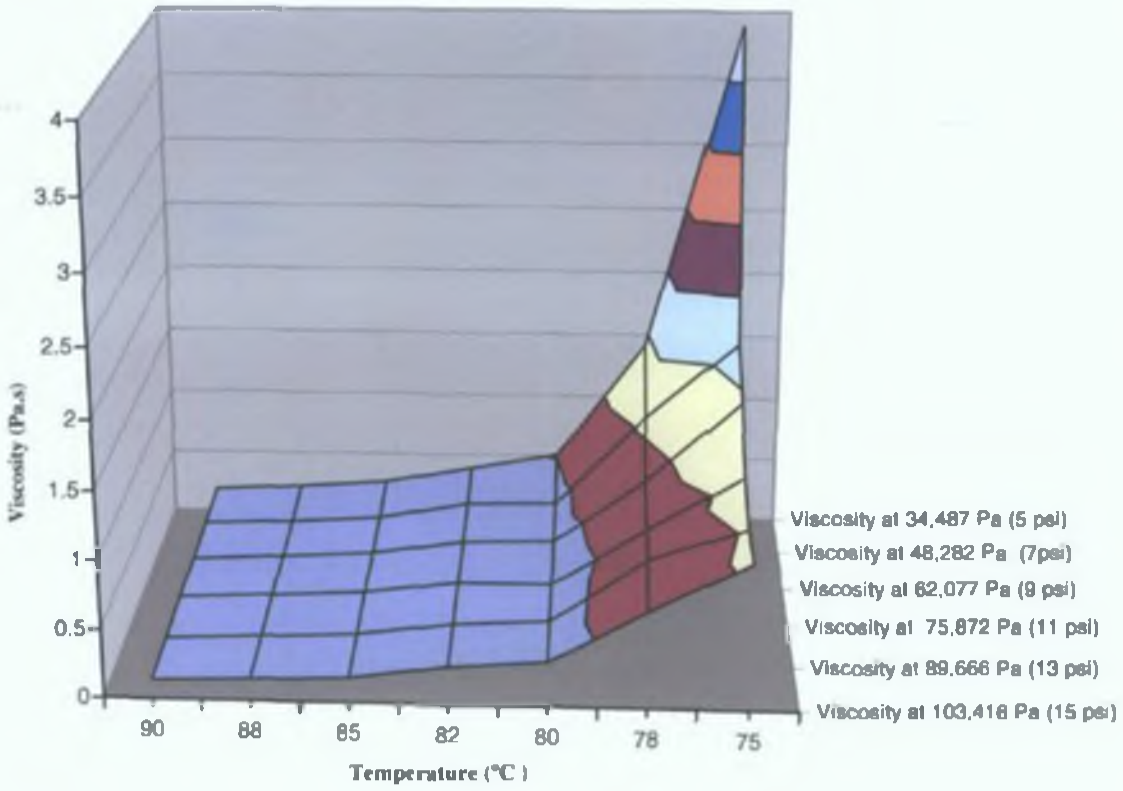


Figure 3.17: Results of viscosity versus temperature measurements

At 34,487 Pa the following equation was fitted to the data ($R^2 = 0.998$):

$y = 0.0002x^4 - 0.0589x^3 + 7.7404x^2 - 451.98x + 9890.5$

where y was the viscosity and x the temperature. Similarly, at 82 °C the following equation was fitted to the data ($R^2 = 0.985$):

$y = 1E\text{-}21x^4 - 6E\text{-}16x^3 + 1E\text{-}10x^2 - 1E\text{-}05x + 0.6696$

where y was the viscosity and x the pressure.

3.5 Rapid Prototyping Shape Production

The shapes present below were obtained according to the depositon movements described in Section 2.9 The temperature of the wax was set at 80°C for parameter Set A, see Figure 3.18. This pattern was repeated with a wax temperature of 85 °C, see figure 3.19.

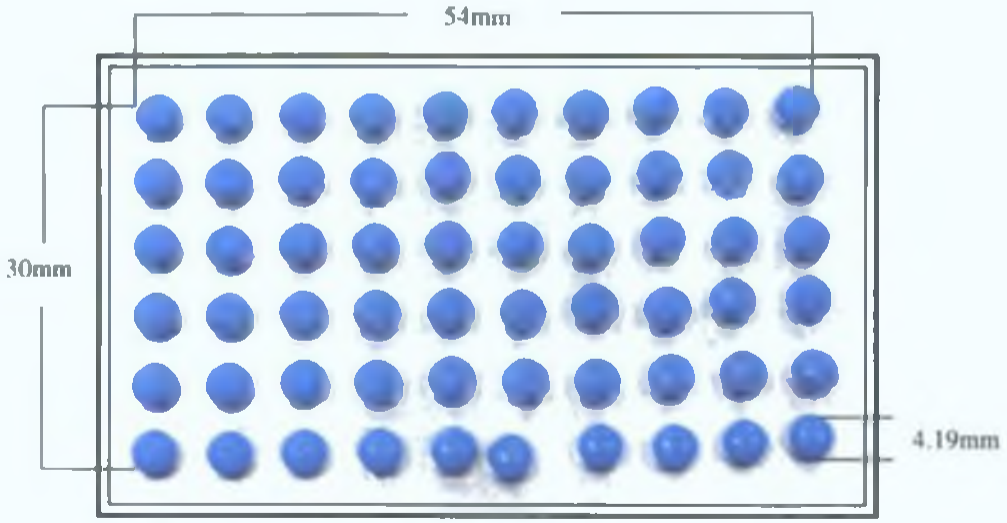


Figure 3.18: Pattern (A) shape built at 80 °C

In this case, as shown in the figure below, the diameter of the droplets are large compared in the first shape.

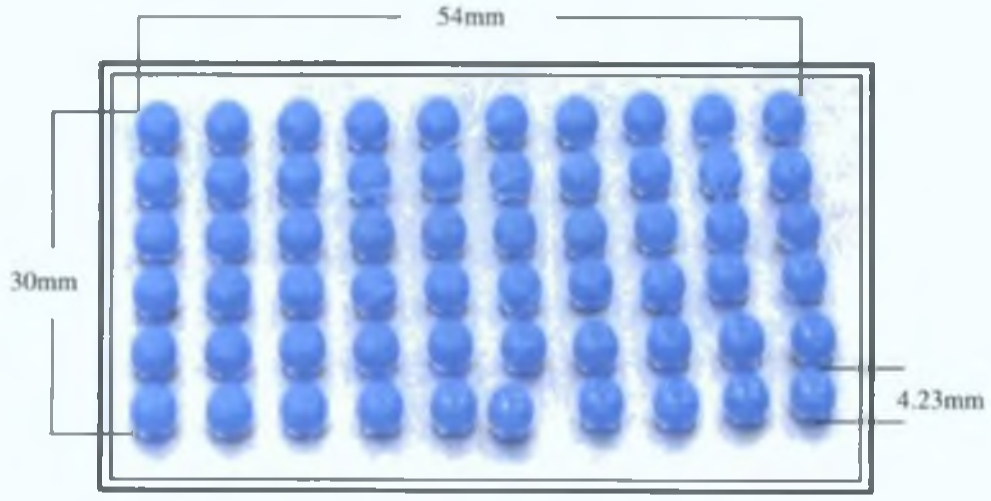


Figure 3.19: Pattern (B) the shape was built at 85 °C

Pattern A was repeated at 80 °C, this time with one set of pattern A drops deposited on top of a previous set, Figure 3.20. Three layers of pattern A were also deposited one on top of the other see Figure 3.21. The depositon of one droplet upon anther was difficult unless the deposition occurred slowly this ensured the previous drop was fully cooled before deposition of the next layer of drop.

Figure 3.20: Two-layers of pattern (C) deposited

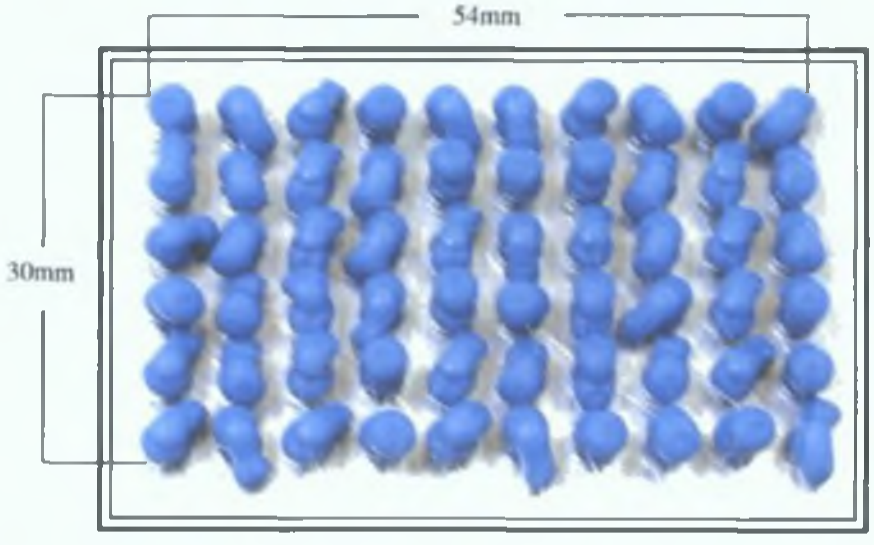


Figure 3.21: Three-layers of pattern (C) deposited

Figure 3.22 shows the deposition of pattern D at 84 °C as described in Section 2.9. Figure 3.23 shows the depositon of tow layer of pattern D on top of each other. Due to reduced heat extraction from the drops in the second and subsequent layers it was found that these drops tended to flow off to some degree before completely solidifying.

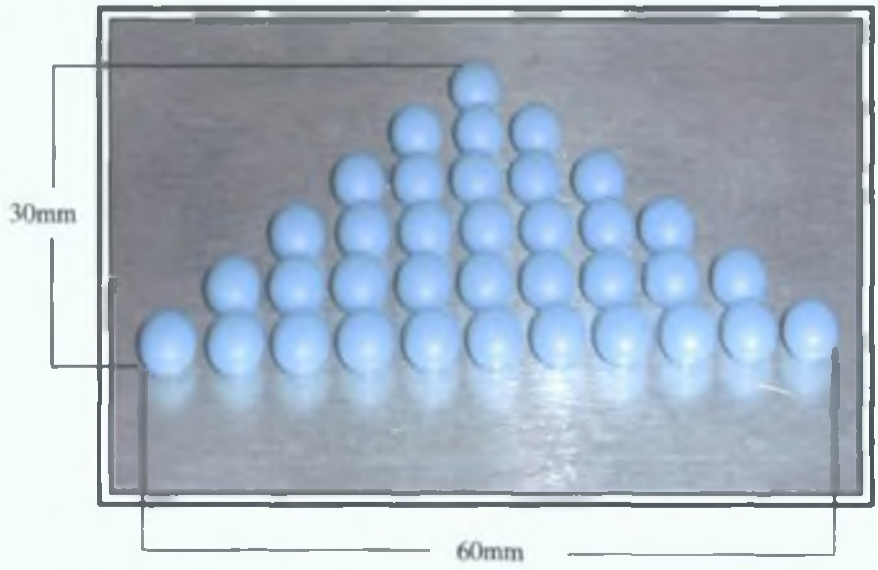


Figure 3.22: Shows the deposition droplet of pattern (D) at 84 °C

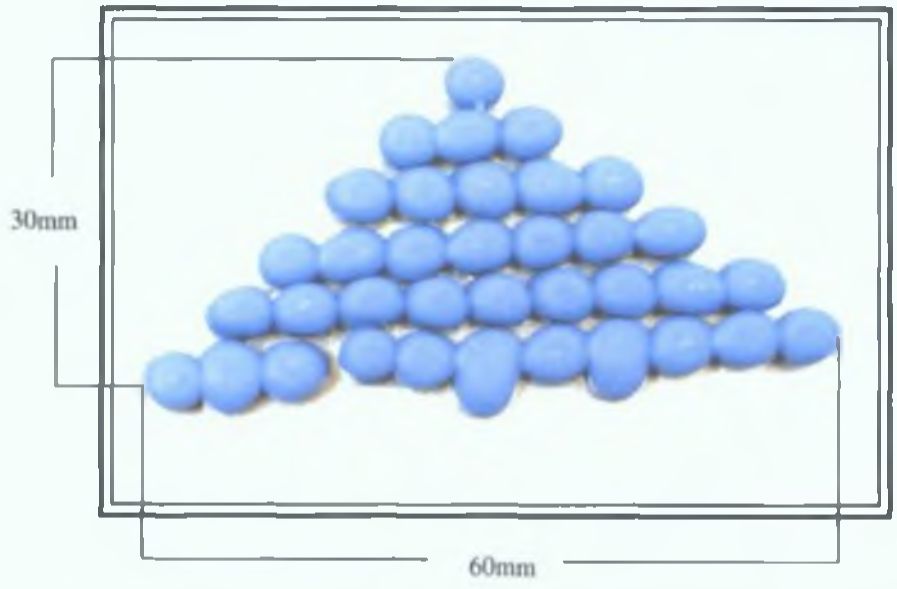


Figure 3.23: Shows the two-layer deposition of pattern (E) at 84 °C

Figure 3.24 shows the deposition of pattern F at 85 °C.

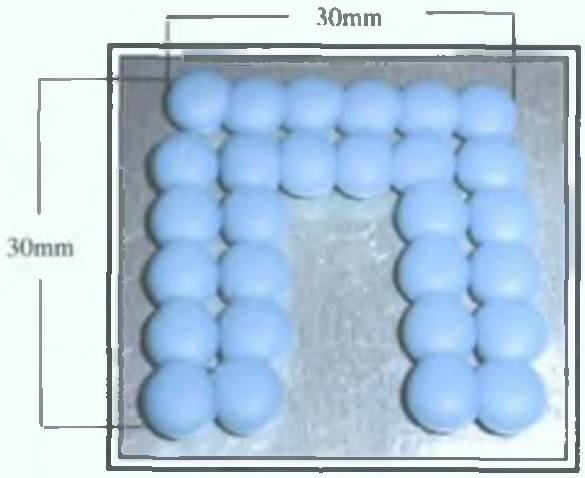


Figure 3.24: Deposition of pattern (F) at 85 °C

Figure 3.25 shows the extrusion of wax at 90 °C into a square mould a (40 × 40 mm) at 41368.5 Pa (6 psi).

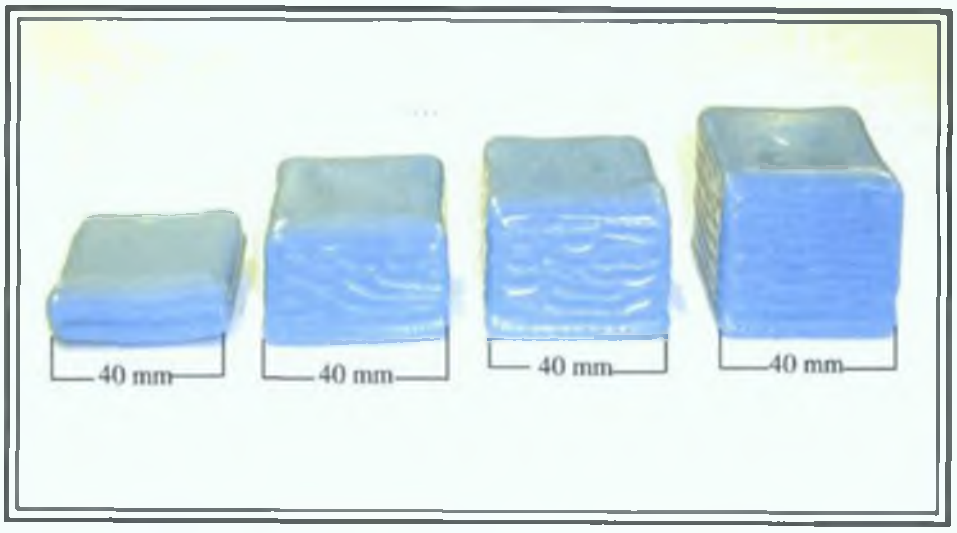


Figure 3.25: Deposits of extruded wax into a square mould at 90 °C, pattern G

The same experiment was repeated for an annular mould, as shown in Figure 3.26. An interesting observation in the ripple effect produced on the side of these patterns.

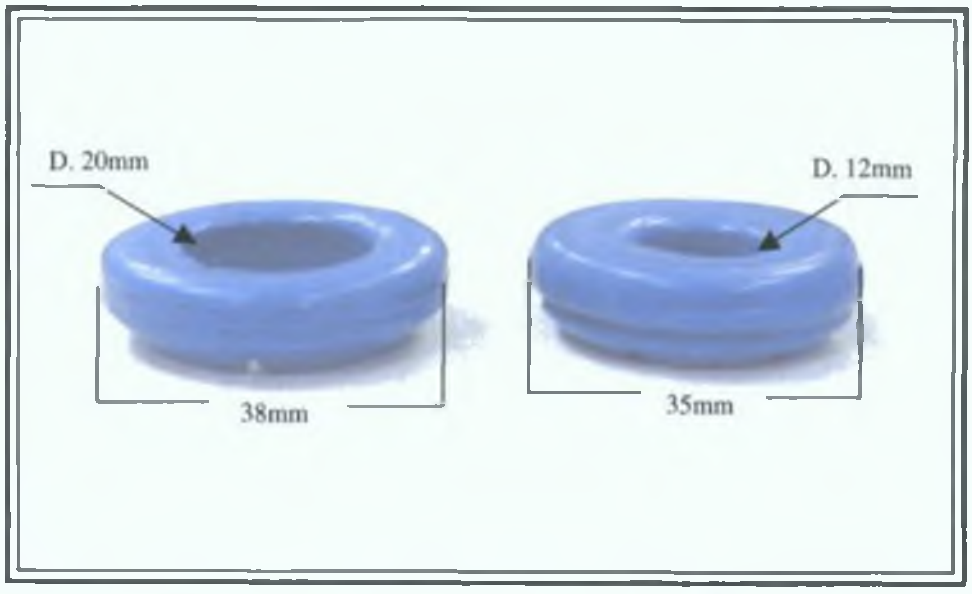


Figure 3.26: Annular pattern produced from wax at 90 °C and with 41368.5 Pa (6 psi) depositon pressure, pattern (G)

3.4.1 FDM Of 3-D Shapes

Three-dimensional objects were by using the FDM process. The nozzle was moved in the x-y direction the temperature was set at 81 °C. The models were obtained by depositing multi-layers onto a polystyrene plate. Some of the patterns generated can be seen in Figures 3.27 and 3.28.

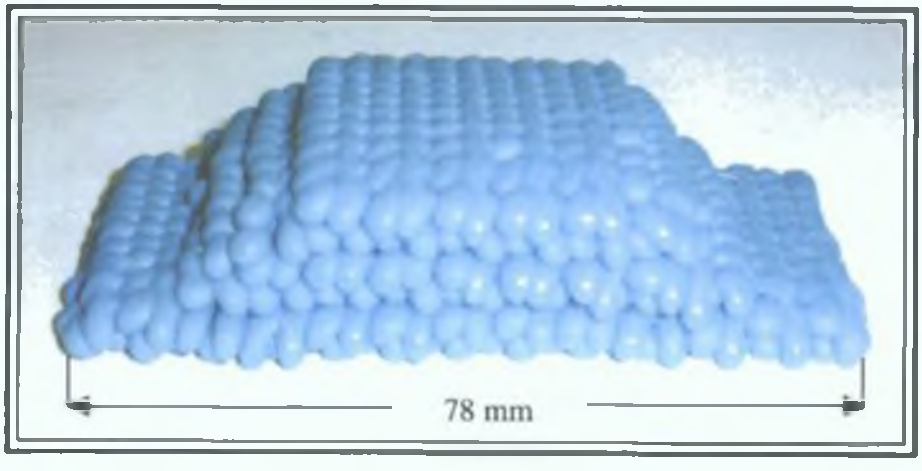


Figure 3.27: Shows 3-D stepped structure at 81 °C (78mm length and 26 drops, 30mm wide, 10 drops for the bottom layer)

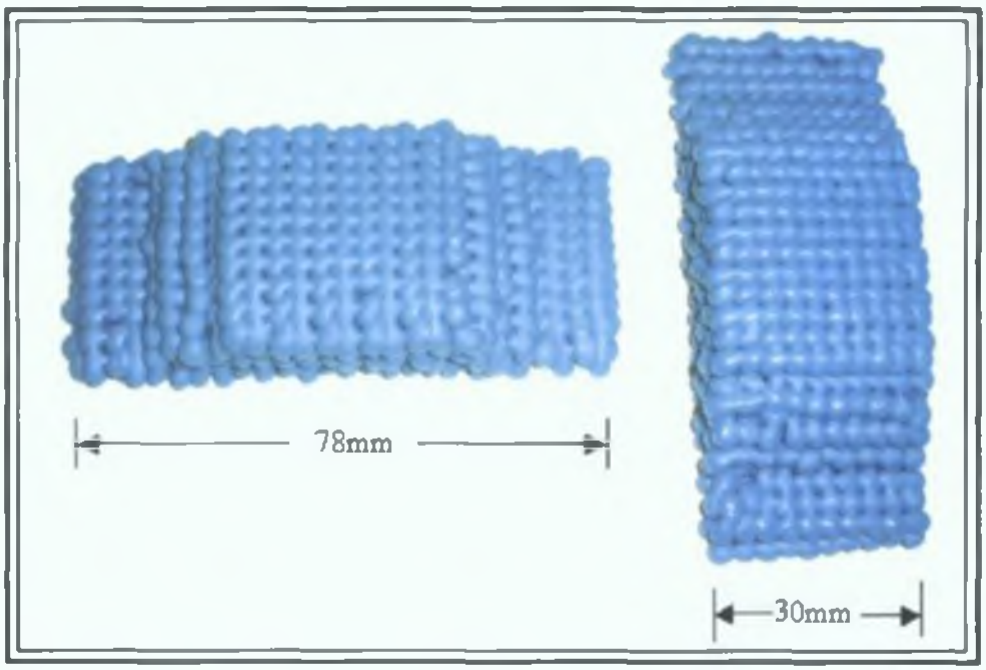


Figure 3.28: 3-D stepped structure deposited at 81 °C

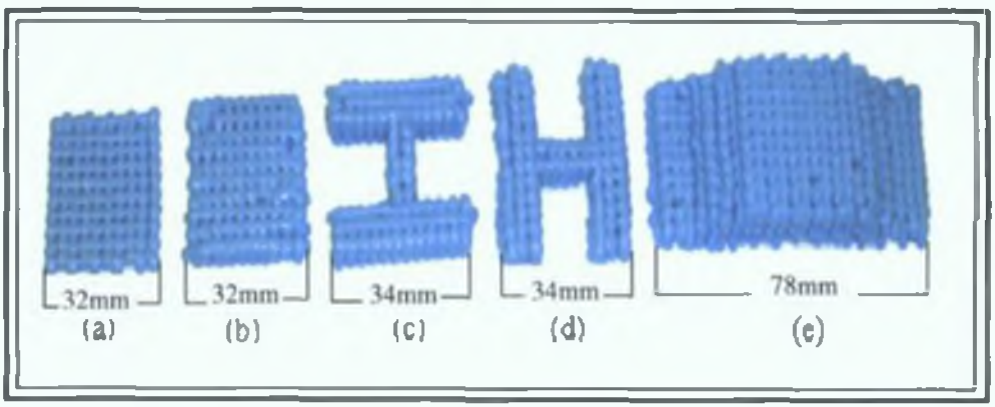


Figure 3.29: (a) 2-D square (30mm by 30mm), (b) two layers of (a) structure, (c) three layered I-beam structure, (34mm high by 34mm wide, 3 drops thick and 12 drops long), (d) I- beam structure repeated, (e) as figure 3.28 is repeated.

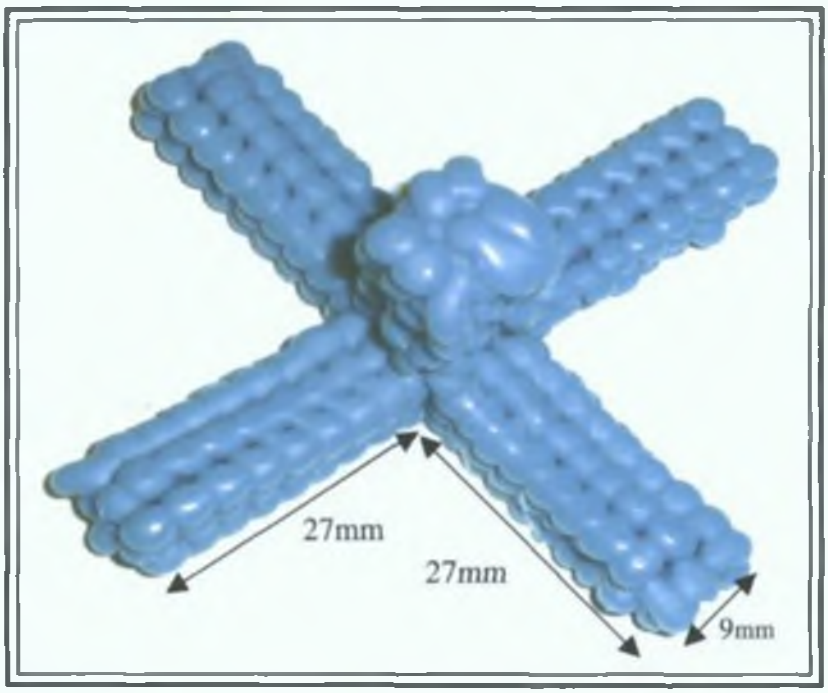


Figure 3.30: Impeller with shaft, the blade is 3 drops thick and wide, and 21 drops long. The central shaft a square of 3 drops side length (when viewed from above) and is 8 drops high

An impeller structure was produced with wax at 83 °C using the current system and aluminium plate to characterise the systems capabilities. A group of these impellers can be seen in Figure 3.31. The blade is in general 3 drops thick, there are 21 drops from tip to dip along the two blades is each direction. The central shaft is a square with side lengths of 3 drops and the square shaft is 8 drops high above the blades. Some deformation can be seen near the top of these models. The central model in this figure however has remained in its required shape. This is due to the fact that the central shape has only one drop thick blades compared to the other models. This meant that during model creation the final shaft drops had further to fall for the central model. This allowed the drops to solidify more quickly when they landed on the model.

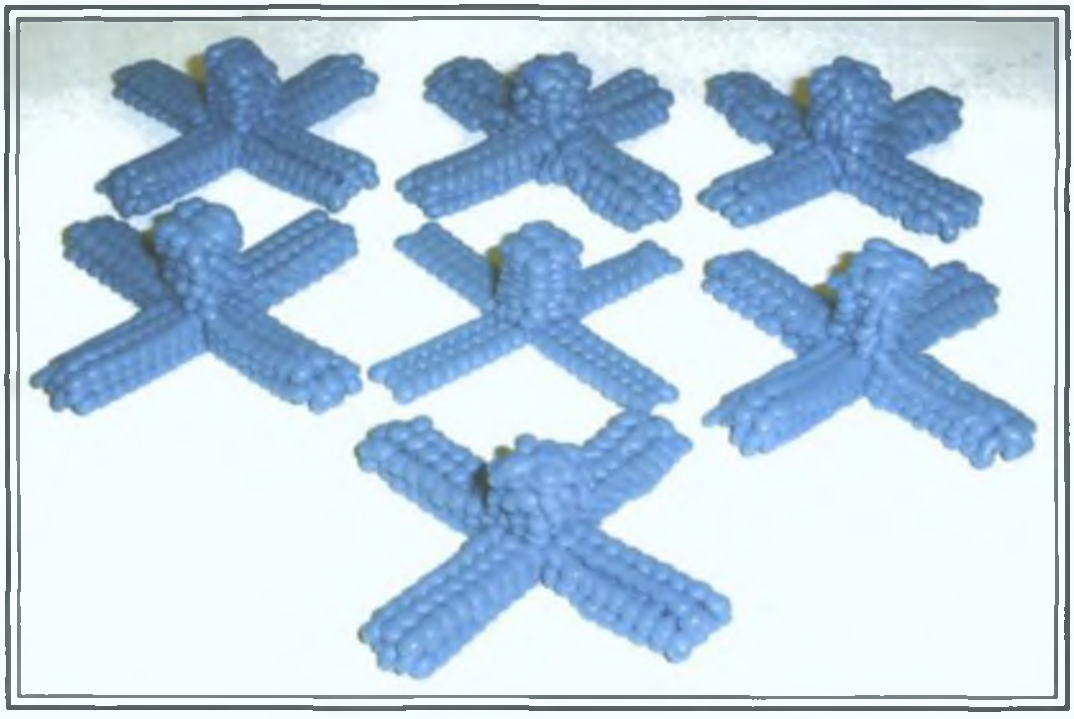


Figure 3.31: Examples of impeller structure produced

The same experiment was repeated a number of times to build the impeller shape but using airflow to cool the droplet. A better result was obtained as can be seen by comparing Figure 3.32 with Figure 3.33.

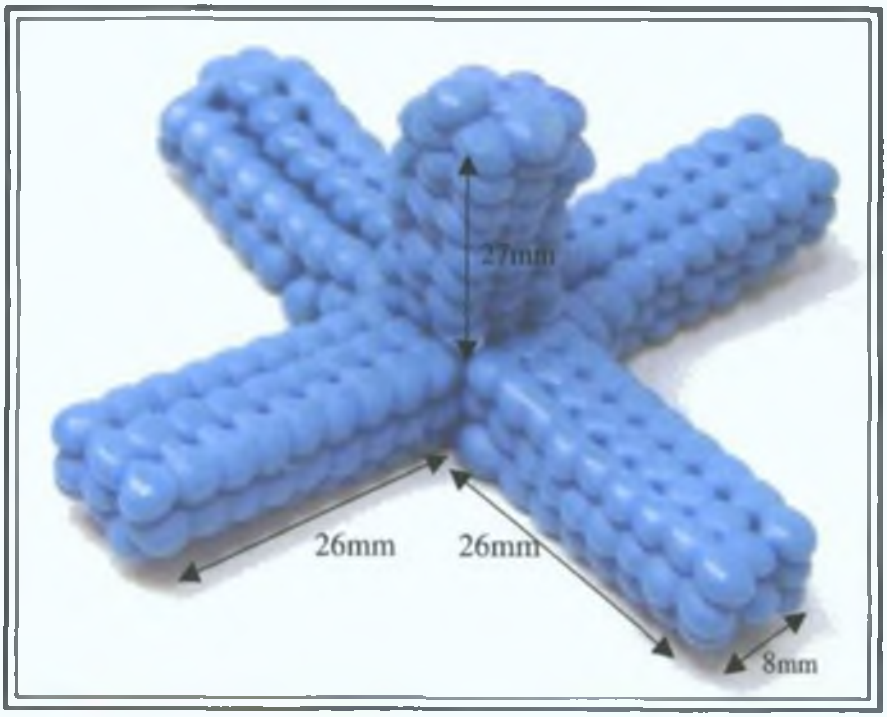


Figure 3. 32: Impeller shape produced by using airflow at 83 °C

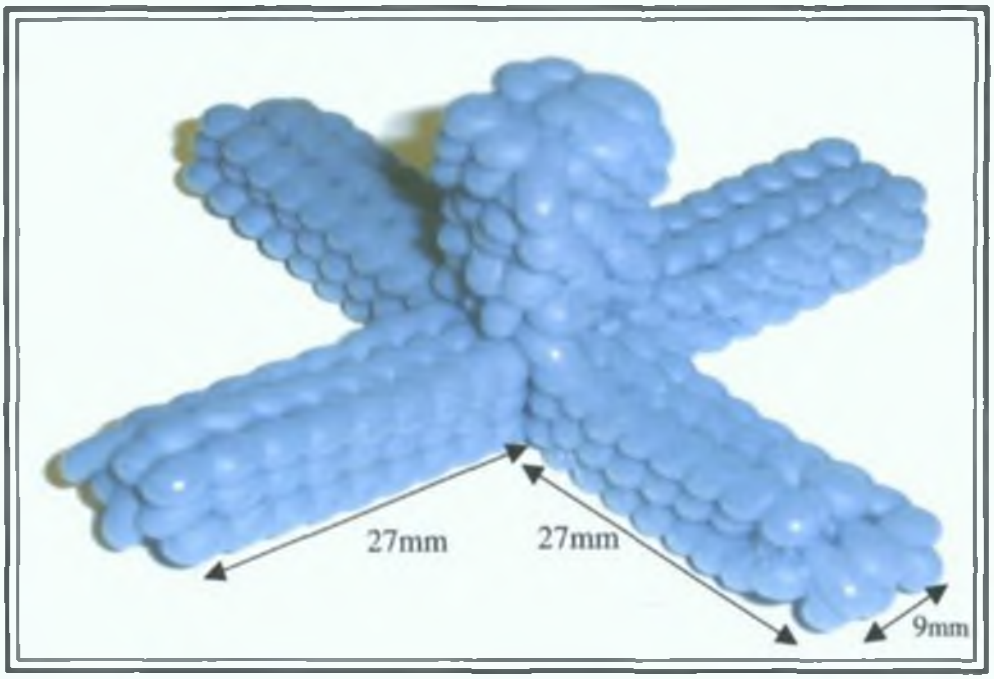


Figure 3. 33: Impeller shape produced with out using airflow with was at 83 °C

A slight upward bend in the blades can also be noticed. This was due to the thermal stress of solidification on the aluminium plate.

3.6 Droplet Size Analysis

The accuracy of a part to be built is highly dependent on the ability to control the accuracy of the building unit, the droplet. The temperature of wax was very influential over the size of the size of droplet and hence of the final surface finish of models produced on the system. Figure 3.34 shows the variation of droplet dimensions (diameter and height) at various temperatures. Droplet sizes, ten for each temperature, were measured using a digital vernier scale. A larger droplet diameter and smaller height were obtained with increased temperature. It was found that temperature had much less effect on the height of the droplets than the diameter, as show in Figure 3.34.

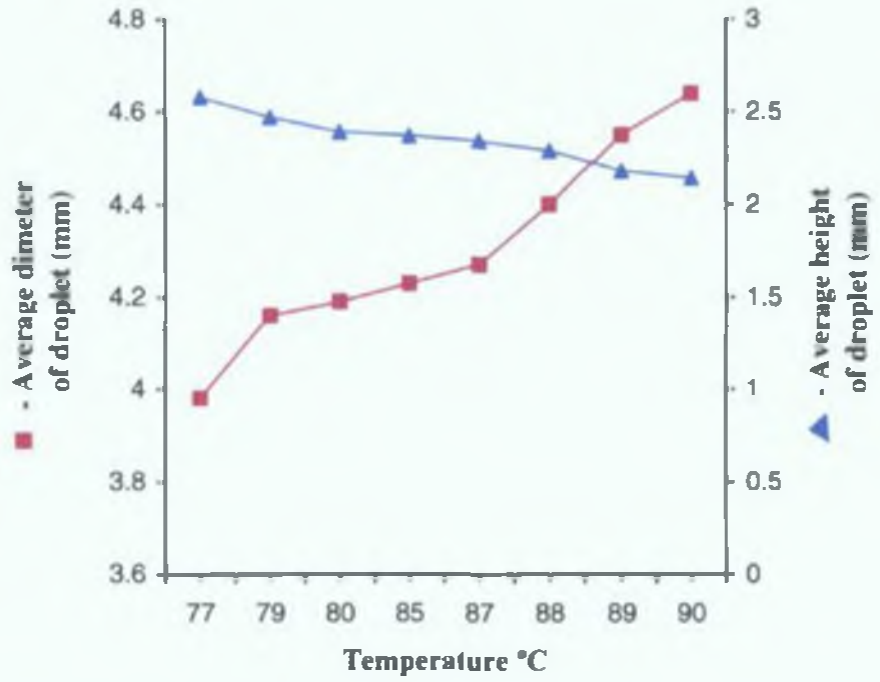


Figure 3.34: Diameter of droplet and height for various temperatures

Figure 3.35 shows how the droplet volume varied with processing temperature. At 79 and 80 °C a noticeable change in the volume can be seen. This mirrors the diameter change in droplet size noted at these temperatures in Figure 3.34.

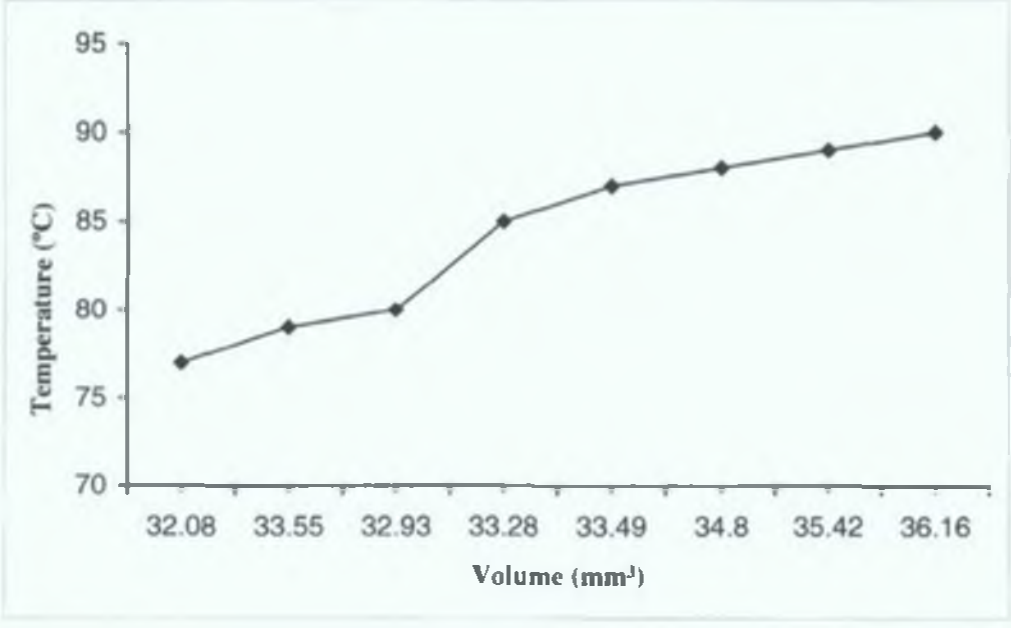


Figure 3.35: Droplet volumes recorded at the various processing temperatures

3.6.1 Calculating the Standard Deviation of Diameters and Heights of Droplets

The calculation of the standard deviation for the diameter of a droplet at a temperature of 77 °C, was 0.06 mm and the standard deviation of height of droplet was 0.02 mm. The standard deviation of the diameter of a droplet at a temperature of 79 °C was 0.15 mm and the standard deviation of height of droplet was 0.06 mm. The calculated standard deviation of diameters and heights of droplets at various temperatures are shown in Table 3.1.

Table 3.1: Shows the standard deviation for diameter and height of droplet

Temperatures (°C)	Standard deviation of diameter (mm)	Standard deviation of height (mm)
77	0.06	0.02
79	0.15	0.06
80	0.17	0.09
85	0.06	0.018
87	0.09	0.06
88	0.08	0.04
89	0.06	0.02
90	0.07	0.02

The 90% confidence interval for the diameter and height of wax droplets for various temperatures was calculated by using this formula:

$$\mu = \bar{x} \pm t_{n-1} \frac{s}{\sqrt{n}}$$

Where μ is confidence interval, t is the factor from the t-distribution for the degrees of freedom n-1, S is the standard deviation, and n is the number of data.

Using the t table, the 90 % confidence interval was used to calculate the confidence interval for the diameter and height of droplets. Table 3.2 shows the values of the standard deviation and confidence interval for the diameter of the droplets. Table 3.3

shows the values of the standard deviation and confidence interval for the height of droplets.

Table 3.2: Standard deviation and confidence interval of droplet diameter

Temperatures (°C)	Average diameter (mm)	Standard deviation of diameter (mm)	Confidence interval of diameter (mm)
77	3.98	0.06	± 0.03
79	4.16	0.15	± 0.08
80	4.19	0.17	± 0.10
85	4.23	0.06	± 0.03
87	4.27	0.09	± 0.05
88	4.40	0.08	± 0.04
89	4.55	0.06	± 0.03
90	4.64	0.07	± 0.04

Table 3.3: Shows the standard deviation and confidence interval of droplet height

Temperatures (°C)	Average height (mm)	Standard deviation of height (mm)	Confidence interval of height (mm)
77	2.58	0.02	± 0.01
79	2.47	0.06	± 0.03
80	2.39	0.09	± 0.05
85	2.37	0.01	± 0.01
87	2.34	0.06	± 0.03
88	2.29	0.04	± 0.02
89	2.18	0.02	± 0.01
90	2.14	0.02	± 0.01

3.7 Impeller Size Analysis

The dimensional stability of the system can be seen in the models presented in Section 3.5. Rapid patterns can be generated if a mould is available to accept the deposited wax. The FDM processes are shown to be capable of producing 3-D models. Although the profile of the drop deposited is still visible in the models produced, the overall dimensional stability was seen to be reasonable for a small impeller, especially in the X and Y directions. The addition of an air flow over the falling drop enabled an improved dimensional accuracy to be obtained (see Table 3.4 and Table 3.5).

Table 3.4: Measurements of the length, thickness and height and the number of drops and standard deviation and confidence interval at temperature 83 °C

Measurement number	Length (mm)	Thickness (mm)	Height (mm)	Number of drops
1	64.39	8.27	25.14	8
2	64.83	8.22	24.84	8
3	64.73	8.75	26.93	8
4	65.39	8.75	25.75	8
Average (mm)	64.83	8.49	25.66	-
Standard deviation	0.42	0.29	0.92	-
Confidence interval	± 0.66	± 0.46	± 1.47	-

Another experiment was carried out to build the impeller using an airflow to cool the droplets as they were falling in order to obtain better dimensional accuracy.

The standard deviation and confidence interval of the length and thickness and height was calculated using the same formula as previously.

Table 3.5: Standard deviation and confidence interval of the length and thickness and height of shapes at a temperature of 83 °C using airflow

Measurement number	Length (mm)	Thickness (mm)	Height (mm)	Number of drops
1	64.22	8.73	27.14	8
2	64.42	7.82	26.44	8
3	64.01	8.88	26.94	8
4	64.30	8.23	26.93	8
5	63.97	8.37	26.67	8
Average (mm)	64.18	8.40	26.82	-
Standard deviation	0.19	0.42	0.27	-
Confidence interval	± 0.24	± 0.52	± 0.34	-

These results can be seen in Table 3.5. Comparing the confidence interval without using airflow more dimensional stable impellers were produced with the airflow present.

The physical control of the shapes was achieved through programmed movement of the X-Y table and deposition system as well as the wax temperature and deposition pressure. To enable the system to be utilised to its full effect 3-D CAD files should be used. This format allows extraction of each X-Y coordinated of the slices in terms of (X, Y and Z) positions this can therefore be executed using a C programme to acquire coordinates, and consequently model the coordinates by manipulating the X-Y movement and the depositon control to deposition droplets at each point. The geometry of the droplet must correspond to the size of coordinate differentials in order for deposition to occur correctly. This could be achieved by changing the nozzle dimensions, depositon height, wax temperature, depositon pressure and even the type of wax used. The volume of droplet is generally uniform for a specified temperature. However the volume of the droplets depends temperature.

Droplet Receiving Plate

The thermal conduction of the receiving plate is an important consideration for surface finish and general properties of the model. The polystyrene plates gave visibly superior results when compared with aluminium plate. This however could be

overcome if the aluminium plate was heated to some degree. The thermal conductivity of polystyrene is very low, compared to that of an aluminium plate, therefore the droplets solidify at a slower rate and have more time to bond.

Deposition

During the experimentation, it was observed that a continuous stream of wax could be deposited, (Figure 3.27). This resulted in layered formations being built and bonding was extremely good.

Droplet Size

The volume of droplet increases as the temperature increase therefore in order to obtain better dimensional stability the temperature should be kept as low as possible. Dimensional stability of the drops need to improve above 80 °C see table 3.1 and 3.2.

Wax Processing Temperature And Pressure

At a temperature of 75 °C a critical pressure of 48,281 Pa (7 psi) was needed to reduce the viscosity to 1.75 Pa.s (Figure 3.4 and 3.5). However, the lowest viscosity at this temperature was still relatively high, 0.90 Pa.s at 144.845 Pa (21 psi). Even in the test at 82 °C (Figure 3.9 and 3.10) and at 88 °C (Figure 3.13 and 3.14) a critical pressure of 27,590 Pa (4 psi) was found above which the viscosity behaved in a more linear manner with change in pressure. In order to obtain constant processabilty it would therefore be suggested that a pressure of 34,487 Pa (5 psi) or above should be used during depositon.

Material Deposition In FDM Process

Commercial FDM processes use continuously molten of wax. The wax is made available to the liquefier from the solid wax continuously via a deposition chamber, the material is guided into the heated extruder head. The molten material is then extruded out of a fine nozzle attached at the bottom of the deposition chamber. The pressure required to extrude the molten material is provided, by a plungerhead. The extruder head in the FDM process is similar to a conventional piston extruder. The FDM process acts to deposit the material to build 3-D objects. It was observed in all the experiment in this work that the droplets were very round, uniform, and evenly spaced by the control system. This implies that the droplets are all deposited in the x-

y direction at the same speed, which is one of the basic requirements for a good droplet depositon system. In the deposition experiments, the droplets were deposited onto a receiving plate which was placed 40 mm below the nozzle to allow the droplets to have an adequate length of flying time to be partially solidified. The droplets were then fully solidified to from models as shown in the results Section 3.5. In the results section the measured diameters and heights of droplets against various temperatures are presented.

8. Suggestion for Optimum Parameters for the Production of RP using FDM

To produce optimised 3-D rapid prototypes the following points are recommended.

1- the distance between each droplet is 3 mm in the x-y direction.

2- the distance was 40 mm between the nozzle and the receiving plate to allow the droplets to have an adequate length of flying time to be solidified as droplets.

3- the distance between the plunger and wax inner cylinder is 45 mm to allow wax to be pushed through the nozzle.

4- the distance to move plunger down to pressurise the wax in the inner cylinder is 12 mm in the Z direction and the distance to move the plunger up to retract the wax is 11.99 mm.

5- the temperature of the wax should be between 82 to 85 °C. And the condition of the wax is liquid.

Table 4.1: Optimum parameters for deposition on the FDM system

Temperature °C	82 ± 1°C
Viscosity (Pa.s)	0.39 - 0.22 Pa.s
Pressure	34,487 - 68,974 Pa (5 - 10 psi)
Height of base nozzle from plate (mm)	40 mm

Chapter 4

4. CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

The rapid prototyping technology using fused deposition modeling was investigated and successfully applied in this research to produce two-dimensional and three-dimensional prototypes. The results achieved within this project shows the successful deposition of wax as a prototyping technology. The system controlled by a computer system was used to build various shapes. The demonstration of the various controls of the processes to implement even elementary models displayed the possibilities of the system. The nature of the project was experimentally based, this was due to lack of research literature on such prototyping technologies regarding the deposition of wax.

The physical models achieved were accomplished by the implementation of the procedures described. The present system is relatively simple, this was to ensure that all objectives were reached within the specified time constrains. There are various constraints in relation to type of models that this prototyping method can undertake.

In addition, it was found in experiments that the apparent viscosity of wax decreased when the pressure was increased from 6894 - 206,842 Pa (1 to 30 psi).

4.2 Recommendations

There is a lot of potential with this project for further work to be undertaken. There are possibilities to improve on the current designs. Using a deposition chamber with the ability to change the size of the nozzle head would be an additional parameter benefit. In the future the rapid prototyping system using Fused Deposition Modeling (FDM) can be further improved by implementing rapid prototyping that comprises of additive and subtractive process so that a complex shaped objects can be created. The surface finish could be improved by decreasing the diameter of the nozzle to obtain the better drops to build better shapes and obtain smoothes surface finish. In addition different materials such as plastic, and ceramics could be used to obtain different results.

REFERENCES

[1] B. M. W.Toutaoui, H. W. Gerber. Rapid prototyping technology- new potentials for offshore and abyssal engineering, TFH Berlin University of Applied Sciences, Dept.VIII. Berlin. Germany, 2003.

[2] http://www.me.pus.edu/lamancusa/rapidpro/primer/ htm, March 2002

[3] X. Yan, P. GU. A review of rapid prototyping technologies and systems, Computer-Aided Design, Vol. 28, No. 4, pp. 307-318, 1996.

[4] J. Kietzman. Rapid prototyping polymer parts via shape deposition manufacturing. Stanford University, Ph.D. 1999.

[5] R.I.Campbell and M.R.N. Bernie. Creating a database of rapid prototyping system capabilities, Materials Processing Technology, Vol.61, pp.163-167.1996.

[6] M.Greul, T. Pintat and M.Greulich. Rapid prototyping of functional metallic parts, computers in industry, Vol. 28. pp.23-28.1995.

[7] T. Hong. Rapid prototyping using a precision robotic manipulator, Ph.D.Thesis, Dublin City University, 2000.

[8] http: //www.mtiac.iitri.org/pubs/rp/rp5.htm. Jan 2002

[9] S. Kalpakjian. Manufacturing engineering and technology, 3rd Edition ISBN 0-201-53846-6,1995.

[10] B. Marshall. Quick primer on Rapid fabrication, Machine Design, Vol. 66. (5), pp 150- 152. 1994.

[11] M.Agarwala, D.bourell, J. Beaman, H.Marcus, J.Barlow. Rapid Prototyping, 1, 26, 1995.

[12] A. Nyaluke, B. Nasser, H. R. Leep, H. R. Parsaei. Rapid prototyping work space optimisation, Computers and Engng, Vol.31. No. 12 pp. 103-106, 1996.

[13] A.Licciulli, A. Greco, A. Maffezzoli. Development of a per-ceramic suspension for the free form fabrication of ceramic parts by stereolithography, J.Mat. Sci. Vol.36 pp.99-105. 2001.

[14] R.L, Herman, R.P Hamid. Rapid prototyping, applications in academic institutions and industry, commuters and. Engng Vol. 1-4, pp.345-349. 1995.

[15] D. Brabazon. Lecture notes from module [MM555].

[16] C. W. Hull. Apparatus for Production of Three-Dimensional objects by stereolithography, U.S. Pate. 457330,1984.

[17] C. Machover. The CAD/CAM Handbook, McGraw-Hill New York, ISBN 0-07-039375-3, 1996.

[18] http://www.jharper.demon.co.uk/rptc01.htm. 2003

[19] S. Krar, A. Gill. Exploring advanced manufacturing technologies, ISBN 0-8311-3150-0, 1st Edition 2003.

[20] htt://students.bath.ac.uk/en2hlt.htm. 12-March-2002.

[22] B. Oyvind, NOR-SLA Newsletter, 3,1, Norway, December 1990.

[22] C. Richard .D. Andrew Kusiak. Handbook of Design, Manufacturing and automation, New York, ISBN 047552186, 1994.

[23] http://www.cc.utah.edu/~asn8200/rapid.html. 4-Jan-2004.

[24] I. Zein, W. H. Dietmar, K. T. Cheng, S. H. Teoh. Fused deposition modeling of novel scaffold architectures for tissue engineering applications, Vol. 23, 4, pp. 1169-1185, 2002.

[25] K. Lee. Principles of CAD / CAM / CAE Systems, ISBN 0-201-38036-6, 1999.

[26] D. T. Sham, S.S Dimov. Rapid Manufacturing, Spring, 2000.

[27] http://web.umr.edu/~liou/ME308/RP_Processes.pdf. 13-Dec-1999

[28] P. F.Jacobs. Stereolithography and other RP&M technologies, from rapid prototyping to rapid tooling. New York, ISBN 0-872634671,1996.

[29] P.N. Adriano, D. A. H. R. Leep, H. R. Parsaei. Rapid prototyping: application in academic institutions and industry, Computer and Engng, Vol. 29, No. 1-4, pp. 345-349, 1995.

[30] D. King, T.Tansey. Rapid tooling: selective laser sintering injection tooling, materials processing technology, Vol. 132, Issues 1-3, pp. 42-48. 2003.

[31] A. Rosochowski, A. Matuszak. Rapid tooling: the state of the art, Journal of Material Processing Technology, Vol.106, pp.191-198. 2000.

[32] http://www.hitchiner.com/himco/basics.html. 1-Apr-1998

[33] A. J. Clegg. Precision casting processes, 1st Edition, ISBN 0-08-037878-1. 1991.

[34] L. Gibson, Software solution for rapid prototyping, ISBN 1-86058 360 1, 2002.

[35] G. P. Mikell. Automation, production systems, and computer-integrated manufacturing, Prentice-Hall of India, ISBN - 0130546682 1992.

[36] C. McMahon, B. Jimmie. CAD/CAM from principles to practice", Addison-Wesley England. ISBN-0201565021. 1993.

[37] Z. W. Emory, G. Mikell.CAD/CAM Computer Aided Design and Manufacturing. ISBN – 0131102559, 1984.

[38] J. N. Orr, E. Teicholz. Computer integrated manufacturing. Handbook, McGraw-Hill New York, ISBN - 007477744,1987.

[39] L. Wen, B.Behnam. Simulation system for a surface climbing robot, computers & industrial engineering, 23 (1) 273- 278,1992.

[40] T. Sun, L. Su, C. J, R. J. Mayer, R. A. Wysk. Shape similarity assessment of mechanical parts based on solid models, American Society of Mechanical Engineers. Vol.83 (2). 953-962, 1995.

[41] Y. Koren. Computer control of manufacturing systems, kosaido printing Co., Ltd, Japan. ISBN. 07-06637-3 1983.

[42] A. k. Kochhar, N. D. Burns. Microprocessors and their manufacturing applications, Edward Arnold Ltd. London. ISBN – 0713134704 1983.

[43] P. G. Michelell, W. Z. Emory, Jr., CAD / CAM Computer aided design and manufacturing, Prentice Hall, New Jersey, America. ISBN 013-110130-7.1984.

[44] S. Kalpakjian, Addison Wesley. Manufacturing processes for engineering material, 2end Edition, ISBN – 0201607026, 1991.

[45] A. Sherman, S. Sherman, L. Russikoff. Basic concepts of chemistry, 2end Edition, ISBN. 0-395-28153-9, 1980.

[46] J. O. Robert. Introduction to general, organic, and biological chemistry, 4th Edition, ISBN – 0-023896701, 1997.

[47] http://www.igiwax.com/wax_overview.shtml. 2002

[48] S. Patel, D. R. Nelson, A. G.Gibbs. Chemical and physical analyses of wax ester properties. pp. 7, 2001.

[49] A. Salis, V. Solinas, M.Monduzzi. Wax esters synthesis from heavy fraction of sheep milk fat and cetyl alcohol by immobilised lipases, Vol. 21, issues 4-6, pp. 167-174, 2003.

[50] C. A. Cambers. Understanding waxes proceedings of a one-day seminar on wax pattern making. BICTA, 1.1-1.5.1985.

[51] R. A. Horton. Investment casting in metals handbook. Vol.15, 253-269, published by ASM. 1988.

[52] H. Nakagawa, S Tsuge. Characterization of hydrocarbon waxes by gas-liquid chromatography with a high-resolution glass capillary column, Journal of Chromatography, Vol.260, 1983, pp. 391-409.

[53] http://www.wax.org/wax1/pages/app1.htm. 1-Apr- 2003.

[54] N. Ray. Waxes and related materials. University dental school & hospital,

Wilton. Cork, Ireland, 1998.

[55] http://strohmeyer.com/candel.htm. 1992.

[56] C. W. Keenan. D. C. Kleinfelter. J. H. Wood. General college chemistry. 6th Edition, New York, ISBN 0-06-0436158, 1980.

[57] M. P.Groover. Fundamentals of modern manufacturing, Material Processes and Systems, ISBN 0-13-312182-8, 1996.

[58] M.F. Ashby. Engineering materials: an introduction to their properties and application, 1st Edition, New York, ISBN – 0080261396, 1980.

[59] T. S. Piwonka, K. Awoodbury, J. M.Wiest. Modeling casting dimensions: effect of wax rheology and interfacial heat transfer, materials and design. Vol. 21, pp.365-372, 2000.

[60] L. Argueso. History of pattern waxes composition, Characteristics and Handling Steelfounder's Res. J., Vol.15. pp. 15-18. 1986.

[61] M. Denn. Process fluid mechanics. Englewood cliffs, New Jersey, ISBN 0-13-723163-6, 1980.

[62] D. T. Drew. Absolute vs. Kinematic Viscosity: A key field level monitoring parameter, USA 1999.

[63] C. B. Philip. Measurements of the viscosity of water, 150 S. Woodlawn Ave. Bloomington, Indiana University, IN 47408, 2000.

[64] http:\www.eurotherm.com.13-Feb-2004

[65] M. Montero, S. Roundy, D. Odell, S.A.Hoon, P. K.Wright. Material characterization of fused depositon modeling as by designed experiments. University of California, Berkeley, California 94710. Gyeongsang National University, Chinji, Korea 660-701.

[66] PC-23 indexer User Guide, P/N: 88-007015-03E, Compumotor Division, Parker, U.S.A., 1987.

[67] Y.Yan, Z. Xiong, Y. Hu, S. Wang, R. Zhang, C. Zhang. Layered manufacturing of tissue engineering scaffolds via multi-nozzle deposition, material letters, Vol. 57 pp.2623-2628. 2003.

[68] G. Wallnau. Statistics for the behavioral sciences, 3rd Edition. ISBN 0-314-90876-5. USA, 1991.

[69] R. P. Robert. Understanding statistics in the behavioral sciences, 4th Edition, ISBN 0-314-02691-6. USA, 1994.

APPENDIXES

Appendix (A) PC-23 RESET, READ, WRITE DRIVERS

The following routines will compile under Borland or Microsoft C.

They are intended to demonstrate basic communication routines in C.

```
#include <stdio.h>
#include <conio.h>
#include <stdlib.h>
#include <dos.h>
#define    FAIL          0X20
#define BIT2MASK   0X04
#define READY      0X16
#define    CB        0X60
#define IDB_M      0X10
#define CHAR_READY 0X70
#define ODB        0X8
#define ACK        0XE0
#define ALDONE     0X02
#define BADADDR    0XFF

#define HALT       (CB | BIT2MASK)
#define RESTART    0X40                    /* byte to restart the PC 21 */

void initialize (void);
void writech (char);
char readch (void);
void writecmd (char *s);
void readanswer (char *s);
void callstay();
int axis, address ;                        /* normally 300 hex */

int main()
{
```

```
char *message,*answer;

/* message = is for storing the final command to writecommd function */
/* answer  = is for storing the line command from the file */

FILE *fp;                                   /* fp is the file pointer */
int ch;
char *input;
int true = 0,start = 0,end = 0;
int counter = 0,i;
int a;
answer="";                                  /* initialization to empty string */


f((fp=fopen ("c:\datafile.txt","r")) = = NULL)
{
printf("Unable to open the file.");
return 0;
}

initialize ();                              /* RESET THE PC23 */

printf("\n The following program example demonstrates the basic");
printf("\n use of RESET, READ, and WRITE C drivers for the PC23.");
printf("\n\n The C source file is motorm.C.\n");


while ((ch=fgetc(fp)) != EOF)
/* starting to read the file until the end of file by one character each time */
{
if(ch= =34)             /* if ch eqaul to " */
{
if(true= =0) {true=1;start=1;end = 0;}    /* this is the start of line */
else
```

```
{ true = 0;start=0;end=1;}        /* this is the end of the line*/
}
if(start = =1)                    /* if it is the start of the line */
{
input=(char *) malloc(200*sizeof(char));      /* allocate memory */
counter = 0;                      /* counter variable set to zero*/
start = 0;
}
if (true = = 1)          /*If it is not end of the line */
{
input[counter]=ch;      /* inserting character in the input string from the file */
counter++;          /* increasing the counter variable*/
}
if(end = =1)  /*If it is end of the line*/
{
printf("\n");
input[counter]=34;        /* Inserting the " character at the end of the line" */
message =(char *) malloc((counter) * sizeof(char)); /* malloc is used for memory
allocation */
for(i=0;i<counter;i++)
message[i]=input[i];      /* this loop insert the readed character string in to the
message string */
printf("%s",message); /* printing the message string */
writecmd(message);    /* sending the message to the machine */
while((inportb(address+1) & ALDONE) != ALDONE);
readanswer(answer);     /* Reading the completed message from the machine */
printf("\n%s",answer);    /* printing the readed message */
answer="";
free(message);    /* free function deallocate the memory which allocated my malloc
function*/
free(input);  /* we need to deallocate all the time when it is allocated my malloc

end = 0;  callstay();   /* This is used for delay */
}
```

```
if(kbhit()) exit(1);              /*kbhit() use to recognise any key hit and exit() for exit
from the program*/
}
fclose(fp);                       /*closing the open file */
 return 0;
}
/*
*****************************************************************
*
INITIALIZE: RESET THE PC23 BOARD.  ASSURING THAT THE BOARD IS
READY TO ACCEPT COMMANDS FROM THE USER PROGRAM.
*****************************************************************
***** */
void initialize ()
{
char i;
int status_addr=0;
unsigned char statbyte;
printf("\n\n");
printf("Enter the Decimal value Board Address for the PC-23 : ");
scanf("%d",&address);
if ((address < 768) || ( address > 812))
{
printf ("\n\nInvalid address, check PC-23 dipswitches\n\n");
exit(1);
}
status_addr=address+1;
outp(status_addr,HALT);  /* initialize procedure */
while (!((statbyte=inp(status_addr)) & FAIL) );
if(statbyte==BADADDR)
{
printf ("\n\nInvalid address, check PC-23 dipswitches\n\n");
exit(1);
}
```

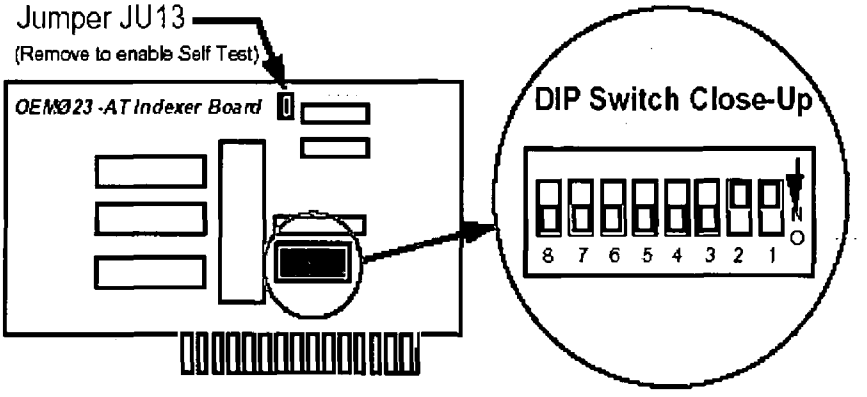
```
outp(status_addr,RESTART);
outp(status_addr,CB);
while (( (statbyte=inp(status_addr)) & READY) != READY );
}
/*****************************************************************
*
WRITECH: WRITES A SINGLE CHARACTER TO THE PC23. PC23
COMMANDS ARE GENERATED BY SENDING MULTIPLE CHARACTERS
TO IT.
*****************************************************************
***** */
void writech (char alpha)
{
while (!(inp(address+1) & IDB_M));
outp (address,alpha);
outp (address+1, CHAR_READY);
while (inp(address+1) & IDB_M);
outp(address+1,CB);

while (!(inp(address+1) & IDB_M));
return;
}
/*
*****************************************************************
*
READCH: READS ONE CHARACTER OF A PC23 RESPONSE TO A STATUS
REQUEST.
        RETURNS THE CHARACTER RESPONSE.
*****************************************************************
/
char readch()
{
char alpha=0;
while (!(inp(address+1) & ODB));
```

```
alpha = inp(address);
outp (address+1,ACK);
while ((inp(address+1) & ODB));
outp (address+1,CB);
return(alpha);
}
/*****************************************************************
*
  WRITECMD: WRITES A COMMAND STRING TO THE PC23.
*****************************************************************
/
void writecmd(char *s)
{
while (*s)
 writech (*s++);
return;
}
/*****************************************************************
*
READANSWER: READS A COMPLETE PC23 STATUS REQUEST RESPONSE
STRING.
*****************************************************************
/
void readanswer (char *s)
{
while ((*s++ = readch()) != 13);
*s = '\0';
return;
}
void callstay()
{
delay(2000);
}
```

Appendix (B) Setting The Address

For the computer to control the PC-23 indexer, it must know where to write instructions and read responses. The address is set using the 8-position DIPswitch located on the PC-23 indexer card.

This package consists of eight switches representing a binary number. Only two of the four address locations are significant one for control one for data. Input and output operations use same address. The address may be set to any number that the PC will recognize as valid.



The PC-23 indexer consists of two parts, which are a main circuit board and an adaptor box. The main circuit board is incorporated with the personal computer via ISA slot in the motherboard. The cable harness with four flat cable connectors from the adaptor box run through the slot in the PC access panel and plugged into the main circuit board. The adaptor box is external to the personal computer and connected to the KS-drives.

Figure B1. Shows the adaptor box with wire harness connected to the main circuit board which is in turn situated in the personal computer motherboard.

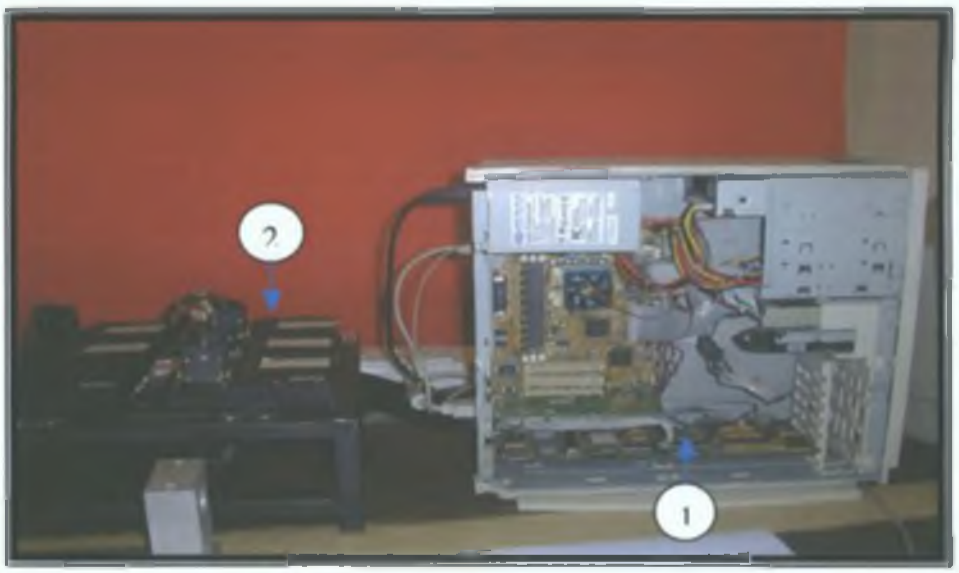


Figure B.1: picture of PC-23 indexer card

1- Indexer card 2- PC-23 indexer

The DIP switches are negative true in that any switch in the position marked ON has a binary value of zero. Switches that are OFF have a non-zero binary value. The values of DIPswitches 1 through 8 is the board's base address. The binary values assigned to each of the eight DIPswitches are listed in the Table [B1].

Table B.1. Switches values and base address settings

Switch No	Address	Binary value (OFF) Decimal / Hex		Default Setting
1	9	512	200	OFF
2	8	256	100	OFF
3	7	126	80	ON
4	6	64	40	ON
5	5	32	20	ON
6	4	16	10	ON
7	3	8	8	ON
8	2	4	4	ON

The adaptor box has three 25-pin connectors for each axis. Only the Motor Driver connection is absolutely required for controlling any axis. The Motor Drive will provide the output signals to the KS-drive to step the motor, change direction de-energise the motor and so on. All signals connected to the adaptor box are optically isolated from the computer. As a result, power is required to drive the isolated portion of the circuit. An external fixed power supply of 5 VDC at 10A is connected to one of the Auxiliary connectors of the adaptor box.

Appendix (C). Compressor (Jun-Air)

Figure C.1: Picture of the compressor (Jun-air)

Appendix D.

Table D.1: The temperature and time for investment wax

Hot plate setting	Time (min)	Temperature °C	Condition
Setting max 1	Started time at16: 50	97.5	Liquid
Setting 2	16:53	99.00	Liquid
Setting 3	17:02	98.00	Liquid
Setting 4	17:08	96.3	Liquid
Setting 5	17:11	94.7	Liquid
Setting 6	17:15	91.3	Liquid
Setting 7	17:19	88.0	Liquid
Setting 8	17:23	84.1	Liquid
Setting 9	17:25	82.0	Liquid
Hot plate setting off	17:26	81.1	Liquid
Off	17:27	79:7	Liquid
Off	17:28	78.8	Liquid
Off	17:29	78.3	Liquid
Off	17:30	77.2	Liquid
Off	17:31	76.5	Liquid
Off	17:32	75.5	Liquid
Off	17:33	74.0	Liquid
Off	17:34	73.0	Liquid
Off	17:35	72.4	Liquid
Off	17:36	71.3	Liquid
Off	17:37	70.5	Liquid
Off	17:38	70.2	Liquid
Off	17:39	69.4	Liquid
Off	17:40	68.2	Liquid
Off	17:41	67.3	Liquid
Off	17:42	66.5	Liquid
Off	17:43	65.9	Liquid
Off	17:44	65.1	Liquid
Off	17:45	64.8	Liquid
Off	17:46	64.2	Liquid
Off	17:47	63.4	Liquid
Off	17:48	62.8	Liquid
Off	17:49	61.6	Liquid
Off	17:50	60.6	Liquid
Off	17:51	60.5	Liquid
Off	17:52	59.7	Liquid
Off	17:53	59.3	Liquid
Off	17:54	58.7	Liquid
Off	17:55	58.0	Semi-solid
Off	17:56	57.8	Semi-solid
Off	17:57	57.1	Semi-solid
Off	17:58	56.7	Semi-solid

Off	17:59	55.9	Semi-solid
Off	18:00	55.7	Solid
Off	18:01	55.2	Solid

Temperature of wax in centre, turn of the hot plate.

Setting off	18:27	40.5	
Off	18:28	41.7	Melting on outside, solid in middle
Off	18:29	46.4	Melting on outside, solid in middle
Off	18:30	50.0	Melting on outside, solid in middle
Off	18.31	52.9	Melting on outside, solid in middle
Off	18:32	54.8	Mostly liquid, solid in centre
Off	18:33	56.6	Small bit of solid
Off	18:34	59.8	Very small bit of solid
Off	18:35	62.5	Completely liquid

Table D.2: The temperature and time for melting candle wax

Hot plate setting	Time (min)	Temperature °C	Condition
Setting max 1	Started time	70	Start to melting
Setting on	1	74	
Setting on	2	75	
Setting on	3	77	
Setting on	4	79	The top starting
Setting on	5	80	
Setting on	6	83	
Setting on	7	84	Liquid
Setting on	8	86	Liquid
Setting on	9	87	Liquid
Setting on	10	88	Liquid
Setting on	11	91	Very liquid
Setting on	12	94	Very liquid
Setting on	13	95	Very liquid
Setting on	14	96	Very liquid
Setting on	15	97	Very liquid
Setting on	16	98	Very liquid
Setting on	17	99	Very liquid
Hot plate setting off	18	84	Liquid
Off	19	77	Liquid
Off	20	74	Liquid
Off	21	70	Liquid
Off	22	65	Liquid
Off	23	60	Liquid
Off	24	59	Liquid
Off	25	57	Liquid
Off	26	65	Liquid
Off	27	54.5	Beginning to solidify
Off	28	54	Semi-solid
Off	29	53.7	Semi-solid
Off	30	53	Solid

Appendix E.

Table E.1: Measurement of the diameter and height of droplets at various temperatures

Temperature 77 (°C)		Temperature 79 (°C)		Temperature 80 (°C)		Temperature 85 (°C)	
Diameter (mm)	High (mm)	Diameter (mm)	High (mm)	Diameter (mm)	High (mm)	Diameter (mm)	High (mm)
3.87	2.56	4.01	2.42	3.90	2.32	4.25	2.56
3.91	2.56	4.32	2.56	3.90	2.31	4.20	2.58
4.01	2.55	4.04	2.42	4.20	2.45	4.25	2.59
3.95	2.57	4.31	2.54	4.19	2.42	4.22	2.55
3.96	2.62	4.32	2.53	4.21	2.43	4.13	2.61
4.00	2.57	4.29	2.52	3.92	2.29	4.11	2.57
4.02	2.62	4.31	2.54	3.73	2.24	4.11	2.59
3.99	2.62	3.99	2.42	4.17	2.52	4.13	2.58
4.09	2.60	4.07	2.40	4.22	2.48	4.07	2.60
4.02	2.58	4.00	2.41	4.16	2.45	4.14	2.57
Average	Average	Average	Average	Average	Average	Average	Average
3.98	2.58	4.16	2.47	4.19	2.39	4.23	2.37
Std dev	Std dev	Std dev	Std dev	Std dev	Std dev	Std dev	Std dev
0.0623	0.0263	0.1535	0.0663	0.1783	0.0933	0.0638	0.0182
CI	CI	CI	CI	CI	CI	CI	CI
± 0.0361	±0.0152	±0.0890	±0.0384	±0.1033	±0.0541	±0.0370	±0.0105

Temperature 87 (°C)		Temperature 88 (°C)		Temperature 89 (°C)		Temperature 90 (°C)	
Diameter (mm)	High (mm)	Diameter (mm)	High (mm)	Diameter (mm)	High (mm)	Diameter (mm)	High (mm)
4.19	2.30	4.42	2.37	4.55	2.19	4.62	2.16
4.19	2.27	4.46	2.31	4.57	2.18	4.57	2.15
4.35	2.37	4.37	2.32	4.54	2.16	4.70	2.13
4.28	2.37	4.48	2.27	4.55	2.19	4.73	2.16
4.38	2.42	4.30	2.25	4.49	2.18	4.74	2.18
4.39	2.42	4.50	2.30	4.59	2.22	4.64	2.15
4.34	2.38	4.30	2.23	4.67	2.19	4.73	2.16
4.16	2.26	4.38	2.31	4.62	2.23	4.60	2.11
4.30	2.39	4.33	2.23	4.46	2.17	4.50	2.10
4.16	2.27	4.53	2.33	4.49	2.13	4.65	2.18
Average	Average	Average	Average	Average	Average	Average	Average
4.27	2.34	4.40	2.29	4.55	2.18	4.64	2.14
Std dev	Std dev	Std dev	Std dev	Std dev	Std dev	Std dev	Std dev
0.0916	0.0634	0.0836	0.0458	0.06377	0.02836	0.07871	0.02699
CI	CI	CI	CI	CI	CI	CI	CI
± 0.0566	± 0.036	±0.0484	±0.0265	±0.0369	±0.0164	±0.0456	±0.0156

Appendix F.

Standard Deviation

The standard deviation is the most commonly used and the most important measure of variability. Standard deviation uses the mean of the distribution as a reference point and measures variability by considering the distance between each score and the mean. determines whether the scores are generally near or far from the mean [68]. The standard deviation, it is the average difference between a number in the data set and the mean. The standard deviation has many important characteristics. First, the standard deviation is a measure of dispersion relative to the mean. This differs from the range, which tells the spread of the two most extreme scores. Secondly the standard deviation is sensitive to each score in the distribution. Thirdly like the mean, the standard deviation is stable with regard to sampling fluctuations. If samples were taken repeatedly from populations of the type usually encountered in the behavioral sciences, the standard deviation of the samples would vary much less from sample to sample than the range. Finally, both the mean and the standard deviation can be manipulated algebraically [69].

Confidence Interval

Confidence Interval is an interval on the real number line that is constructed by using the sample data, and is expected to contain the true parameter in a specified portion of samples, that is, with some specified level of confidence.

A confidence interval is an interval used to estimate the likely size of a population parameter. It gives an estimated range of values (calculated from a given set of sample data) that has a specified probability of containing the parameter being estimated. Most commonly used are the 95% and 99% confidence intervals that have 0.95 and 0.99 probabilities respectively of containing the parameter. The width of the confidence interval gives some indication about how uncertain the unknown population parameters are.

Confidence intervals are constructed at a confidence level, such as 95%, selected by the user. What does this mean? It means that if the same population is sampled on numerous occasions and interval estimates are made on each occasion, the resulting intervals would bracket the true population parameter in approximately 95% of the cases.

Calculating the standard deviation of diameters and heights of droplets

This approach was used to calculate the standard deviation of the diameter of droplets for various temperatures. The formula used to evaluate the obtained data is defined as follows:

$$\bar{x} = \frac{\Sigma x}{n}$$

where,

$\bar{x}$ is the mean value

Σ is the sum of readings

n is the number of data

x is the value of each datum

In order to calculate the standard deviation, one must use the following formula.

$$S = \sqrt{\frac{\Sigma\left(x-\bar{x}\right)^2}{n-1}}$$

where

S is the standard deviation

$\bar{x}$ is the mean value

These two formulas were used to obtain the mean and the standard deviation of the diameter and heights of droplets of wax.

Appendix G.

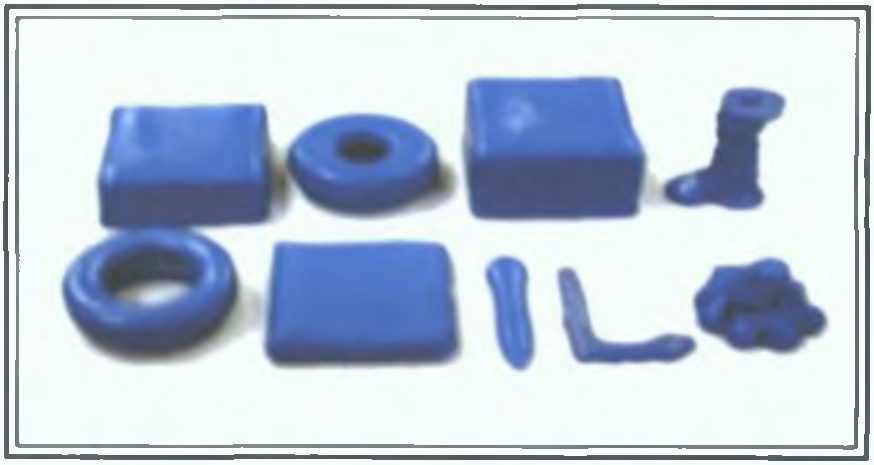
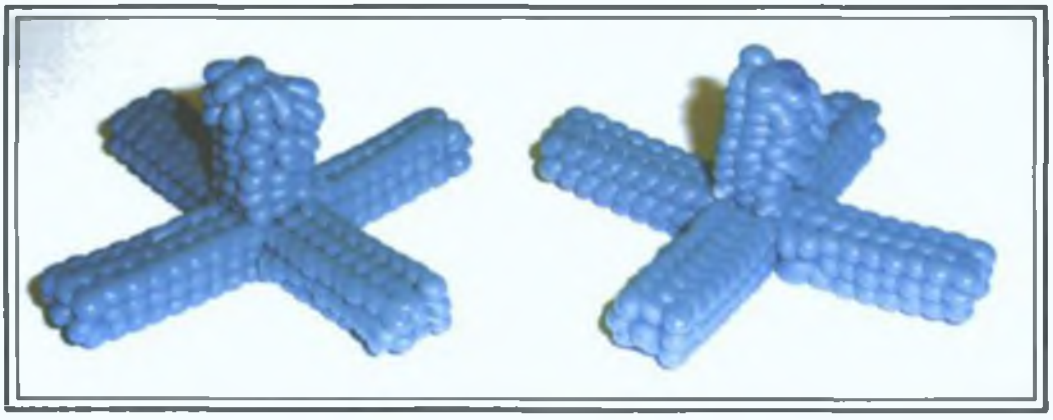


Figure G.1: Shows the different format models of wax

Figure G2: Repeated view from different angle of prototypes

Figure G.3: Repeated view for difference models



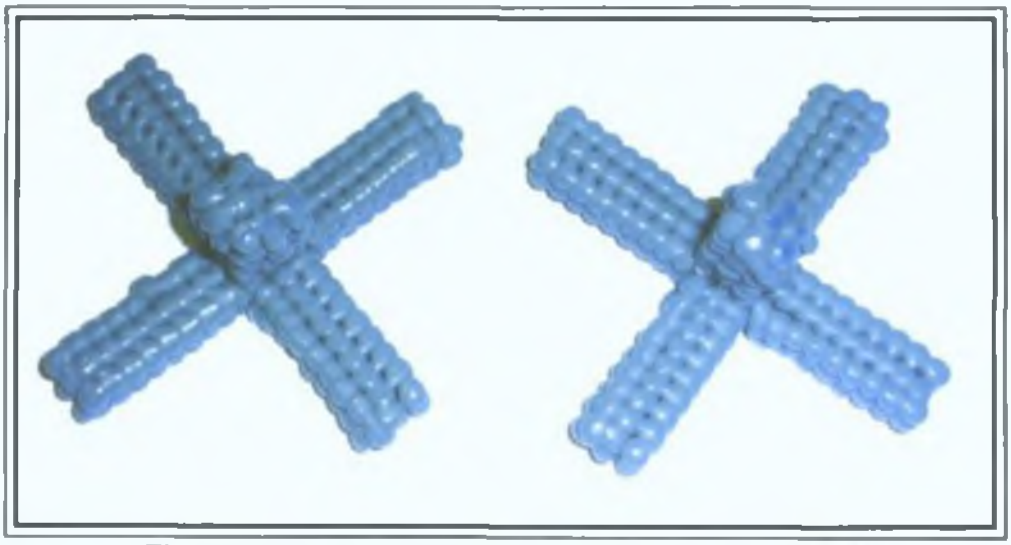


Figure G.4: shows Groups of impeller structure view