Application of Rapid Prototyping to Create Additive Prototype Using Computer System

Meftah O. Bashir, Fatma A. Karkory

Abstract—Rapid prototyping is a new group of manufacturing processes, which allows fabrication of physical of any complexity using a layer by layer deposition technique directly from a computer system. The rapid prototyping process greatly reduces the time and cost necessary to bring a new product to market. The prototypes made by these systems are used in a range of industrial application including design evaluation, verification, testing, and as patterns for casting processes. These processes employ a variety of materials and mechanisms to build up the layers to build the part. The 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. This work was to find out the properties of the wax materials used in this work 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. 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.

Keywords—Rapid prototyping, wax, manufacturing processes, additive prototyping.

I. INTRODUCTION

RAPID prototyping (RP) technologies first emerged in 1980with the advent of Stereolithography, the first commercial RP system, marketed by 3D Systems. Since then several other companies have jumped into the market selling different types of rapid prototyping processes [1], [2]. With the growing proliferation of rapid prototyping (RP) technology, the selection of an appropriate rapid prototyping system is becoming an increasing difficult task organisation of an intending to adopt the technology to serve their specific needs.

The choice of a rapid prototyping system on a number of factors or selection criteria such as price, accuracy, build envelope, build material, build speed, surface finish, and end applications. At present, there are around 20 RP vendors around the word, marketing around 40 RP systems with each system having its strengths, limitation and application [3]. The selection process is further complicated by a general shortage of benchmark standards and industry experience with most of these systems. Recent efforts in the direction of selecting an RP system have been directed to the development of computer-based selector programs [4]. The computer then divides the drawing into layers and gives the rapid

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manufacturing machine a description of each individual layer. The machine then creates these layers, one on top of another, to produce a whole part. There are many kinds of rapid prototyping now available within the manufacturing industry. Prototyping has become a necessary and means to test and physically examine design, which are otherwise viewed with difficulty from either two dimension or three dimension schematic formats. These three-dimensional RP machines allow designers to quickly create tangible prototypes of their designs, rather than just two-dimensional pictures.

Prototypes can be used to demonstrate the concept, design ideas and the company's capability in producing it. There are number RP technologies on the market, most of which work under the same fundamental principles. CAD data for the designed part, in a specific file format (usually STL nowadays), is processed and oriented in an optimal build position. The data is, then, sent to the RM machine where it is numerically sliced into thin layers. The RP machine then fabricates each two-dimensional cross-section and bond it to the previous layer. A complete prototype is thereby built by stacking layer upon layer until the prototype is completed.

There are two main types of RM, subtractive and additive; subtractive techniques involve the removal of material from a block to produce the prototype.

The CAD data is converted into CNC data in order to control the CNC equipment for automated cutting of the block. Generally, softer materials are machined to produce the prototype so that high cutting speeds can be used (for example polystyrene or plastic). Similarly, a prototyping aluminum injection mould tool may be produced for evaluation, with this technique, whereas conventional prototyping methods would produce a steel die. Most modern RP techniques are however additive. Rapid Prototyping builds up a 3D object [5].

Factors Fused Deposition Modeling, this method is most easily explained by understanding its name. Deposition entails that something will be deposited, and then fusion will bond that which is deposited to the rest of the model [6]. FDM is the second most widely used rapid prototyping, after sterolithography. The wax is melt and an extrusion from nozzle. The nozzle is heated to melt the wax and has a mechanics which allows the flow of the melted wax to be turned on and off.

The nozzle is mounted to and off. The nozzle is mounted to a mechanical stage that can be moved in both horizontal and vertical direction. The concept is that a material is fed through a heating element, which heats it to a semi-molten state [7].

The FDM technology allows a variety of modeling materials and colors for model building [8]. Available

materials are wax, plastic, paper, ABS (acrylonitrile butadiene styrene), adhesive material, all the materials are non-toxic and can be in different colours [9].

II. EXPERIMENTAL SET-UP

A. System Design

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 work

B. Deposition Chamber

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. The height dimension chosen was 250mm making the chamber a long cylindrical shape, as shown in Fig. 1.

The nozzle feature itself is protruding from the bottom of the deposition chamber, as shown in Fig. 1.
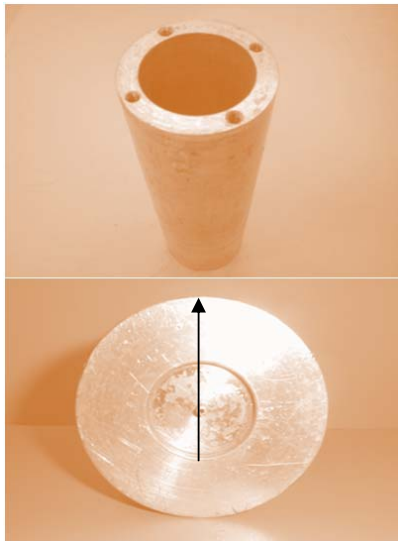

Fig. 1 Deposition chamber, bottom of deposition chamber showing nozzle feature

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.

C. 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 Fig. 2. The temperature of an electrical mica resistance band heater was controlled by a Eurotherm™ model 2116 PID 48W× 48H, analogue temperature controller [10]. 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.
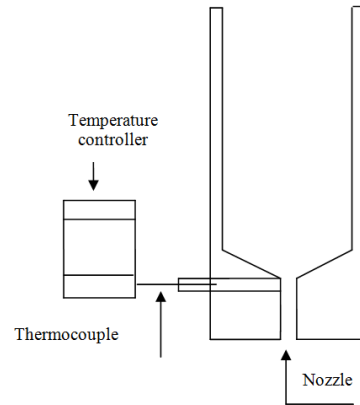

Fig. 2 Diagram of deposition chamber, thermocouple and temperature controller

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 element was attached to the deposition chamber with three tightening jubilee screws, as shown in Fig. 2.

D. Motion Control System

The control of the X-Y table was fundamental to the success of the developed FDM system. The controller is used a Compumotor PC-23 that 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. 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 an 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 500 kHz. The PC-23 gives feedback on the positions of the axis after motion has been completed. Fig. 3 shows a schematic illustrating of the system control process [11].
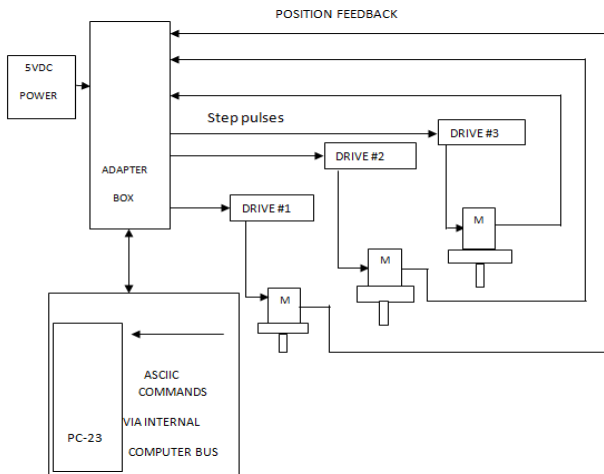
Fig. 3 Schematic of the FDM control process

E. 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);
```

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 liner 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, the velocity is set to 5RPS. The motors will rotate 1 revolution in 0.2 sec so the linear velocity was 1.5 mm / 0.25 = 6 mm/sec.

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

$$x = s \times \frac{1.5}{5000} \qquad (1)$$

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

$$x_1 = 5000 \times \frac{1.5}{5000} = 1.5 \; mm \qquad (2)$$

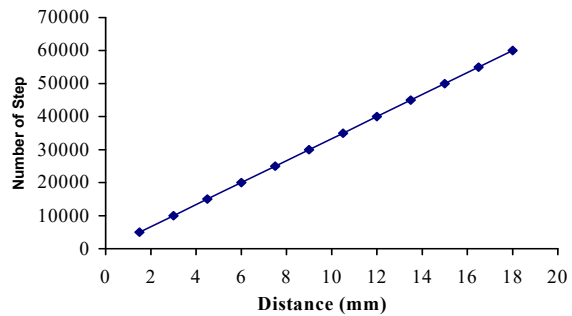A graph of the number of motor steps against the distance travelled as shown in Fig. 4.

Fig. 4 Graph the distance moved in the x or y direction versus the number of steps

F. 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 plunger head 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 (V1) and faster retraction movement (V5) gave better results.

G. Procedures for RP Experiments

The set-up used to obtain required shapes was shown in Fig. 5. The procedures followed to build various shapes are discussed below. Some parameters used are shown in Table I.

In this experiment was obtained model of impeller geometry Fig. 5, is shown the x-y direction to deposited the three layers, the system was moved 27 mm in the x direction and was moved 9 mm in the y direction and to deposited layer up to other layer to produce impeller shape with shaft, the shaft was deposited three drops wide and eight drops heights, the central shaft a square three drops side length and the final shapes was showed in result. Another experiment was carried out with the same setting parameter but using the airflow to cool the droplet. The result showed that optimal bonding was obtained between deposited drops.

TABLE I
PARAMETERS USED IN THE RAPID PROTOTYPING EXPERIMENTS

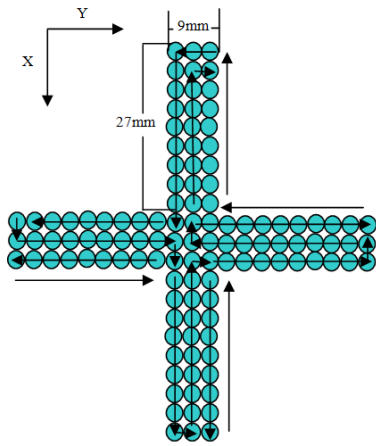| parameters	Temperature $c°$	Pressure (psi)	Distance(mm) X dir / Y dir	
A	80	2	30	54
B	85	3	30	54
C	80	2	30	54
D	84	3	30	60
E	84	3	30	60
F	85	3	30	30
G	90	6	40	40

Fig. 5 The impeller geometry
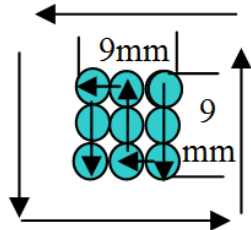
Fig. 6 The shaft of impeller

Fig. 7 Deposits of extruded wax into a square mould at 90 °C

Parameter G in 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 ºC in the deposition chamber. The pressure was constant at 6 psi. A container to receive the wax extruded through the nozzle was put in place until the container was filled. The container was then removed to allow the mould to cool.

These steps were repeated in such a way until the required pattern was obtained as shown in Fig. 7.

Fig. 7 shows the extrusion of wax at 90°C into a square mold a (50 × 50 mm) at 41368.5 Pa (6 psi), theses can be used based somehow on RP technologies.

The applications for RM are rapidly growing. 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.

III. RESULTS AND DISCUSSION

Viscosity is the property that determines the ease with which a fluid will flow [12]. Viscosity can be categorized as absolute (dynamic) viscosity, or kinematic viscosity [13]. The viscosity depends on temperature, density, and pressure, viscosity is the property that describes the magnitude of the resistance to shear forces in the liquid. A fluid dose not permanently resists increasing shear stress, it continues to deform-it flows. The velocity of flow increases with increasing shear stress.

A. System Operation

The basic principle of RP technique is to build 3D physical models, layer by layer, directly driven by the computer system [14]. The geometry deposited for parameter A setting is shown Fig. 8. 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.
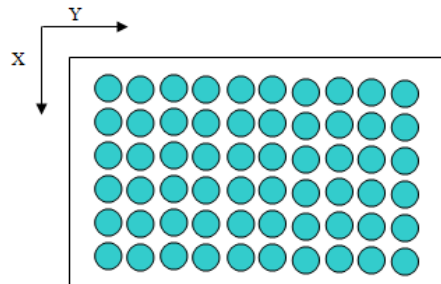

Fig. 8 Geometry deposited for parameter (A) settings

The first droplet is shown in Fig. 9. After that the plunger was moved back up (11.9mm) and then motor 1 was moved (6mm) in the X direction, see Fig. 9, to drop the second droplet, and so on. Those steps were repeated until the required shape was obtained. Fig. 9 shows the droplets location as well as the nozzle path.
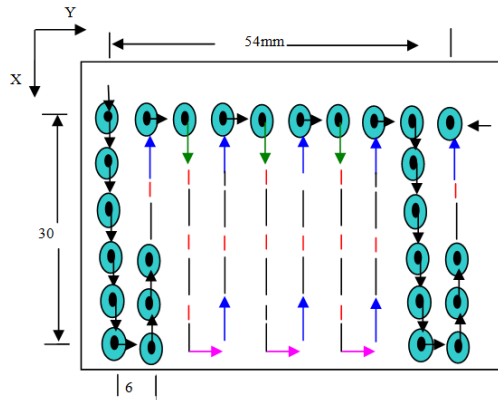
Fig. 9 X-Y nozzle path for parameter geometry

Deposition temperatures in the range of 75 to 90°C and pressures in the range of 34,487 to 172,370 Pa were investigated. For viscosity measurement the set pressure, supplied from a Jun-Air compressor, was applied between the plunger and the wax surface in the depositor. The deposition plate was placed 40 mm below the 20 mm long nozzle, which had an internal diameter of 1 mm. This capillary geometry allowed the depositor to be used as a capillary viscometer to measure the viscosity of the wax. The equation used for the viscosity, η, measurement is as:

$$\eta = \frac{\Delta P \pi r^4}{8L\phi} \qquad (3)$$

B. Wax Viscosity

From the capillary viscometer viscosity equation presented in this work, it can be seen that flow rate of the wax for a specified pressure difference needed to be determined for 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 Fig. 9. The experiment was repeated at constant temperature but for figure levels of the pressure producing the graph in Fig. 10. 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 the pressure was noted.

In this experiment, the temperature was set at 80 °C the condition of material as a liquid. The pressure was set at 6,897 Pa (1 psi) and raised in the experiment of 7 psi for each experimental run until 15 psi was reached. A gain, the viscosity decreased when the pressure was increased. The influence of pressure on the viscosity for this experimental run is shown in Fig. 11. For the pressure from 62,076 – 103,461 Pa (9 psi to 15 psi) the values of the viscosity were almost constant. For at 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 keeping the temperature at 80°C or above and also leave the pressure at 5 psi 34473.78 Pa or above.
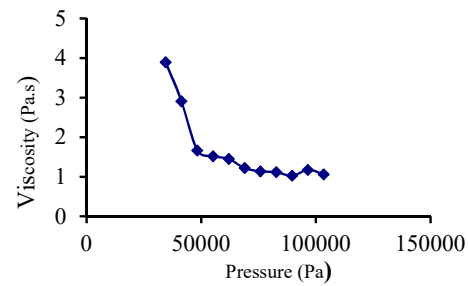

Fig. 10, illustrated relation between the pressures from 34,473 Pa to 103,421.35 Pa (5 to 15 psi) effect on the viscosity, with a constant temperature of 75 °C
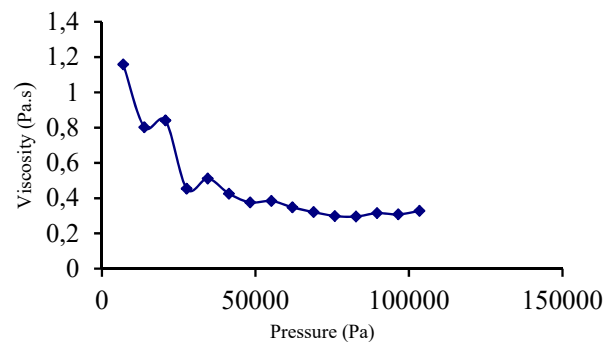

Fig. 11 Illustrated influence the pressure from 6,897 to 103,461 Pa (1 to 15 psi) on the viscosity at the temperature of 80°C

The decrease in viscosity with increasing pressure was also most notable for the lower deposition temperatures and pressure. In the first test, when the pressure was constant at 34,487 Pa and the temperature at 75ºC, the value of viscosity was 3.89 Pa.s. Upon increasing the test temperature to 78ºC it was observed that the value of viscosity decreased to 1.41 Pa.s. In general, as the temperature increased the viscosity decreased. For each test pressure, a marked increase in the viscosity was noted at a temperature of 80°C and below. A similar marked increase in the viscosity was noted below 34,487 Pa. With the upper and lower bounds of the temperature and pressure determined the system accuracy could then be examined under these conditions.

IV. CONCLUSION

Prototyping has been one of the essential processes in the design and manufacturing cycle. Most of the time, a conceptual design has to be developed into a physical product. Additive prototyping processes rely on making objects by adding one layer of material to another until the final shape is produced. The methodologies for creating the solid model and the subsequent model manipulation for the additive prototyped models were described. 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 and temperature was increased. The viscosity measurements, however, indicated that a minimum temperature of 75ºC should be used to obtain adequate fluid flow. A pressure above 32,487 Pa was also required in order to provide sufficient fluidity. Upper bounds of 80ºC and 67,974 Pa were also noted from these experiments. Above these settings the wax would be too fluid and would flow from the deposition chamber uncontrollably. However, with selection of the processing parameters the x-y direction to deposit the three layers, the system was moved 27 mm in the x-direction and was moved 9 mm in the y-direction and to deposited layer up to other layer to produce impeller shape with shaft.

REFERENCES

[1] M. Burns, *Automated fabrication, PTR Prentice Hall*, New Jersey, 1993.
[2] R. F. Aubin "A World Wide Assessment of Rapid Prototyping Technologies", *PROCEEDINGS of Solid Freeform Fabrication Symposium, Austin taxas, 1994, pp. 118-145.*
[3] T. Wohlers "Global Application and Trends in Rapid Prototyping", Keynot address at the word congress on Manufacturing Engineering and Rapid Product Development, Cairns, Australia. Sept 1997 pp, 15-17.
[4] Hornberger, et al, *Rapid Prototyping Program,* Santa Clara University, California, 1993.
[5] J. H. Oh, W. Cao, S. Kirihara, Y. Miyamoto, K. Matsuura, M. Kudoh "Process Control of Reactive Rapid Prototyping for Nickel-Aluminides-II," *Materials Science and Engineering A349,* 2003, pp.294-299.
[6] D.T. Sham, S.S. Dimov, *Rapid Manufacturing*, Springer, 2000.
[7] M. Montero, S. Roundy, D. Odell, S.H. Ahn and K. P.Wright, *Material Characterization of Fused Deposition Modeling (FDM) ASB by Designed Experiments*, Society of Manufacturing Engineers. 2001.
[8] X. Yan, P. Gu, *A Review of Rapid Prototyping Technologies and Systems, Computer-Aided Design*, 1996, pp. 307-318.
[9] http://www.caip.rutgers.edu/~kbhiggin/VDF/ FDM.html.27-Spt-2003.
[10] http/www.eurotherm.com. 13-Fed-2004
[11] PC-23 indexer User Guide, P/N: 88-007015-03E, Compumotor Division, Parker U.S.A, 1987.
[12] M. Denn. Process Fluid Mechanics. Englewood cliffs, New Jersey, ISBN 0-13-723163-6, 1980.
[13] D. T. Drew. "Absolute vs. Kinematic Viscosity"A Key Field Level Monitoring Parameter, U.S.A, 1999.
[14] B. Marshall. "Quick Primer on Rapid Fabrication, Machine Design" vol. 5, pp. 150-152 1994.