CHAPTER 3

EXPERIMENTATION

3.1 FUSED DEPOSITION MODELING

3.1.1 Introduction

The FDM is one of the most widely used rapid prototyping systems in the world. FDM is today the second most common commercial layered manufacturing system. The main reasons of its increasing popularity and use have been its reliability, safe and simple fabrication process, low cost of material and the availability of a variety of thermoplastics. Ever since the first FDM system was launched in early 1990s, the Stratasys Inc. USA has been marketing improved FDM systems on a regular basis. However, research has also been going on in universities and research institutions around the world to increase its applications, to develop new materials and to improve the FDM process (Masood 1996).

The FDM method forms three-dimensional objects from computer generated solid or surface models like in a typical RP process. Models can also be derived from computer tomography scans, magnetic resonance imaging scans or model data created from 3D object digitizing systems. The FDM 2000 system is shown in Figure 3.1
3.1.2 Working principle

The FDM system consists of the main 3-D Modeller unit, slicing software and a workstation. The process starts with the creation of a part with a CAD system as a solid or surface model. The model is then converted into a .STL file and sent to the FDM slicing software. There, the .STL file is sliced into thin cross sections of a desired resolution, creating a .SLC file. Supports are created if required by the geometry and sliced as well. The sliced model and supports are converted into a .SML file that contains actual instruction codes for the FDM machine. The technical characteristics of FDM 2000 system is summarized in Table 3.1. The block diagram of FDM process is shown in Figure 3.2.
Table 3.1  Technical characteristics of FDM 2000 system (Stratasys, 2000)

<table>
<thead>
<tr>
<th>Build Size</th>
<th>Parts up to 254 x 254 x 254 mm can be built.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Achievable Accuracy</td>
<td>Models can be produced within accuracy of 0.127 mm.</td>
</tr>
<tr>
<td>Size and Weight</td>
<td>660 (w) x 914 (h) x 1067 (d) mm, 160 kg.</td>
</tr>
<tr>
<td>Power Requirements</td>
<td>220-240 V AC, 50/60 Hz, 10A or 110-120 V AC, 60 Hz, 20A.</td>
</tr>
<tr>
<td>Modeling Materials</td>
<td>ABS (white), ABSi, Investment Casting Wax, Elastomer.</td>
</tr>
<tr>
<td>Road Width / Slice Thickness</td>
<td>Operator may optionally select road widths between 0.305 mm and 0.98 mm and slice thickness from 0.178 mm to 0.254 mm for a T12 nozzle.</td>
</tr>
<tr>
<td>Software</td>
<td>Quick Slice orients and slices the .stl file and generates FDM2000 tool paths.</td>
</tr>
<tr>
<td>Support Structure</td>
<td>Automatically generated with Support Works Software; Breaks-Away Support System (BASS) allows easy support removal.</td>
</tr>
</tbody>
</table>
The cross-section of the extrusion head is shown in Figure 3.3. Fused deposition modeling builds a 3D object, layer by layer from a CAD design. Spooled filaments are fed into a liquefier head via computer driven rollers. The motion of the extrusion system operates under three-dimensional computer numerical control. The liquefier head is machine controlled for movement in the horizontal X-Y plane. To complete the three axis movement, a fixtureless build platform moves in the Z direction. In the commercially available FDM machines, a continuously wound spool of polymer is guided to the liquefier via a winding path before being fed into a pair of counter rotating rollers as shown in Figure 3.3. The filament softens and melts inside the liquefier to a temperature just above its melting point. The molten polymer is extruded out of a nozzle at the end of the liquefier. The positive force required for this extrusion is small and is provided by the rollers driving the incoming filament. A continuous positive displacement is provided in this manner.
It fabricates parts by extruding molten thermoplastic material or wax through a small nozzle to form a thin bead or road that is deposited in a predetermined pattern to complete each build layer, bonding the extrudate to adjacent and previously deposited roads. The most common build material used with FDM systems is P400 ABS plastic and it is available in several stock colours, including white, red, blue, green, yellow and black. Inside the flying extrusion head, the filament is melted into liquid above its melting temperature by a resistant heater. The head traces an exact outline of each cross-section layer of the part.

As the head moves horizontally in X and Y axes the thermoplastic material is extruded out a nozzle by a precision pump. The material solidifies in 1/10 second as it is directed on to the workplace. After one layer is finished, the extrusion head moves up a programmed distance in Z direction for building the
next layer. Each layer is bonded to the previous layer through thermal heating. The designed object is fabricated as a three-dimensional part based solely on the precise deposition of thin layers of the extrudate. The deposition path and parameters for every layer are designated depending on the material used, the fabrication conditions, the applications of the designed part and the preferences of the designer (Iwan Zein et al 2002). The processing parameters of filling each layer depend on the earlier inputs into the slicing software. These include the FDM head speed, the roller speed, the slice interval and the direction of deposition within each layer.

Once built, the supports are removed after part building by breaking them away from the object. In a newer Stratasys machine, two modeling materials can be dispensed, through a dual tip mechanism (Gasdaska et al 1998). More recently, a system called Fused Deposition of Multiple Ceramics (FDMC) with four independent filament feed mechanism has been developed for the purpose of achieving fused deposition of multiple ceramics (Jafari et al 2000). Subsequently, the system has led to the fused deposition of multiple materials (Pilleux et al 2002). When a dual or multiple head FDM machine is available, the supports can be built from a softer material, so they can be broken away easily. Alternatively, they can be built from a water-soluble material, so that they can be simply washed away after part building has been completed. This allows more complex parts to be built.

### 3.2 PROCESS PARAMETERS

The first step in the experimentation was to identify the process parameters that were likely to affect the surface qualities of FDM parts. The
main concern for most RP users is part accuracy. Production of parts with high surface quality is a challenging task in layered manufacturing. The quality of a prototype is manifested by several parameters. For many engineering applications, surface finish is an important criterion. Several attempts have been made in the past to make a systematic analysis of errors and quality of the prototypes. The dimensional variability of LOM was studied by adopting fish bone diagram approach to systematically evaluate the major factors affecting the castings produced (Wanlong Wang et al 1996). If strength is of primary concern, a negative air gap can be used to create a stronger part. It was found that parts with an air gap smaller than -0.0762 mm simply did not build well due to excess material build up on the nozzle and the material itself. It should be noted that for relatively thick parts, a negative air gap can degrade surface quality and dimensional tolerances (Sung- Hoon Ahn et al 2002).

Layer building rapid prototyping techniques result in surfaces that frequently require a secondary finishing operation to achieve the desired surface quality. For rapid prototyping to become economically and technologically more attractive, it must be able to achieve higher accuracy and have the ability to directly generate fine parts and smooth surfaces while further minimizing build time without incurring expensive developmental costs. An economical way of achieving these goals without major changes in the developed hardware and software architecture is to re-tune the control factors of the existing rapid prototyping process for the given machine. Most users attempt to minimize build time by manipulating initial manufacturer suggested build parameters. They may not realize that interactions between these build parameters can severely affect the quality of their parts. On the other hand, with proper adjustment of the build parameters, part quality can be significantly improved
and build time can be greatly reduced without the necessity of incurring additional expenses (Jack G. Zhou et al 2000).

The type of energy source and its control in the building process affect the achievable dimensional accuracy and the manufacturing cost as well. In FDM, layers are formed with molten thermo plastic extruded from a nozzle. The large inertia associated with the molten material and the mechanical control has sufficient influence on the dimensional accuracy of an FDM part. Some of the sources for dimensional inaccuracies are oversize in Z direction (expansion) due to over cure, void in the part and curling (Xu et al 1999).

Dimensional accuracy has become a prerequisite for successful application especially in tooling and rapid manufacturing. Accuracy of component assembly and functionality is improved with improvement in surface quality. Owing to the nature of layered manufacturing, however, the stair-step effect dominates the surface quality issue. Any part facets that are inclined with respect to the Z-axis will possess some degree of stair-step error. Minimizing this effect generally means trying to expose the least number of inclined and curved features to the Z-axis. In addition, research has shown that decreasing the layer thickness in regions of high surface curvature provides a measurable decrease in the stair-step effect (Lan et al 1997).

Fabrication of quality prototype parts is not yet fully automated. Typically, quality of the production is dependent on the skill level and experience on the FDM machine operator. The potential benefit from improved process understanding is two-fold. First, understanding the build parameter effects on the process response will aid development of intelligent process
control and automation efforts. Second, understanding the process response will allow users to produce parts with desired physical characteristics by selecting appropriate values prior to processing. FDM parts can exhibit internal defects of several forms such as voids, pores, delaminations, cracks, etc. These can arise from several reasons, for example, FDM system hardware and software limitations, poor material characteristics and poor process optimization.

Process variables that affect the FDM process can be divided into four categories. These are operation specific parameters, machine specific parameters, materials specific parameters and geometry specific parameters. These variables are inter-dependent and hence need to be optimized concurrently to fabricate high quality FDM processed parts (Mukesh K. Agarwala et al 1996). The current FDM system results in parts with surface and internal defects, which if not eliminated, severely limit the structural and functional properties of the parts thus produced. Therefore, there is a need to identify the origin of these defects that arise due to current strategies used in FDM systems and eventually develop and implement novel processing strategies to eliminate such defects in FDM parts. The main process variables that an FDM process planner needs to consider are build orientation, layer thickness, road width, air gap, build temperature and interior fill strategy (Ziemian and Crown 2001).

3.2.1 Selection of process parameters

Process parameters are the defined variables that influence and control FDM process. A number of parameters, some user defined and others defined by geometry or material considerations affect the quality of parts fabricated.
Best results are obtained using optimal process parameters. Some of the undesirable effects can also be minimized by suitably controlling the process parameters. The intricacies of the control parameters and the interdependency of the variables that collectively work to produce models were sorted out in a methodical approach in order to improve the quality of the component. The FDM machine allows the user to control the envelope temperature, liquefier temperature, modeling speeds, materials, road width, layer thickness and air gap to name just few variables. Each of these variables can alter the resulting model. The appropriate setting of these parameters by the operator is the key to quality model production. Without proper limits being set, negative results will occur. The objective of this study is to analyse the effect of process variables on the surface quality of the components produced by the FDM process.

The process variables in FDM such as road width, build layer thickness, air gap and liquefier temperature are the most vital among the control parameters. The control parameters will affect the output of the process and are controllable in a run. Though there are other factors like speed of deposition, envelope temperature, nozzle diameter, flow rate and build orientation etc., are, however kept constant in this study. To improve the surface quality of the prototype, the process parameters, such as layer thickness, road width, air gap and liquefier temperature may be varied.

The current study investigates the effects of process parameters on surface integrity, such as surface finish, porosity, dimensional accuracy in terms of reduction in width and deviation in thickness of prototypes built using the FDM method. The input and output parameters considered for this study are listed below.
Input parameters

- Road Width
- Slice Thickness
- Liquefier Temperature
- Air Gap

Output parameters

- Surface Finish
- Porosity

Dimensional accuracy in terms of

- Percentage of reduction in width
- Percentage of deviation in thickness

3.2.2 Input parameters

3.2.2.1 Road width

The material extruded out of the heated liquefier head in the FDM system is deposited in the form of a fine bead of material which is referred to as a road. The width and thickness of the road is defined by the user in the build file for the part. Often voids are present at the turns and road ends of the tool path. Most existing voids are located at road ends and sub perimeters. The sub perimeter region is composed of individual roads separated by the air gap. In FDM, every layer is filled by roads according to a certain path; roads can be
considered as the real building units of the process. It has been observed that the road shape and the road-to-road interaction, as well as path, strongly affect the properties and performance of the finished product (Anna Bellini and Selcuk Guceri 2003). Based on the system parameters for nozzle T12, the levels considered were 0.305 mm, 0.643 mm and 0.98 mm to analyse the effect on surface quality.

3.2.2.2 Slice thickness

Slice thickness refers to the distance traveled in the Z-direction between successive layers and has a direct impact on the build time and the surface quality of the sloped surfaces. Each of the three different nozzle tip sizes on the FDM 2000 (T10, T12 and T16) has an associated range of recommended layer thickness. This is the specified slice thickness that the model is sliced into the Z-axis. This variable can be set within a range on most rapid prototyping machines. The layer thickness is increased from minimum to maximum slice fabrication thickness, which is given as one of the input parameters.

The geometric inaccuracies and surface finish problems of RP part can be controlled by minimizing the layer thickness. Higher part densities are obtained by using a lower layer thickness. The lower layer thickness resulted in better bonding between layers thus improving the part density.

For FDM and 3DP systems, the stair stepping effect does not appear to be the main factor in determining surface roughness. In particular, upward facing surfaces on the actual built part and most surfaces on the FDM and 3DP
parts displayed much lower surface roughness than that calculated using equation: \( Ra = \frac{a \sin \theta}{4 \tan \theta} \), where \( Ra \) is the arithmetic average surface roughness, \( a \) the layer thickness and \( \theta \) is the angle between the surface normal and the vertical direction. This should encourage system developers and researchers to look at other ways of improving surface roughness apart from reducing layer thickness (Campbell et al 2002). Based on the system parameters, the layer thicknesses of 0.178 mm, 0.216 mm and 0.254 mm has been considered for this work.

3.2.2.3 Air gap

Air gap is the horizontal space between the roads of FDM material, also known as road-to-road gap or inter road gap. The default is zero, meaning that the roads just touch. The air gap value can be modified to leave a negative gap, meaning that the two roads partially occupy the same space. During raster filling of a layer, voids are left due to incomplete filling at points where the raster segment turns around at the perimeter known as sub-perimeter voids. At the point where the path of the liquefier approaches the perimeter, the travel direction of the liquefier alters to a path that is tangent to the perimeter.

Normally air gap is set at zero in the quick slice software; however, when the part is built there is always a physical gap between the adjacent roads and voids at sub perimeter, as it is evident from the scanning electron macrograph shown in Figure 3.4. In this work, based on the system parameters for nozzle T12, the level of air gap considered were 0.00 mm, -0.005 mm and -0.01 mm to see whether it influences surface quality.
Figure 3.4  SEM showing that the roads do not touch even at zero air gap, presence of sub-perimeter voids and inter road gap.

3.2.2.4 Liquefier temperature

Liquefier temperature is the model temperature. This is the temperature at which the material is melted. It controls the viscosity of molten material that is extruded from the nozzle. The variation in model temperature would affect the fluidity of the material as it is being laid. This factor was selected to see if it influences surface quality. The levels considered were 250°C, 270°C and 290°C based on the system parameters for nozzle T12.

3.2.3 Output parameters
3.2.3.1 Surface roughness

Surface finish or surface roughness is a key issue facing rapid prototyping technology. Since RP parts are widely used as patterns and
functional parts, controlling surface finish becomes more and more critical. Number of process variables is responsible for surface roughness. However, with a careful optimization of the process parameters, it is possible to obtain an acceptable surface quality (Karapatis et al. 1998). Post-processing the part to get the desired surface finish is a commonly employed technique, but the main goal of using RP for speedy introduction of products in the market is defeated by the time delays involved in post-processing. Post-processing may also lead to undesirable loss in dimensional accuracy on the part. The surface roughness of the components produced is measured by the Ra value. Therefore the objective is to minimize the surface roughness (Ra value) in order to prevent post-processing.

### 3.2.3.2 Porosity

Porosity will affect the surface quality of the component. The entrapped and/or absorbed gases and moisture can lead to porosity. While processing parts in a FDM machine very little conventional porosity is encountered, however, unfilled spaces may exist which may adversely affect the surface quality of the parts.

### 3.2.3.3 Dimensional accuracy

Dimensional accuracy is extremely important in any product development cycle, as it directly affects part functionality. The accuracy depends on the material, part geometry and operating parameters for a given machine. The relative importance of the accuracy of various part features is attainable from designer defined tolerances. Dimensional accuracy is quantified
as the average absolute deviation between measured points from the actual part surface and the associated nominal part surfaces as representing within CAD model (McClurkin and Rosen 1998).

In fact, for RP processes that employ heat energy to solidify the material, the subsequent prototypes tend to shrink after cooling, resulting in dimensional deviations of a physical prototype. The deviation from width and thickness were attributed to poor adhesion between adjacent layers and adjacent roads. The linear dimensional accuracy can be related to the percentage shrinkage of the model in axis being considered. If the shrinkage values are lower than the actual values obtained, significantly affects the accuracy of the FDM products (Onuh 2001).

Dimensional accuracy in terms of width reduction and thickness deviation, corresponding to shrinkage and expansion in the linear directions are measured in this work.

3.3 FABRICATION

Experiments were conducted on Stratasys FDM2000 machine using specific combination of levels of significant process parameters. All the experiments were conducted randomly to distribute the error due to noises equally among all the experiments. In FDM, material is laid down layer by layer. First the perimeter is laid down and then according to the orientation angle in the inside of the perimeter the roads are laid out over the entire layer. The same process is repeated for next layer but the orientation angle will be perpendicular and the roads are laid in opposite direction. The working principle of FDM machine is shown in Figure 3.5.
The fabrication was made by the successive deposition of the filaments in a layer by layer manner, finishing each layer before proceeding to the next one. The layers were deposited parallel to each other in each layer and perpendicular to the direction of the immediate upper and lower neighboring layers. In order to obtain the better surface quality, optimum process parameters must therefore be defined.

The three levels of process parameters used for fabrication of RP components are shown in Table 3.2. Each of the four process variables were studied at three levels corresponding to a high, medium and low classifications. All experimentation was done with the T12 tip size, as it is expected that the effects of the process variables on build goals would be similar for the other tip sizes as well. In this experimental work P400 ABS plastic was used as a build material due to the robustness and multifunctional characteristic.
Table 3.2  Three levels of process parameters for fabrication

<table>
<thead>
<tr>
<th>Process Parameters</th>
<th>Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Minimum</td>
</tr>
<tr>
<td>Slice Thickness</td>
<td>0.178 mm</td>
</tr>
<tr>
<td>Road Width</td>
<td>0.305 mm</td>
</tr>
<tr>
<td>Liquefier Temperature</td>
<td>250°C</td>
</tr>
<tr>
<td>Air Gap</td>
<td>-0.01 mm</td>
</tr>
</tbody>
</table>

The following steps were carried out for fabrication of the components

1. A suitable model was chosen for fabrication. For this purpose, many models were modeled using CATIA V5 software. One of the models was then chosen, after considering following factors.
   a. The component should have a flat surface, a concave surface and a convex surface.
   b. The component should be measurable in size.
   c. The component should be small, since the time taken for fabrication should be less.

2. After choosing the model, the CAD format of the model was converted to STL format using CATIA V5 software. STL format is the standard format, which many modeling software provide for exporting the CAD models to a neutral format, so that other software could use the models.

3. STL is the de-facto standard of RP process. STL format model was then fed to Quick Slice software. Quick Slice software was developed by Stratasys Corporation, developers of FDM2000 machine.
4. The Quick Slice software takes input as slice thickness, road width, air gap, nozzle diameter, material type etc. The software calculates various machine specific parameters like time, filament usage etc.

5. The file was then converted to SML format. SML format is a machine specific parameter. This is the format, which FDM machines recognize. This file was then fed to the FDM2000 machine.

6. The FDM2000 machine, which is interfaced to a computer, then checks the given input file and takes the necessary details from the file.

7. FDM2000 then starts building the component layer by layer.

8. The above procedure was repeated for various values of slice thickness, road width, liquefier temperature and air gap.

3.4 MEASUREMENTS

Required numbers of experiments have been conducted with desired process parameter settings. For the study of the surface roughness, the roughness average was taken as a parameter, defined as the arithmetic mean of the deviations of the roughness profile from the central line along the measurement. Surface roughness, Ra in $\mu$m was measured with Taylor Hobson surtronic 3+ surface roughness tester.

The dimension of the rapid prototypes were measured after fabrication using Brown and Sharp CMM and compared with the actual dimension given in 3D solid modeling. Equation (3.1) and (3.2) was then used to calculate the % of reduction in width and % of deviation in thickness.
Width reduction and Thickness deviation were calculated as follows:

\[
\text{Deviation in thickness (\%) = \left( \frac{\text{theoretical thickness} - \text{measured thickness}}{\text{theoretical thickness}} \right) \times 100} \tag{3.1}
\]

\[
\text{Reduction in width (\%) = \left( \frac{\text{theoretical width} - \text{measured width}}{\text{theoretical width}} \right) \times 100} \tag{3.2}
\]

The weight of the components was measured by electronic weighing machine and the porosity of the components fabricated is calculated by using the formula shown in equation (3.3).

\[
\text{Porosity} = \left( \frac{\text{void volume}}{\text{theoretical volume}} \right) \times 100 \tag{3.3}
\]

\[
\text{Void volume} = \text{theoretical volume} - \text{experimental volume}
\]

Experimental volume = mass / density, mm\(^3\)

Theoretical volume is calculated from dimensions of the part.

Density of ABS = \(1.05 \times 10^{-3}\) gm/mm\(^3\)

### 3.5 SCANNING ELECTRON MICROSCOPIC STUDY

SEM visualization and analysis were carried out on a few ABS components. They were coated with a thin film of gold by sputtering to make the surface under observation electrically conductive. Macrographs were taken using stereoscan 440 (Leica Cambridge) SEM. The observations from the SEM analysis are included throughout the thesis presentation in the relevant discussions.