An Investigation into curved layer deposition for Fused Deposition Modelling

Vivek Anand

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Dr. Sarat Singamneni

Contents

An Investigation into Curved layer deposition for fused deposition modelling.

Abstract

Rapid prototyping is a form of additive fabrication which is used to make three dimensional objects with shorter lead times. Fused Deposition modelling (FDM) is a type of Rapid prototyping, in which a semi solid plastic material is extruded layer by layer to build up a part. This is achieved by modelling of the desired part in 3D and converting this into 2D slices, which would be then readable by the machine and will hence build the part layer by layer. This type of fabrication is now being used in a number of applications from moulds for industrial components to reconstructing human body parts; however this type of manufacturing has not been widely accepted because of a number of limitations in the areas of – range of materials suitable, reduced output quality and strength, dimensional accuracy etc.

The main barrier with this type of Rapid prototyping technology is that they are created by adding layers on top of one another. These create a lamination effect resulting in parts which are weak in strength. In addition there may be more issues like poor surface finish, large number of layers which may increase production time. A little of these shortfalls could be corrected if the material could be deposited in a curved fashion compared to the traditional flat layer deposition approach. Developing a curved layer deposition methodology can improve part quality by reduced lamination, reduction in the staircase effect which leads to improved dimensional accuracy of the part and improved strength due to better bonding and continuity between layers.

The main aim of this project is to create a new type of rapid prototyping in which the layers of material which make up the part can be deposited in curved layers. This will help in the direct production of parts of curved and complicated shapes and sizes. This in turn will enable in an improvement in the production times of the parts manufactured as flat layers, better product strength, and improved overall surface quality. This is achieved by doing preliminary research and investigation into the concept of curved layer fused deposition modelling (CLFDM), studying the work done on this field till date, analyzing the shortcomings and develop a working

methodology to print simple curved parts. These curved parts can then be tested for their varied properties and compared to the same parts printed as flat layers.

This project involves in the design and development of a test bed based on the Fab@Home machine around which this whole project is based. In order to print the sample parts, they are modelled as per the desired shape and requirement. This model is then converted into a format which mainly contains all the points through the body of the model. This file is then given into a curved slicing algorithm which generates the slicing procedure readable by the fab@home machine which will then be used in printing the physical part initiating the curved layer deposition process.

Acknowledgement

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I am also grateful to the School of Engineering, AUT University for providing me with all the equipment required for the completion of the project. Again, I would like to thank Dr Sarat for part funding for this project which has been extremely beneficial.

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Vivek Anand

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List of Abbreviations

3D: Three dimensional

ABS: Acrylonitrile Butadiene Styrene

B-Rep: Boundary Representation

CAD: Computer Aided Design

CLFDM: Curved Layer Fused Deposition Modelling

CSG: Constructive Solid Geometry

FDM: Fused Deposition Modelling

FEA: Finite Element Analysis

FEM: Finite Element Method

FFE: Fractional Factorial Experiment

GUI: Graphic User Interface

IGES: Initial Graphics Exchange Specification

LOM: Laminated Object Manufacturing

LENS: Laser Engineered Net Shaping

MATLAB: Matrix Labarotary (Numerical computing software)

PC: Personal Computer

PVC: Polyvinyl chloride

RP: Rapid Prototyping

SLS: Selective Laser Sintering

STL: A file format native to the stereolithography CAD software created by 3D systems

Chapter 1

Introduction

1.1 Rapid prototyping

Rapid prototyping is a form of manufacturing where the materials are added layer by layer to definite points in space to build up a solid part. This type of technology is often referred to as also layered manufacturing, rapid manufacturing or additive fabrication. During the beginning stages of use of this technology it was mainly used to build smaller models or prototypes of new products or products being developed but due to their much wider range of applications, they are now being used in different fields. They range in various sizes depending upon their need and quality desired. They are also suited when high quality parts have to be made for relatively small numbers.

Rapid prototyping involves a process in which a 3D model of the desired part is built layer by layer through the process of additive fabrication. Modeling software such as Solid works or other animation software can be used for the purpose of modeling which is then converted into thin slices. The sliced file has all the information of the specific points which are the shape and geometry of that particular slice or layer. These slices when stacked one on top of the other will encompass the whole part. Charles W Hull was the first to create a unique method of Rapid prototyping [1] which later became available to others as this form of technology grew and more people wanted to build prototypes and models for testing and evaluation purposes. Rapid prototyping finds itself of use in a wide range of industries such as Aerospace, Military, Consumer products but so far is majorly adopted by the motor vehicle industry.

The typical design process in Rapid prototyping is as follows – Concept, Preliminary Design, Preliminary fabrication, Test Production and then Final production.

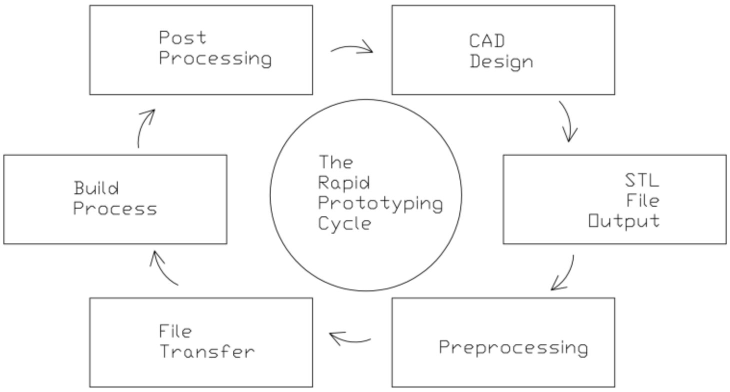


Fig 1.1 The Rapid prototyping Cycle

The Rapid prototyping cycle shown above in Fig 1.1 is a basic outline of the whole process. It starts with the initial CAD design of the required part, which is then converted into a STL (Stereo Lithography) file. This STL file is a raw file and depending upon the machine to be used upon, it can be either fed in directly or given for pre-processing. This type of processing may include checking the file, slicing, deleting or addition of parameters for machine control. The main feature of Rapid prototyping process is its ability to give life to any 3D model, regardless of its shape and specific features which would otherwise be difficult to manufacture through the normal machining process. It can be used to print different parts with complex shapes and features.

In order to manufacture a model with the traditional methods of machining, it can take a long time ranging from days to months depending upon the shape, size or any other intricate feature of the model desired. With Rapid prototyping, this time required is substantially reduced compared to the earlier method.

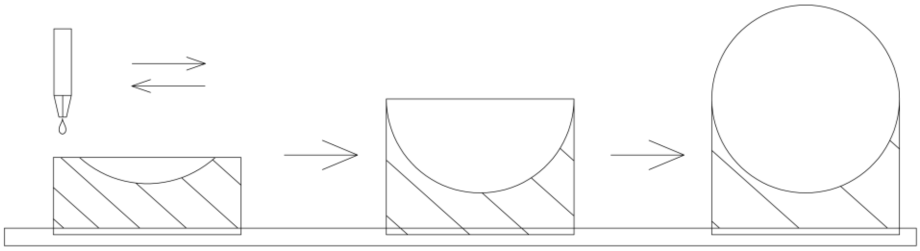


Fig 1.2 The Rapid prototyping Methodology

The methodology for rapid prototyping is shown in Fig 1.2. The true potential of Rapid prototyping will only be realized when different range of materials ranging from metals to polymers can be used in this process. If achieved, this will lead to a cost effective method of production of components, which can be of all the desired properties and used directly as a working component, fully by itself due to its nature or as a part of a material made up of a number of components.

Due to the fact that the materials available to be used with this process at this stage are limited, and the potential for this market is huge, more and more companies are getting involved in research and development of this type of manufacturing process. The involvement of different companies has resulted in the development of a variety of rapid prototyping processes, with main difference mainly being in the style of deposition of layers to build the part. The most common form of deposition is to melt the layer through heat in a deposition chamber which is then extruded through a nozzle and spread into a pattern or a slice. This slice is prepared from the 3D model of the part created through modeling software's available. In another method of deposition laser beams are used to cure deposited materials, in which the material used would be of specific property – laser or ultra violet curable. Different RP processes have their own limitations to be used with certain types of materials. Fused Deposition Modeling, which this project is mainly concentrated at, is mainly compatible with thermoplastics and a limited number of metals. The most common types of rapid prototyping technologies are as follows:

1.1.1 Stereolithography

Stereolithography was introduced in 1987 by 3D Systems Corporation. It was one of the first Rapid prototyping processes to reach the market. In this type of system a low power laser beam is used to cure the models made by photosensitive resins. An STL file is required to be used as an input to the machine which builds the parts. This is done by converting the CAD Model of part into an STL file through the modeling software. Figure 1.3 shows the basic stereolithography setup.

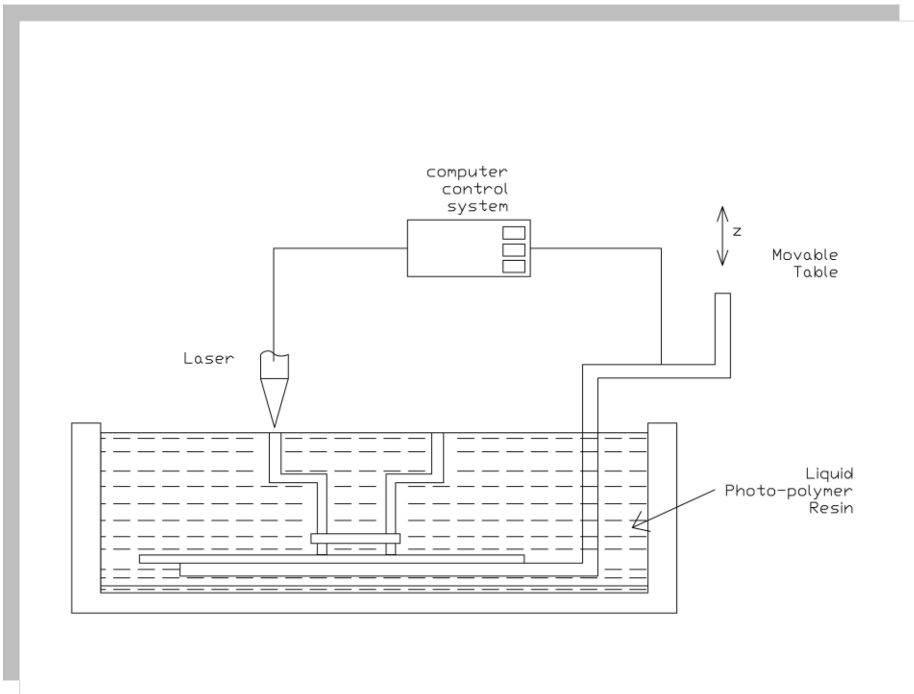


Fig 1.3 Stereolithography

A movable table is placed near the end of the container which is filled with a liquid photopolymer resin. The property of the resin is such that when light of a particular colour strikes it, the liquid turns into solid. The most common form of light used with this type of process is the ultra violet rays but other resins that work with visible light can also be used. [2]

A laser beam is used for tracing the cross section of the object to mould which causes the liquid to harden in the areas where the laser strikes. After a layer has been done, the table lowers to a height equal to the thickness of a layer. To speed the process of recoating, many stereolithography systems drew a knife edge to smoothen the surface. Upon completion of the process the object is elevated from the vat and allowed to drain. Excess resin from is removed manually from the surface of the object. The object is then given a final cure by bathing it in intense light in a closed box similar to oven. After the final cure, supports are cut off and the surfaces are sanded or otherwise finished.

1.1.2 Selective Laser Sintering

Selective laser sintering was first commercialized in the 1987 by DTM Corporation. SLS was developed and patented by Dr Carl Deckard. Unlike other manufacturing processes such as Stereolithography and Fused deposition modeling, SLS does not require support structures due to the fact that part being constructed is surrounded by unsintered powder at all times. In this type of process a high power laser is used to fuse small particles of plastic, metal into a desired three dimensional object.

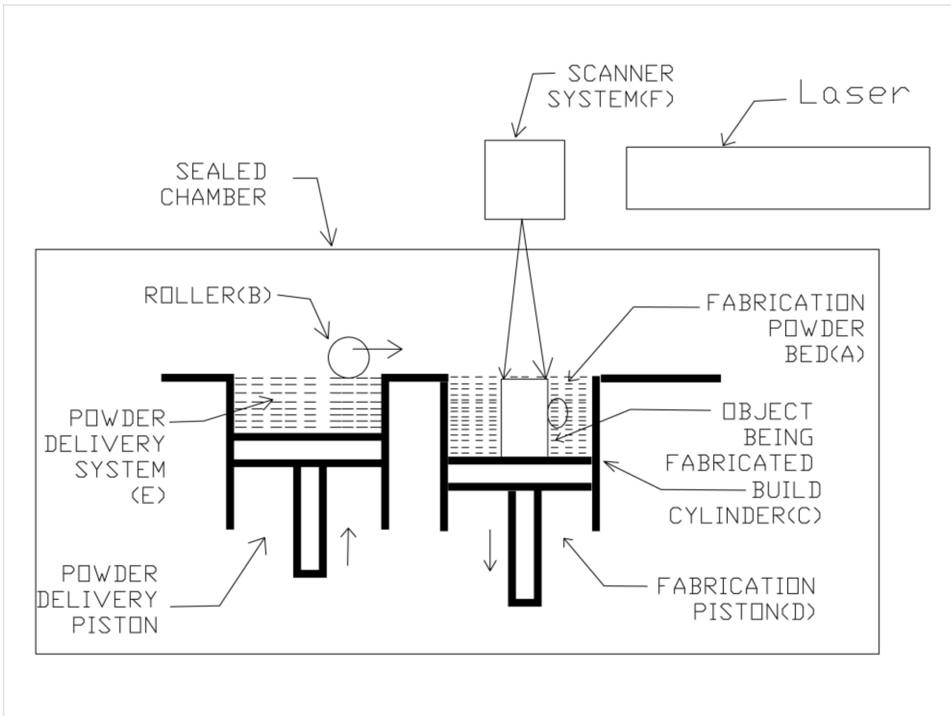


Fig 1.4 Selective Laser Sintering

An SLS setup is shown in figure 1.4. SLS has the capability to be used with a wide variety of materials like green sand, metals and polymers for different applications.

The object to be made is first modeled in CAD software, which is then converted into a STL file. The STL file is a format which contains the whole model in a slice by slice data readable by the corresponding machinery. This file is fed to the machine after which the processing starts. A roller filled with material is used spread the material over a platform which is built up one on top of another. A laser is then used to follow a pattern over a set of points with the information provided in the STL file. The path were the laser is traced is sintered. The platform is then lowered to a height equal to one slice of the model and another layer of powder is deposited over the previous layer. [3]

1.1.3 Laminated Object Manufacturing

Laminated Object Manufacturing is a process in which layers of adhesive coated paper, plastic or metal are glued together to make three dimensional models. Fig 1.5 shows a setup of laminated object manufacturing.

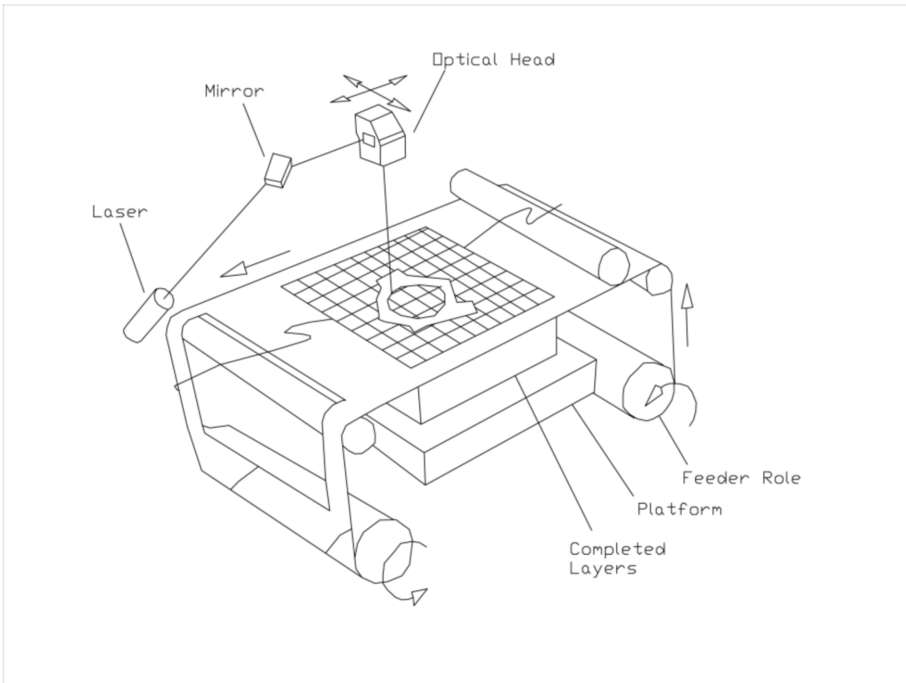


Fig 1.5 Laminated Object Manufacturing

The principal US commercial provider of Laminated Object manufacturing was Helisys, which ceased operation in 2000. However, the company’s products are still sold and serviced by a successor organization, Cubic technologies.

The mixture of an additive and a subtractive gave birth to this form of prototyping. The figure shown above gives an illustrative example of a laminated object manufacturing model. Layers of materials are added one by one and a laser is used to trace the shape of the model at that cross section. As the layer is cut, unnecessary parts on the side are removed. A cylindrical feeder bound with all the material is used as a material supply role. A special type of tape is applied onto the platform so that the material can get attached. The sheet is then fed in, the other side of which is given into a take up role after being processed by the laser. The laminating roller is rolled across the surface which helps in activating the adhesive and also to apply simultaneous downward pressure. A carbon dioxide laser is used to cut an outline of the cross sectional shape of the model. A border is then cut around the desired part which enables the part to stay intact as each new layer is created. The laser then proceeds to create hatch marks or cubes surrounding the pattern within the border. This is done so that the cubes can act as supporting structure to the parts and there is no movement during the building process. [4] This process is repeated till the part is built. When the build is completed the part is then removed from the platform

1.1.4 Fused Deposition Modeling

Fused deposition modeling (FDM) is an extrusion based additive form of rapid manufacturing technology mainly used for modeling, prototyping applications till recently when more development in this sector has enabled parts being used as products and parts for day to day applications. This technology was developed by S.Scott Crump late 80’s and commercialized in the 90’s as a concept modeling device.

The FDM technology marketed is commercially by Stratasys which also owns the trademark for this technology. As FDM is the main topic of research of this thesis, it will be discussed in full detail in the following sections.

1.1.5 Laser Engineered Net Shaping

Laser Engineered Net shaping is one of the first type of rapid prototyping systems to use metals in the deposition system. [5] The parts made from this type of system are full strength metals ranging from steel, titanium, aluminum, vanadium etc. This process was developed by Sandia national laboratories and cooperation from various other industry members. Similar to most of the rapid prototyping process, LENS also used a layer by layer approach to build a part. The CAD model of the part is used to obtain a STL file which is used as an input to the machine which builds the parts from the bottom layer onwards. A high powered laser is used to fuse the metal powder when it is fed from feeder tubes into its focal point. This powder is then turned into a layer when deposited in the required shape. A Sample LENS process is shown in Fig 1.6 below.

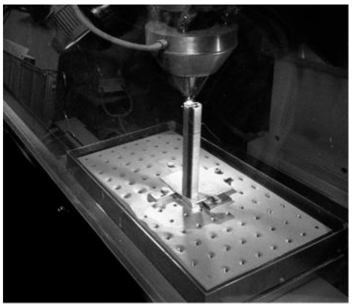


Fig 1.6 A Sample LENS process

The deposition device then moves up the distance equal to the height of one layer to proceed to deposit the next layer. This process is repeated till the complete part is built.

There are various other forms of rapid prototyping methods with similar techniques and methods of deposition which are being developed to cater to the manufacturing needs. Out of the various forms, FDM is the one which is the most successful and important technology available to the market. Because of this status of Fused Deposition Modeling it is always being propagated for further research and investigation. More developments, improvements and advancements in this field will be covered in detail in the following sections.

1.1.6 Rapid Prototyping Technologies at a glance

S.No	Process	Working Principal	Principal Materials	Cost	Application
1	Stereolithography	Low Power laser beam is used to cure the models made by photo-sensitive resins.	Photopolymer Resin	$150k-$400k	Producing models, prototypes, patterns & production parts.
2	Selective Laser Sintering	Uses a high power laser to fuse small particles into a mass representing the desired 3-D object.	Plastic, metal, ceramic or glass powders	$100k-$500k	Prototypes, End parts
3	Laminated object Manufacturing	A Manufacturing process that uses CO2 laser to create successive cross sections of a three dimensional object	Thermoplastics such as PVC; Paper; Composites (Ferrous metals; Non-ferrous metals; Ceramics)	$200k-$800k	Form/fit testing, Less detailed parts, Rapid tooling patterns
4	Fused Deposition Modelling	Fused Deposition Modelling (FDM) is a solid-based rapid prototyping method that extrudes material, layer-by-layer, to build a model	ABS, ABS-M30, Polycarbonate, PC-ABS, PC-ISO, ULTEM, & PPSF (tan). Food-grade ABSi material	$300k-$900k	Commonly used for concept design modelling, low volume production, prototyping, and production applications
5	Laser Engineered Net Shaping	Fabricating metal parts directly from a solid model by using a metal powder injected into a molten pool created by a focused, high-powered laser beam.	Wide range of alloys, including titanium, stainless steel, aluminium, and other specialty materials; as well as composite and functionally graded materials.	$250k-$1mil	Repair & overhaul, rapid prototyping, rapid manufacturing, and limited-run manufacturing for aerospace, defense, and medical markets.

1.2 Fused Deposition Modeling

A detailed discussion of the rapid prototyping method, FDM is necessary, considering the project revolves around certain improvements attempted in the process. Fused deposition modeling (FDM) is an extrusion based rapid prototyping technology which is the main area of research of this project. FDM was developed and patented in the year 1989 by Scott crump. Immediately after in 1990, he then setup Stratasys, a company which now specializes in manufacturing of additive fabrication machines for direct digital manufacturing. In 2007, almost half the amount of all fabrication systems worldwide was supplied by Stratasys making it a consecutive 6th time market leader. FDM, in its working is quite similar to other rapid prototyping systems in which a STL file is fed into the fabrication machine which then builds the model layer by layer [6].

FDM mainly involves a feeder role or coil which is continuously fed into an extrusion head or nozzle. Before the material reaches the nozzle, it is heated to soften the material to a molten state when it can be deposited onto the platform. This is done with the help of heating elements in nozzle which melts the material. This nozzle is controlled by a computer aided manufacturing package which can be used to move the nozzle in horizontal, vertical directions. This whole setup is carried out in a temperature controlled chamber to maintain the quality of the produced parts. As the molten material ejects out of the nozzle, it is then spread onto the platform in the desired shape as a layer. The deposition platform is then lowered to a height equal to one layer height of the part and the deposition process is repeated over the previously deposited layer. This process is repeated layer by layer starting from the base and worked its way to the top to complete the whole model.

One of the important parts of this type of deposition process is the nozzle or the extrusion head which is responsible for melting the material and its deposition. The nozzle is computer controlled and it can be moved in horizontal and vertical directions. A FDM schematic is shown below in Fig 1.7

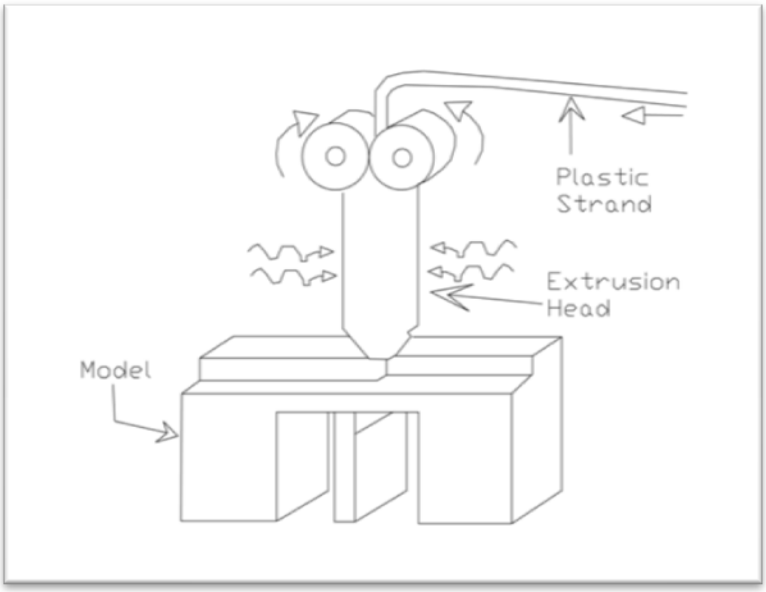


Fig 1.7 A FDM Schematic

The deposition head of the machine mainly consists of the drive block, the tip and the heating compartment. The raw material is fed into the machine with the help of the drive blocks which contain wheels mounted on back of head. These drive blocks are responsible for loading and unloading of the raw materials from the rolls and can be computer controlled for precision. A heating element is used as bubbles wrap for the heating compartment and also blends in an L shape angle. This is done to divert the horizontal flow of the filament to a vertical direction which can be then used as an area to melt the material. External threading is done on the tips so that they can be screwed in with the internal screws on the heating compartment. Tips are mainly used to get high precision thin layers so that the parts produced can be of high dimensional accuracy and good finish.

The materials which are used to print the models need to harden as soon as they are extruded the extrusion head are specifically designed for this purpose. The heat chamber plays a pivotal role in the whole extrusion process. It helps in providing a controlled ambience during the processing of the material and so that there is no interruption in the process and there is free flow during deposition. Following this detail, a section view of the extrusion head is shown in Fig 1.8 below.

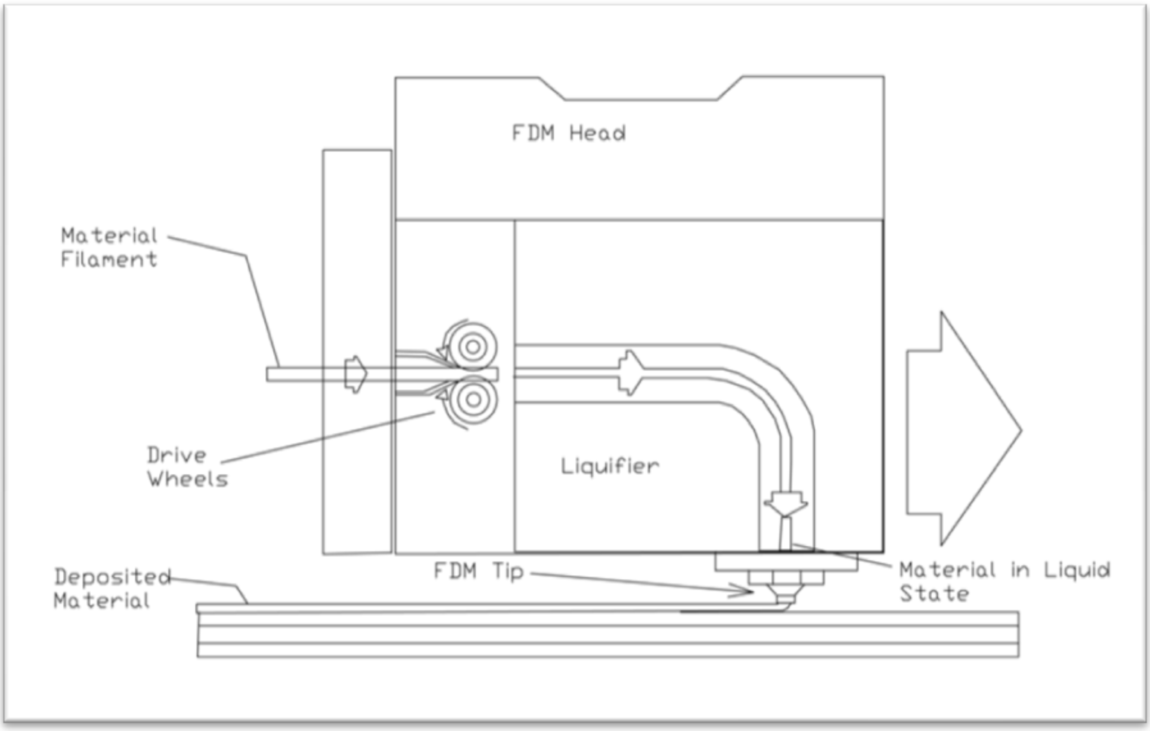


Fig 1.8 Deposition Head

Different types of machines are available in the market today and each machine has its own capability to build parts due to a variety of factors. These would be dependent upon the company manufactured by, the size of the machine, the type of extrusion head used, the range of materials the machine can use etc. The range of materials over which the FDM machines can operate are mainly - ABS (Acrylonitrile Butadiene Styrene), Medical grade ABS, Elastomer and Inverstment casting wax. These materials have properties like high strength, performance and also made of high dimensional accuracy. Owing to these properties they can be easily used in making models, prototypes, concept or design components. They are also used in investment casting and increasingly being used in medical applications, like filling for damaged section of brain. Recent research and development in this field has lead to more companies starting to replace conventional methods of machining and using for making parts which may be used as a smaller part of an assembly or even used as end user parts.

Fig 1.9 Sample of parts made by Fused Deposition Modelling

Out of all the Rapid prototyping processes, FDM has a relatively simple post processing of the part. Most of the processes would need the separation of the base material, or heat treatment in the case of three dimensional printing and SLA compared to which the FDM has a very easy part removal process. This is mainly done by leaving the part to harden in the open and then removing the part away either straight from the bare hand or knife depending upon the bond between the part and the supporting material. Only few other parts would need any other form of minor finishing for using direct in applications. Figure 1.9 shows two parts made by SLS and FDM.

For different applications of fused deposition modeling, there are different types of Rapid prototyping machines available in the market to be chosen from. Stratasys is one worlds leading companies in providing FDM systems and solutions to the market. Stratasys's system brands are mainly - Fortus 3D Production systems, Dimension 3D Printers and RedEye On demand services. Fortus 3D Production systems are considered to be one of the most advanced and popular machines in the world. Some of the Fortus series include Fortus 200mc, 360mc, 400mc and 900mc. which have high performance and have a wide acceptability range of materials which can be used with these machines. Most of the materials largely compatible and used with these machines are thermoplastic materials. These machines are designed and manufactured for highest accuracy and repeatability and hence provide the best surface finish possible. The top end model of Stratasys, the

900mc is capable of producing parts with an accuracy of +/- .0035 inch or +/- .0015 inch per inch with a build envelope of 914 x 610 x 914 mm. The most common types of materials used by FDM systems are ABS, Medical grade ABS, PPSF, PC and production grade thermoplastic material. These materials are mainly used as they can withstand heat and testing of its properties depending upon the functions the material is expected to subjected to during the normal course of its operation. These machines have part tolerances which are substantially improved over other previous FDM systems and do not use resins or powders to give the similar effect of a thermoplastic material but use real material to get the best results. After the component is built, it can be also post processing activities like drilling, painting, casting etc.

The major advantage of this type of rapid prototyping is that it provides high build strength and temperature capability. Once the materials are built, it can be also be dipped in water soluble materials for curing and hardening purposes.

1.3 Technical Limitations

Fused deposition modeling is a type of RP process which uses STL file as input and involves in printing of parts by stacking layer one on top of other. This type of printing methodology apart from fast product development also brings in few shortfalls.

One of the main areas of limitation which particularly exist in FDM is the “stair case effect”. This is mainly due to the deposition method of the process, printing of horizontal layers one on top of the other. The CAD model is first converted into the STL format which is then sliced in flat horizontal layers with each layer having its own shape. The STL file is basically is one which consists of all the points which make up the shapes in each layer and all layers when put together stacks up as a model. The extrusion head, which is responsible for depositing the material on the surface layer by layer, follows the path information stored in the STL file and builds the whole part with an effect in which curved surfaces appear to be a little short or over shoot the actual dimension of the part.

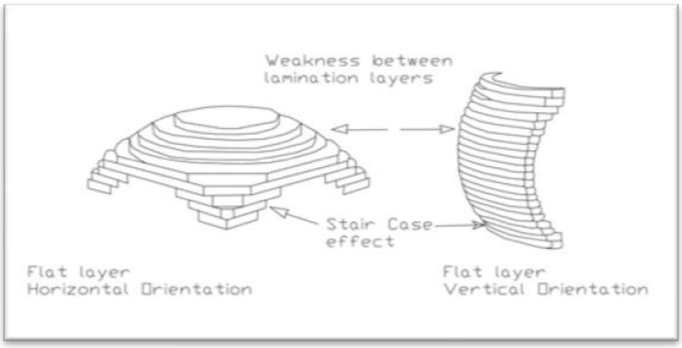


Fig 1.10 Stair case effect

This phenomenon is commonly referred to as the “Stair case” effect, shown in the above figure 1.10. This effect is more prominent when a larger diameter nozzle is used for material deposition.

The straightforward solution to this situation would be to use low diameter nozzle which will print thin layers. In order to achieve better finish and reduced stair case effect, it would take more number of layers to print the same part which results in time consumption. One of the desirable features of a rapid prototyping process is high accuracy, surface finish. To achieve this, the layer thickness has to be considerably reduced, as shown in the figure below. This leads to the increase in the total build time often which is quite a shortcoming.

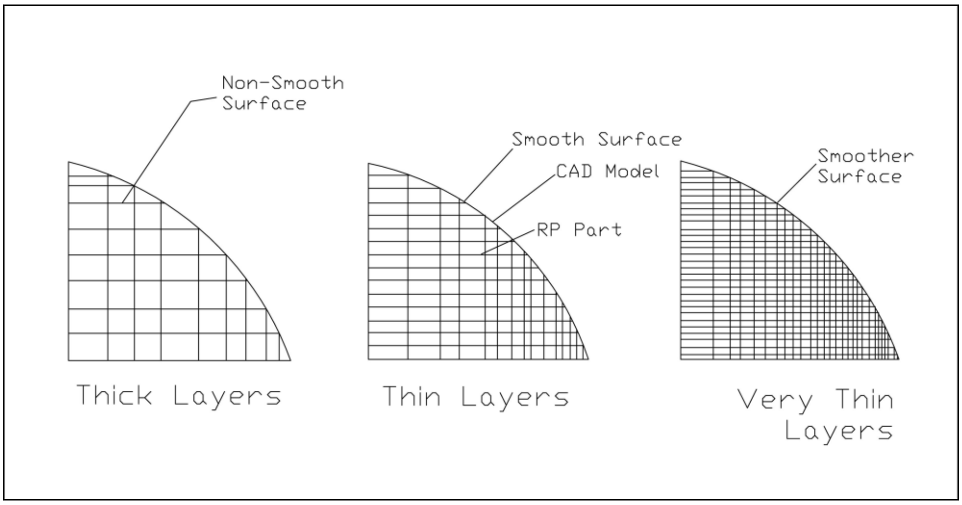


Fig 1.11 Layers and finish quality

Another common area of shortfall of this rapid prototyping process is that this process is directionally dependent. As this process is based material deposition, it’s noted that the parts built in this method are predominant in one direction – the direction in which the extrusion head has deposited the material. Due to this, the strength of the part is affected and the adhesive strength between the layers is reduced which is considerably better in case of continuous filaments. The tensile strength of the part is drastically reduced due to the rater orientation and the occurrence of air gap. When shapes with thin walls and curvature are involved, the filament discontinuation causes the part to be of poor strength and may also lead to failure over a period of time. Fig 1.11 shows that printing with very thin layers gives a smooth finish.

These are some common problems associated with fused deposition modelling the properties which the parts suffer from. To improve this there has been a lot of research and development in this area of rapid prototyping in a bid to improve the deposition techniques and also on the range of materials which can be used with this type of prototyping.

1.4 Literature Review

There are a lot of important factors affecting the quality of parts produced by this method of rapid prototyping but the most important are mainly the speed of deposition, layer thickness and the width of the road. Speed and the road width contribute nearly sixteen percent each at ninety nine percent level of significance [6a]. Layer thickness plays a much important role being effective in the range of Forty Nine and Fifty Two percent at Ninety five percent level of significance without pooling and ninety nine percent level of significance with pooling respectively.

Type of materials used in FDM play a very important part as they are the one's who decide the final use-ability of the part. There have been quite a lot of experiments with different materials in FDM to explore which material suits best and for which purpose. ABS polymer is quite often used a standard material for RP processes, but conventional ABS polymers in filamentary form are known to be of low strength and hardness. In an experiment by Fan Li et al [7] to overcome this, ABS was modified by adding different property modifiers including short glass fiber, plasticizer, compatiblizer. It was found that glass fiber could significantly improve the strength of the ABS filament but it came with a reduction of handelability and flexibility. These two properties of glass fiber reinforced ABS filaments were improved by adding a small amount of compatibilizer and plasticizer.

In attempts to improve the property of materials to be used by FDM process, Iron / nylon mixture consisting of iron metal particles in a p301 mixture was selected by Masood, S.H et al [8] The reason for using iron in the composite mixture was for its reasonably good mechanical and thermal properties and its capabilities of mixing and surface binding with polymers. Three samples of composite materials consisting of iron particles of given volume and a specific particle size were mixed in the matrix of nylon (p301) material. The first sample consisted of 70% nylon and 30% iron by volume with particle size 50-80lm. The second sample consists of 60% nylon and 40% iron with particle size of 50-80lm. The third sample consists of 60% nylon and 40% iron with particle size less than 30 µm. The filaments were made and each type of filament made was tested for its tensile properties. It was found that the variation of modulus of elasticity and tensile strength and tensile elongation of composites were strongly dependent upon the varying size of metal particles.

To investigate the use of medical-grade polymethylmethacrylate (PMMA) in fused deposition modelling (FDM) and to fabricate porous customized freeform structures for several applications including craniofacial reconstruction and orthopaedic spacers, an experiment was conducted by David et al [9]. It was found that a liquefier and envelope temperature of 235 C and 55 C, respectively, as well as increasing the model feed rate by 60 percent, were necessary consistently extrude the PMMA filament. Structures with different porosities and fabrication conditions were produced, and their compressive mechanical properties were examined. Results showed that both the tip wipe frequency and layer orientation used to fabricate the structures, as well as the porosity of the structure had an effect on the mechanical properties.

In another research project by Iwan et al [10], a bioresorbable polymer poly(e-caprolactone) (PCL) was developed as a filament modeling material to produce porous scaffolds, made of layers of directionally aligned microfilaments, using this computer-controlled extrusion and deposition process. Porous FDM scaffolds were made of layers of directionally aligned microfilaments within a geometrical 3D structure. Honeycomb scaffold architectures were made of layers of directionally aligned PCL microfilaments within a geometrical 3D structure. Analysis of the mechanical properties contributed to a better understanding of the anisotropic nature of different designs. Examination of the mechanical deformation indicated that the porous PCL scaffolds demonstrated stress–strain behaviour highly similar to that of a typical porous material undergoing compression. The mechanical properties were found to be generally dependent on its porosity, regardless of the lay-down pattern and channel size which is in parallel with theoretical concepts on the structure–properties relationships of porous solids.

One of the primary goals of any rapid prototyping system is the production of metallic prototypes for functional applications and testing. In 1995, M Gruel et al [11] developed a new rapid prototyping process known as the “multi phase jet solidification”. The basic idea was to extrude material with low viscosity through a jet. The material was supplied in different phases as a powder-binder mixture. The material is heated above its solidification point, squeezed out through a nozzle by a pumping system and deposited layer by layer. The part is then sintered and analyzed for its properties.

Different requirements of this type of rapid prototyping system have been researched upon for its quantification purpose. In order to model and optimize the RP process, a virtual reality system was proposed by Choi et al [12]. This system’s main idea was to improve the quality in a product development cycle by reducing the manufacturing risks involved and in result it reduced the cost factor of the repetitive design, build and test cycle. This system primarily involves in designing and simulation of the rapid prototyping process in a virtual system which helps in getting various parameters of the system like built time, accuracy, part quality, hatch distance and layer thickness. Hardware and software of the RP system are two major areas which are always concentrated upon for improving the part quality of the parts produced by the FDM process.

To improve the finish of the parts produced and to be able to use more variety of materials like ceramic materials, a lot of attempts has been made to improve the hardware part of the process. To prototype a variety of ceramic components, a new process called FDC – Fused deposition of Ceramics was introduced by Allahverdi et al [13]. In this process parts were built by using polymer filaments loaded by ceramics. Based on the modulus of the FDC feedstock and the compressive strength, a process map is developed. This is used to determine the possibility of deposition in advance with a range of FDC compatible filaments. Filaments such as alumina, bit, pmn, pzt and many others have been tested with positive results in the FDC rapid prototyping process. During this process a palladium-silver filament capable of withstanding high temperature was developed for the production of electromechanical components. Alumina, fabricated with photonic bandgap structures and alumina rods were used in various laser applications and as support materials for microwave elements. Another technique was added to the family for the RP processes known as direct metal deposition (DMD) by Mazumdar et al [14]. This process enabled the use and a choice of easily available commercial alloys to produce three dimensional components. In this process, the deposition material used was the H13 tool steel which was successfully used to build 3D components.

To implement the trial of new materials, new systems with different nozzles, like the multi nozzle system were brought in. A multi-nozzle bipolar deposition system having the capability of extruding living cells and bipolar solutions was developed by Khalil et al [15], for construction of a three dimensional freeform tissue scaffold. The deposition process occurs at room temperature and low pressures to reduce damage to cells and is also biocompatible. This system developed also has capability of depositing controlled amount of cells, growth factors, scaffold construction and also other compounds of bioactive nature which have precise spatial position to form complex cell structures.

The final part built is also quite dependent upon many crucial factors, which includes the orientation of the deposition head. To build the best part with good accuracy and finish, within the limits of manufacturing time and build cost, the ability to evaluate the best part build part orientation was quite important and was found by Xu et al [16]. A range of parts made with different orientation features will have crucial consequences on the part build time and quality; this is mainly due to the specific characterstics of the LM technology. To improve this accuracy and build time, the different types of orientation required may be preset in advance. To determine the optimal direction to build a part through a hybrid rapid prototyping process, Hu et al developed an algorithm by taking into consideration the attributes of the deposition process and the CNC machining process.

Hardware of the machines used in these RP processes has been having continuous improvement as shown above and at the same time there also has been considerable improvement in the quality of the parts produced by the RP processes. For eg, materials like metal, functional and structural ceramics, were also tried in different experiments to produce parts which required high accuracy. In 1996 a study by Mukesh et al [17] showed that with the deposition systems then, there was high chance that the structural properties of the metal and ceramic parts are limited with different internal and surface defects.

A project study was carried out by Anna Bellini et al [18] in which mechanical tests were carried out to test the parts fabricated using FDM. It was observed that road shape and road to road interaction, as well as the path strongly affect the properties and performance of the finished product. As an input to the FDM machine, STL files are required which contain the information to build the whole part. These STL files can be easily converted or obtained by the Cad model files from different modeling software's available in the market today. Before the deposition is started the part is to be sliced layer by layer. This is done by slicing algorithms developed till now and quite a lot of research has been done in this area. It is quite important that the algorithm is written in a way to reduce the effects of anisotropy and stair case effect discussed earlier. It was found that the input of sliced a tessellated data from the software model of the part would be required for the rapid prototyping systems, so that the requirement to slice an equivalent model which has been tessellated is eliminated. Hacker et al [19] continued to add that rounded or tubular designs can be improved for their accuracy and even before the printing process is started, the processing time can be improved by providing the adequate data to the RP system.

There have been a number of attempts to reduce the build time and increase part surface quality and there is still ongoing research going on in this area. PM Pandey et all [20] proposed a slicing procedure for fused deposition modeling based on real time edge profile of deposited layers. This was done by limiting the surface roughness value (Ra), which describes surface quality. A software was developed which does the slicing of the CAD model created by sweeping a Bezier curve around an axis. The software for direct slicing of axis symmetric parts takes the control points of Bezier curve, maximum and minimum fabrication thickness available in the FDM machine and maximum Ra value desired on the part surface as input. The software gives the variable slice thickness list, overall part surface roughness and the graphics of the slices formed. It was observed that the number of slices were reduced and hence the build time. The major advantage being the part quality expressed in terms of Ra value which is used in design and manufacturing which is being quite realistic.

Part quality can also be improved by modifying the pattern of deposition. To improve the scanning efficiency in FDM, Yang et al [21] developed an equidistant path generation algorithm. To evaluate the path generation algorithm, simulated and experimental analyses were carried out and it was proven that this deposition can improve the rapid prototyping process by increasing part quality and processing efficiency.

To determine the most crucial elements affecting the quality of prototypes in fused deposition modeling, a work study using Taguchi methods was undertaken by Anitha et al [22]. It was found that without pooling, only the layer thickness is effective to 49.37% at ninety five percent level of significance. On pooling it was found that the layer thickness is effective to 51.57% at ninety nine percent level of significance. The significance of layer thickness is further strengthened by correlation analysis, which indicates a strong inverse relationship with surface roughness.

In an experimental work done by L.M.Galantucci et al [23], have studied the influence of FDM machining parameters on acrylonitrile butadiene styrene (ABS) prototype’s surface finish. The surface finish of products after the modification of extrusion parameters has been measured and processed through designed experiments. The roughness of FDM prototypes is analyzed. Process parameters have been shown to affect the Ra. In particular the slice height and the raster width are important parameters while the tip diameter has little importance for surfaces running either parallel or perpendicular to the build direction. A chemical post-processing treatment was analyzed which yields a significant improvement of the Ra of the treated specimens. The proposed chemical treatment is economic, fast and easy to use.

Despite all the research and development done in this field which have been discussed above and more in the industries R & D labs, accuracy of the part and surface quality are key criteria for this form of rapid prototyping. Printing of curved surfaces with high precision and eliminating stair case effect has been a area of repeated problem occurrence where many have tried to provide solution in their own literature review's but they still have their shortcomings – mainly associated with curved surfaces.

Even though there has been a continuous development of these rapid prototyping processes, improvisation in its application, product development and other areas have quite significantly improved, there is a downside in getting a balanced result in the material front. Materials, which can be rapid prototyped and engineered to be used as end solutions right to the customer or as a part of a component are still yet to come in a big way in the consumer market. The processes which currently use low or poor quality material for most of the part and are only good for testing of limited properties as those materials may not be deemed fit. Only with continuous machine and material improvements the dream of building products with true engineering value can be realized.

Stair case effect, as discussed earlier is a common defect in FDM methods is a major reason for poor surface quality of parts produced. Due to this the number of layers to make up the part is high which results in increased build time and poor strength in some cases. In case of thin shell type and curved parts these problems are severe, critical and undesirably high in most cases. FDM has been used to recreate parts such as skull bone replacements, turbine blades, etc. Using conventional FDM parts to manufacture curved shell type parts results in poor quality parts with discontinuous filaments.

The main obstacle for the application of new materials with specific properties for FDM often comes from the use of intermediate precursors such as a filament. Also during the extrusion phase, frequent buckling causes the interruption of the process.

In spite of this, several researchers have attempted at the use of different materials for FDM. While experimenting with ceramics, Lauren et al [24] found that feedstock materials with a slenderness ratio greater than a critical value do not buckle during fused deposition. This critical value depends upon factors like volumetric flow rate, capillary action and a scaling factor constant.

1.5 Research question and objectives

It is evident that FDM research encompassed use of different materials and deposition styles such as use of nozzles of different styles and sizes and adaptive slicing for better surface quality etc. Almost in all cases, the slicing strategy is flat layered, in that the part is cut into several horizontal layers, though the part orientation may change. The most obvious error in such a case is the stair step effect in curved parts, as shown in Fig. 1.10. The question is, what would happen if curved layer deposition is used as shown in Fig. 1.12.

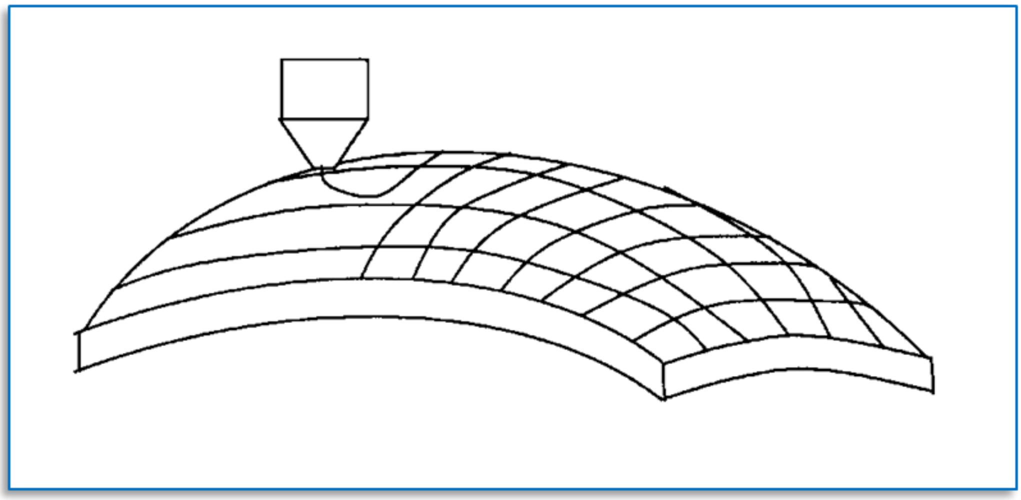


Fig. 1.12 Curved layer deposition

Some of the immediate observations are:

- Better surface quality due to the elimination of the stair-step effect
- Improved strength due to fiber continuity
- Better dimensional quality

The actual influence of the curved layer deposition however needs to be ascertained through investigations involving experimental and numerical approaches. A preliminary set of mathematical algorithms, and software and hardware solutions were already developed as part of a previous investigation. The actual improvements possible in the mechanical characteristics of parts produced by the curved layer deposition scheme need investigation and the current project is aimed at this.

While developing means of practically implementing the curved layer deposition scheme, the effectiveness of the approach needs to be verified through experimental investigations involving the multi-factorial approach, in order to be able to find the influences of different parameters. The following are the main objectives:

- Development of a FDM test bed.
- Deposition of different materials using flat and curved layered techniques.
- Experimental evaluation of the influence of the deposition technique.
- Experimental investigation of flat and curved layer FDM parts under varying conditions using a multi-factorial approach.
- Finite element simulation of Flat and Curved Layer Fused Deposition Modelling.
- Corelation of results from physical and numerical experiments and evaluation of CLFDM against traditional FDM.

Chapter 2

Mathematical Modelling for Curved Layer Fused Deposition Modelling.

2.1 The Rapid Prototyping (RP) routine

To meet today's customer demands, develop technologically advanced products, show innovation and get ahead of competition, companies have to put in more resources and invest into state of the art manufacturing facilities. Due to a lot of constraints mainly being time and material and the need to bring out new products in less time, more companies are now resorting to new Rapid prototyping technologies which help them to create an actual prototype model from the CAD design. This eliminates the number of months and days required to design, draft, manufacture for a part which may or may not be successful at the first instance it is produced.

In recent times, there has been a lot of growth in the Rapid prototyping technologies. Most of these developments are related and more focussed towards materials, deposition style and printing methodologies as companies want to see the end result in less time. This has lead to a lot of research and development in the programming end of this whole process namely computer aided drafting, computer aided machining and computer numerically controlled machining tools. Though there are a number of rapid prototyping processes they operate more or less on a similar set of operating procedures.

A basic of outline of a rapid prototyping process may be as follows:

- Designing the model with the help of a software modelling package.
- Exporting the designed model as a "STL" file.
- Modelling of support structures as base for the main part.
- Checking, slicing of STL files.
- Printing of the actual part.

- Separating the Main part with its support structures.
- Finalizing, curing, and finishing of the finished parts.

The main form of input for making a physical model is a three dimensional model of the object which is made from a modelling software like Solidworks, Catia etc. Fig 2.1 shows the step by step procedure for rapid prototyping. As an alternative to modelling, an existing physical part may be scanned digitally. This process of getting a three dimensional model from a physical part is not a clear-cut and accurate method. The resolution of the part would be less but may be improved by using laser digitizer or a machine which is purpose built to measure co-ordinates.

The solid model designed on the modelling software needs to be converted into a more machine readable format which is called a STL file. The STL file is made of triangular faces which put together form the model. This file contains all the x, y and z co-ordinates of the whole model which forms of the basis of three dimensional printing. The STL file is then sliced by horizontal planes into thin slices. The thickness of the layer is equal to the distance between two consecutive adjacent planes. Depending upon the type of the STL model, a support structure may or may not be generated. The model is imported into the software which mainly acts as a medium between the machine and computer. The orientation is then adjusted to suit if required and the model is set to start printing.

The co-ordinates and boundary information of each layer is sent one by one to the rapid prototyping machine after it is sliced. The machine now starts to build the model layer by layer as per the information stored in the STL file, conveyed by the mediating software.

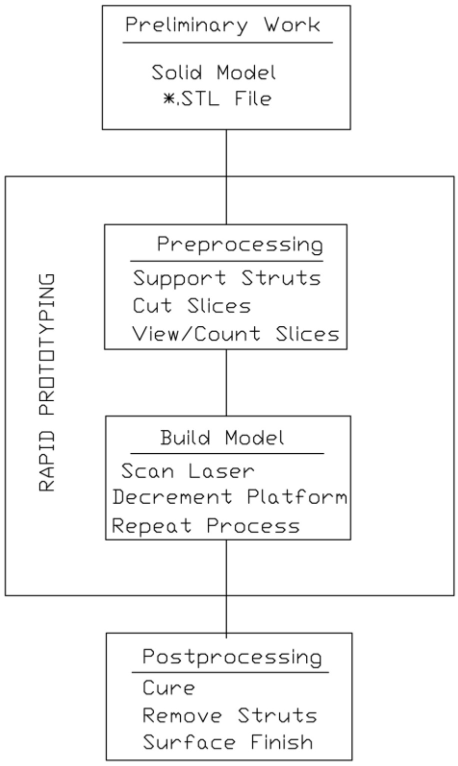


Fig 2.1 Procedure of Rapid prototyping

The process of deposition of the material may be in either solid, liquid or powder form. In case of a FDM process, the tool head will move and deposit the material as per the co-ordinates stored in the STL file. In case of a SLS process, powders are gradually sintered to form layers and photo sensitive epoxy resins are cured in a SLA process to form layers one on top of other. Any support structure is first removed after the model has been printed. The methods of this removal may vary on the process and the model created.

2.1.1 Modelling

Developing the CAD model is one on the first steps in any type of rapid prototyping process. A branch of computational geometry known as computer aided geometric design which is used in the development of virtual models. The first kind of models made in earlier days was the two dimensional geometric models which are basically two dimensional figures of objects which were fairly simple in nature. Flat objects could be easily represented with two dimensional models but its applications were limited to simple models. It could not be used to portray complicated designs and shapes and so was not of much help in rapid prototyping.

The collection of a number of points of an object in 3D space usually consisting of a number of geometric entities like lines, circles etc came to be known as three dimensional models. Over a period of years a number of three dimensional modelling software packages have been developed which have all the capabilities to design a part and provide necessary data for production and processing. As technology advanced, these software packages advanced and they have are now being used for other purposes like slicing into layers, giving out codes for manufacturing etc.

Different entities like volume and surface models, circles, curves and lines are put together to make a complete three dimensional solid model. When lines are put together to represent three dimensional objects with the help of co-ordinates they are known as wireframe models. These models are known for their small size but can be a bit deceiving in its nature. Curved surfaces, complicated surfaces and planes are put together and constructed to form shell or boundary model. From a manufacturing perspective this model is capable of representing the solid at its best. For generating the CNC cutter tool paths, the interior information required from the solid models would not be available. It would also be difficult to estimate the mass and inertia properties and hence for a solid model, constructing a surface is not advised.

The most ideal representation of a solid would be its solid or volume model which has the most description and may also be relatively difficult to construct. This technique is quite useful to get all the information required for manufacturing the model. Many of the modelling software's available in the market use the solid model.

2.1.2 Modelling Construction

A lot of detailing aspects like tolerance, dimension, and material specification go into consideration when a three dimensional model is being constructed. A model can be constructed in a number of ways like: Boundary Representation, sweeping and constructive solid geometry.

2.1.3 Boundary Representation

Boundary representation is also known as either B-Rep or BREP. It is a method wherein limits are used for representing shapes. A collection of connected surface elements is used to construct a solid. Topology and Geometry are two main compositions of a Boundary Representation.

Topology

-- records the connectivity of the faces, edges and vertices by means of pointers in the data structure.

Geometry

-- describes the exact shape and position of each of the edges, faces and vertices.

* The geometry of a vertex is just its position in space as given by its (x,y,z) coordinates.

* Edges may be straight lines, circular arcs, etc.

* A face is represented by some description of its surface (algebraic or parametric forms used).

Vertices, faces and edges are the main topological items in a boundary representation. A face is a bounded portion of a surface; an edge is a bounded piece of a curve and a vertex lies at a point. Fig 2.2 shows faces, edges and vertices. Other elements are the shell, the loop and loop-edge links which are used to create the edge circuits. The edges are like the edges of a table, bounding a surface portion. Compared to the constructive solid geometry (CSG) representation, which uses only primitive objects and Boolean

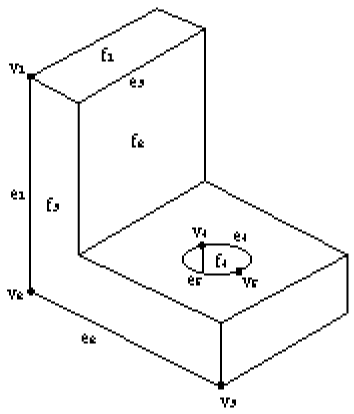


Fig 2.2 Faces, Edges and Vertices

operations to combine them, boundary representation is more flexible and has a much richer operation set. This makes boundary representation a more appropriate choice for CAD systems.

2.1.4 Sweeping

Sweeping is a method of producing solid models for manufacturing. Depending upon the size, shape and complexity any of the methods – Revolve, Extrusion and Sweeping with guide lines can be used for sweeping.

Revolve is a feature were models are generated by revolving around the centre axis. The main limitation of this type being that this method is best suitable for models which are symmetric over the centre axis. Fig 2.3 shows an example of the revolve feature.

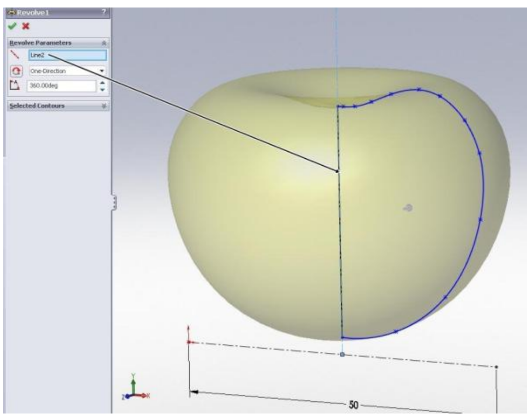


Fig 2.3 "Apple" made with the revolve feature.

Extrusion is the most common method of producing common solid models. It forms the basics of simple and complex parts of various shapes and sizes. As a first step, a two dimensional model is created of the object whose 3D model is desired. Once this is ready, the model is then extruded in the direction and to the width as required. Taper along the linear direction can also be accommodated. Any variations in direction different to direction of the standard possible extrusion would be difficult to create. A sample extrusion is shown in fig 2.4 below.

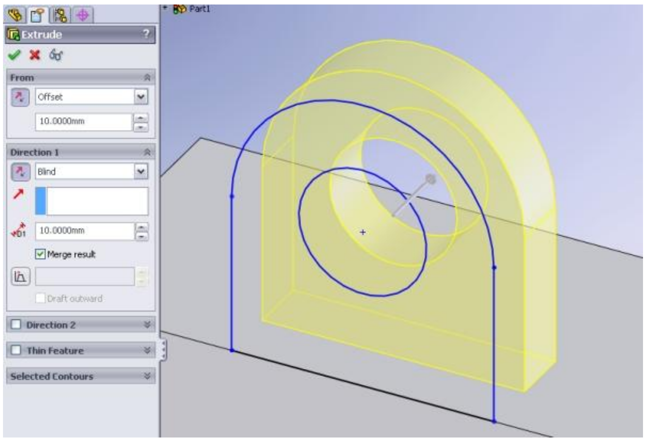


Fig 2.4 Extrusion

Sweeping with the help of a guide curve is a feature similar to extrusion as it allows an object to be extruded in different forms as long as there are guide curves which act as boundaries and guidelines as extent to which the material is extruded. A sample sweep is shown in fig 2.5 below.

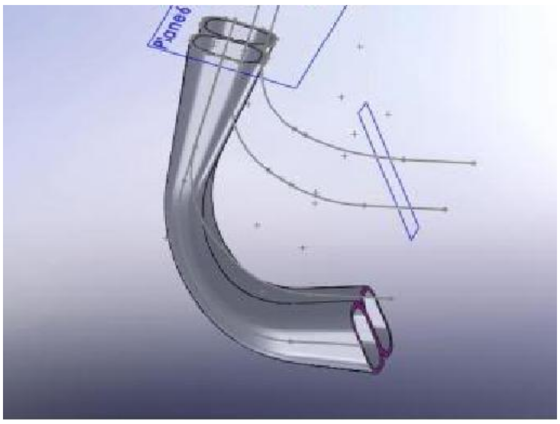
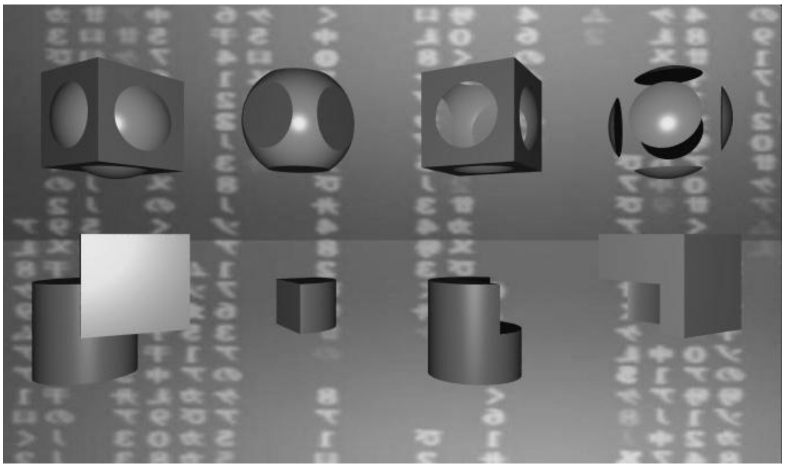


Fig 2.5 Sweeping

2.1.5 Constructive Solid Geometry

Constructive solid geometry (CSG) is a technique used in solid modeling. CSG is often a procedural modelling technique used in 3D computer graphics and CAD. Constructive solid geometry allows a modeller to create a complex surface or object by using Boolean operators to combine objects. Often CSG presents a model or surface that appears visually complex, but is actually little more than cleverly combined or decombined objects. In some cases, constructive solid geometry is performed on polygonal meshes, and may or may not be procedural and/or parametric.

Constructive solid geometry has a number of practical uses. It is used in cases where simple geometric objects are desired, or where mathematical accuracy is important. The Unreal engine uses this system, as does Hammer (the native Source engine level editor), and Torque Game Engine/Torque Game Engine Advanced. CSG is popular because a modeler can use a set of relatively simple objects to create very complicated geometry. When CSG is procedural or parametric, the user



UNION INTERSECTION DIFFERENCE

Fig 2.6 Constructive Solid Geometry

can revise their complex geometry by changing the position of objects or by changing the Boolean operation used to combine those objects. Fig 2.6 shows the types of constructive solid geometry.

One of the advantages of CSG is that it can easily assure that objects are "solid" or water-tight if all of the primitive shapes are water-tight. This can be important for some manufacturing or engineering computation applications. By comparison, when creating geometry based upon boundary representations, additional topological data is required, or consistency checks must be performed to assure that the given boundary description specifies a valid solid object.

A convenient property of CSG shapes is that it is easy to classify arbitrary points as being either inside or outside the shape created by CSG. The point is simply classified against all the underlying primitives and the resulting boolean expression is evaluated. This is a desirable quality for some applications such as collision detection.

2.2 STL Format and Slicing Technique

A STL file is a format used by Stereolithography software to generate information needed to produce 3D models on Stereolithography machines.In fact, the extension "stl" is said to be derived from the word “Stereolithography”. STL is a file format native to the stereolithography CAD software created by 3D Systems. This file format is supported by many software packages. It is widely used for rapid prototyping and computer-aided manufacturing. STL files describe only the surface geometry of a three dimensional object without any representation of color, texture or other common CAD model attributes. The STL format specifies both ASCII and binary representations. Binary files are more common, since they are more compact. A sphere in STL format is shown below in fig 2.7

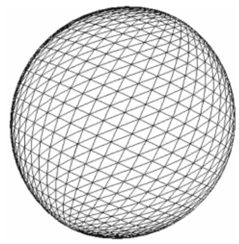


Fig 2.7 A Sphere in STL Format

A STL file is a triangular representation of a 3D object. The surface of an object is broken into a logical series of triangles (see illustration at right). Each triangle is uniquely defined by its normal and three points representing its vertices.

The file begins with a solid record, (which can include a name for the object), and ends with an endsolid record. Each triangle begins with a facet record and ends with an endfacet record. The normal vector, if given, is included as part of the facet record, and is identified by the normal keyword. The normal vector should have unit length. The three vertices of the triangle are delimited by outer loop and endloop records. Each vertex is described on a vertex record that lists its (X,Y,Z) coordinates.

An ASCII STL file for a four-face figure that's a slice of a cube would be:

```
solid cube_corner
  facet normal 0.0 -1.0 0.0
    outer loop
      vertex 0.0 0.0 0.0
      vertex 1.0 0.0 0.0
      vertex 0.0 0.0 1.0
    endloop
  endfacet
  facet normal 0.0 0.0 -1.0
    outer loop
      vertex 0.0 0.0 0.0
      vertex 0.0 1.0 0.0
      vertex 1.0 0.0 0.0
    endloop
  endfacet
  facet normal 0.0 0.0 -1.0
    outer loop
      vertex 0.0 0.0 0.0
      vertex 0.0 0.0 1.0
      vertex 0.0 1.0 0.0
    endloop
```

```
    endfacet
    facet normal 0.577 0.577 0.577
      outer loop
        vertex 1.0 0.0 0.0
        vertex 0.0 1.0 0.0
        vertex 0.0 0.0 1.0
      endloop
    endfacet
  endsolid
```

The facet record has the form:

* The normal vector, 3 floating values of 4 bytes each;
* vertex 1 coordinates, 3 floating values of 4 bytes each;
* vertex 2 coordinates, 3 floating values of 4 bytes each;
* vertex 3 coordinates, 3 floating values of 4 bytes each;

2.2.1 Binary STL File

A binary version of STL exists because ASCII STL files can become very large. The header of a binary STL file is generally 80 characters which should never begin with 'solid' because that will lead most software to assume that this is an ASCII STL file. A 4 byte unsigned integer follows the header indicating the number of triangular facets in the file. Following that is data describing each triangle in turn. The file simply ends after the last triangle. Fig 2.8 shows a sample binary STL file.

Each triangle is described by twelve 32-bit-floating point numbers: three for the normal and then three for the X/Y/Z coordinate of each vertex - just as with the ASCII version of STL. After the twelve floats there is a two byte unsigned 'short' integer that is the 'attribute byte count' - in the standard format, this should be zero.

```
UINT8[80]          -   Header
UINT32             -   Number of triangles

foreach triangle
  REAL32[3]        -    Normal vector
  REAL32[3]        -    Vertex 1
  REAL32[3]        -    Vertex 2
  REAL32[3]        -    Vertex 3
  UINT16           -    Attribute byte count
end
```

Fig 2.8 A sample Binary STL File

Slicing models is now possible by a number of methods irrespective they were made in B-Rep, STL or CSG, but STL gives the easiest method so far. It also gives a far accurate, reliable result first time, every time. Due to the nature of the STL having no topographic data, there may be some or little problems with these files from time to time. Other errors like Gaps, degenerated facet, non manifold topology, overlapping occur in polygonal approximation models which are made by many commercial tessellation programs by various Cad vendors. Also, all the rapid prototyping machines available in the market not readily accept STL files. Some of them may require processing to be accepted. STL however is by far the most commonly accepted file for different rapid prototyping machinery in the world.

2.2.2 Flat layered Slicing

A new form of manufacturing emerged in the ‘80s with technologies starting to build parts layer by layer. This technology helped decrease the total time it would take for a product to be designed and built. Stereolithography apparatus, shown in Fig 2.9 is a good example for layered manufacturing.

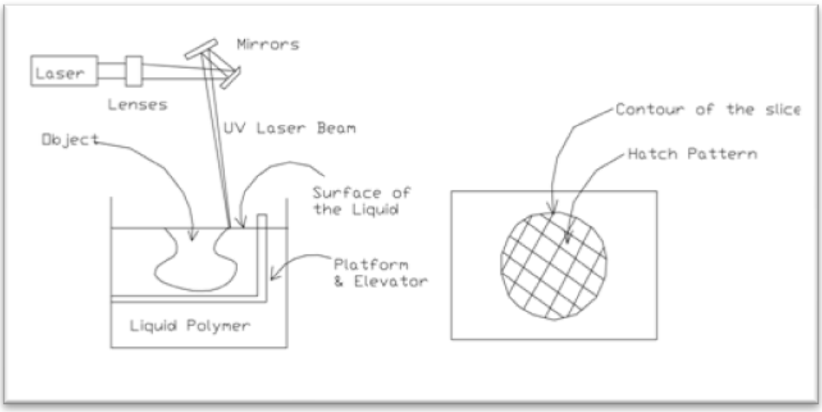


Fig 2.9   Stereolithography Apparatus

A set of parallel planes are used to slice the model to be manufactured. A layer is the distance equal to the distance between two adjacent slices. At the start of the process the platform is placed at the very top of the surface of liquid and the gap being equal to thickness of the end layer. A laser is used which is used to scan the surface as per the contour required at that particular layer. The insides of the contour are then hatched using a unique pattern. Curing of material takes place when it is exposed to the laser beam. Photopolymers are chosen as materials for this reason. To add layers and to build the part, the platform is moved downwards. Once the part is prepared it is removed from the vat and the part is sent for its finishing. Post processing may generally include treatment by heat such as curing in a dedicated oven. This also helps in curing any remaining liquid in the part.

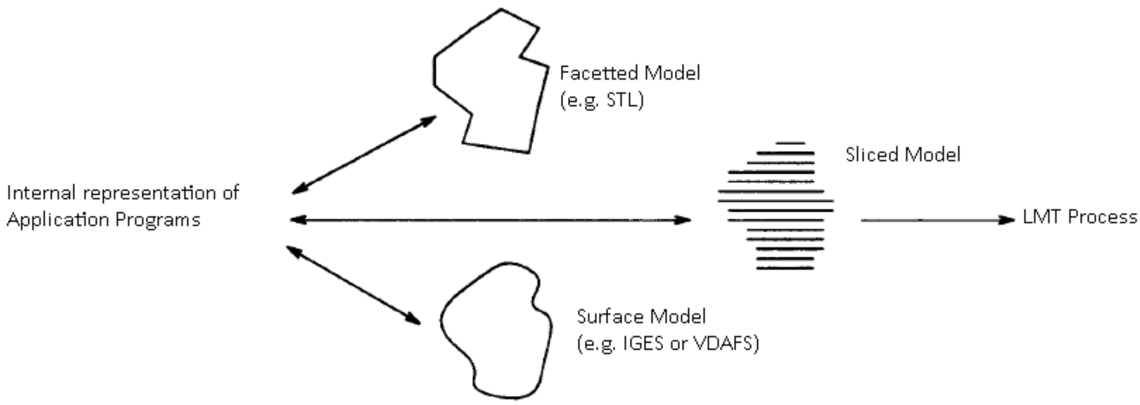


Fig 2.10 Transition States of model manufactured via Layered Manufacturing

Different processes may either vary with the type of material used or the type of deposition of material. Fig 2.3 shows the steps involved in transfer of data to these processes. These transitions show that formation of these states is easily possible. The different transition states of model manufactures via layered manufacturing are shown in Fig 2.10. Medical imaging systems give output as slices from which intermediate slices can be then interpolated to be used in a layered manufacturing process. In other cases, sliced models may not be acceptable so a facetted model (STL file) may be created and sliced. These factors depend on different machines and their capabilities to handle information.

2.2.3 Slicing Methodology

The STL model is primarily made from the cad model of the part required to be printed. As one of the very first steps, it needs to be sliced layer by layer at a particular angle. A number of two dimensional layers stacked on top of each other to build up a 3D model. Fig 2.11 shows an example of a sliced CAD file. The distance between the layers known as the Z thickness can be varied as per the requirement. This process may require a number if hit and trials as results are not always right the first time. Defects like inaccuracies, surface roughness tend to crop up due to an error called stair case effect which is prominent in this type of deposition technique.

The process of slicing starts with the proper positioning and orientation of the STL file. The file is then intersected with a number of parallel planes to slice it. The thickness of the filament which is to be used for deposition is taken as distance between every consecutive plane. The stl file does not have extra information on the inner geometries or details of the model as it is a triangular facet model, which means that the model is made up of triangles of different shapes and sizes. Information about the layer contour is obtained when the set of adjacent consecutive planes intersect the triangle-faceted wireframe solid model. A series of contour curves are obtained by this slicing process.

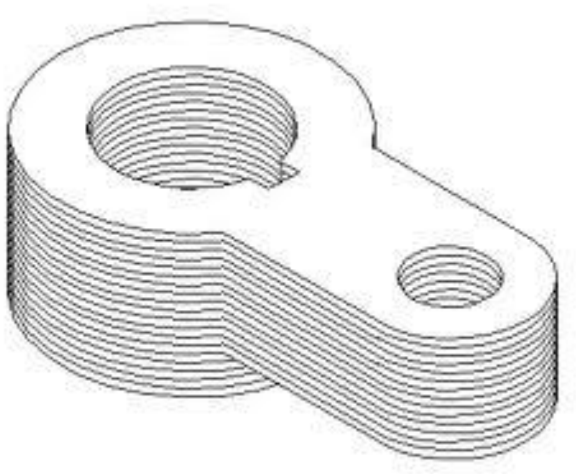


Fig 2.11 an example of a sliced CAD file

The main exercise of the slicing process would be to get the intersection points, as all the curves are made up of small sections of lines and planar triangles put together form the facets of the solid model. These intersection points are used in generating the tool path cutter information later on. The rapid prototyping machine is not able to point out which part is solid, because the resultant of the intersection just gives a set of lines. Lin et all in 2002 mentions that the counter clockwise and clockwise direction represent the outer and inner loops respectively. In simple terms, the contours of layers are what the rapid prototyping machine works on as a basis. The solid part is recognized as the left hand side of the contour and the positive direction of the contours follow the counter clockwise direction. The model is ready for processing and tool path generation once the solid part is identified.

2.2.4 Cutter path generation

Depending upon the rapid prototyping machine and software the part may require a support material as a base over which the Actual part is made. Small machines like Fab@home, Reprap due to their form factor have limited capabilities and so have to be given the stl model of the support unit if the main model requires a base for its existence. The tool path, which the machine will then use to build the model layer by layer, is dependent on the user. Depending upon the requirement of desired properties of the model in terms of surface finish, strength and build time the users also have a number of options in tool path to chose from.

At the very outset of generating the tool path information, it has been found that a number of vectors which are in unsorted state are available. These vectors are not necessarily in sequence and are also not connected. Because of which the layers cannot be identified by the rapid prototyping machine. These vectors need to be arranged in a form which can be then easily read by a rapid prototyping machine. The triangular facets containing a number of vectors in the same plane are connected with straight lines to each other.

The stl file contains triangular facets who share edges with other similar triangular facets. Lines are used to connect all the section points which makes the outer surface smoother and then forms the cutter path of the slice. The tool path pattern is dependent upon the choice of the user; it can both be set at 90Degrees or 45degrees and set the same pattern automatically for every layer. The tool path is created with larger air gap in the middle if the parts are to be hollow inside.

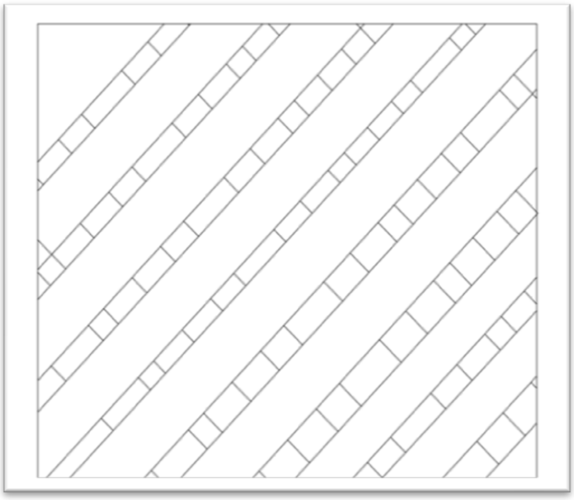


Fig 2.12 A model being printed with perpendicular tool path

However in between adjacent layers tool path patterns are usually set perpendicular to each other for better strength and performance. Fig 2.12 shows a model being printed with perpendicular tool path.

When the deposition nozzle is filling in the patterns or tracing the cutter path contours, the output condition is set to be “on”. When the deposition nozzle is moving from one layer to another or is in some kind of transitional state like either travelling home or safe position, the output condition is set “off” so that there is no wastage of material. Once the tool path is generated for the main model, the same for the support structure is created. This is done automatically by latest machines and advanced programming but in case of a small scale rapid prototyping machine txt files for each part and support material have to be made manually.

Once the required stl and/or txt files are ready containing tool path information it is then fed to the rapid prototyping machine. The machine is then set for its home, origin and safe positions before the printing is to be started. The part file is then imported, orientation is corrected if required and the part is ready to be started for printing.

2.3 Curved layer fused deposition modelling: Existing solutions

Most of the famous and reputed fused deposition modelling machines and systems running successfully are mainly printing in flat layers. There has been a lot of development in both software and hardware for flat layer fused deposition modelling (FLFDM). A number of algorithms have been developed for slicing which are able to produce a variety of models with complex shapes and sizes. However, not many have ventured into the area of curved layer deposition for fused deposition modelling (CLFDM). The research done at Auckland University of Technology in the recent times is only next to one of the first papers which talked about a slicing algorithm for curved deposition by Choudhary et al [25] in 2008.

For proper reproduction of path shape by curved layer fused deposition modelling, filament paths have to be determined. The filaments in a layer are all in a single plane in case of the conventional fused deposition modelling. Because of this, the adjacent filaments will have uniform superimposition over each other and so there would be a good unilateral bonding. However, due to the fact that adjacent filaments do not lie in the same plane in curved layer fused deposition modelling, proper lateral bonding becomes an important point to consider.

Filament location was so planned so that there is a constant bonding with the previous surface printed. A strategic plan chosen was to build curved layers from the bottom moving towards the top till the part is fully made. Initial point determination and correction of each point to satisfy strength requirement is used to determine filament cross section locations.

A graphic simulation is done based on the new approach used for curved layer fused deposition modelling. The inter layer overlap and overlap of adjacent filaments is observed. A significant amount of reduction in step stair effect in case of curved layer fused deposition modelling to that of a conventional layer manufacturing process was found. There was no continuity of filaments in many cross sections in case of a FDM created part. Also it was found that in case of a tensile force across, the curved layer part would span the whole extent of the part, quite opposite to a part which would be resisted primarily by the inter filament bonds when made with FDM; and hence the inter layers were considered to be stronger than the part generated by FDM.

It was also found that one layer is in contact above it through a thin annular area when made by FDM while in case of CLFDM, filaments were deposited with sufficient overlap with a suitable chosen chord of contact between tubes. This shows that the shear strength of a part created in CLFDM would be quite strong as compared to a part with very low shear strength made with conventional FDM process. Also a woven net like structure was made in curved layer fused deposition modelling which would provide strength uniform throughout the part. Similar improvements in FDM generated parts could be possible with cross rasterfill but it would hardly do any good do to better inter-layer adhesion properties. The main advantage of curved layer fused deposition modelling is in creating curved, shell type parts were parts made with normal, convention FDM methods may be of poor strength and surface finish. Employing longer filaments or roads and obtaining curved inter – layers of larger area per layer improved strength. Apart from strength, another main drawback of the conventional FDM process – step stair effect is also reduced to almost zero providing more accurate and desired parts. Initially, it may need capital investments for modification of tools and machinery equipment to suit this methodology but there would be also simultaneous gains like reduced build time and number of layers and even more as mentioned above.

A research study has been recently undertaken in Auckland University of Technology by Bin Huang [26], who has done preliminary investigation for developing a software procedure for curved layer fused deposition modelling. A detailed understanding of modelling of 3D surface, fitting a surface model and setting data points is required for the implementation of curved layer slicing. For its practical implementation, the curved layer algorithm needs to be integrated with a hardware system.

The most important task in developing a curved layer slicing algorithm is to gather important key point data. Accuracy of the data points from the surface translates to a solid construction of subsequent curved layers. Data generation from the surface can be done by any of the common methods like surface modelling, STL file and G and M codes. A Curved surface can be expressed either by using a mathematical model or by a series of data points. Mathematical models can be used to calculate surface point data. Based on key point data, computation and calculation of coordinates on any number of surface points is allowed by mathematical models.

The desired shape is first made with the choice of any three dimensional modelling application available in the market. Another method of obtaining a three dimensional model is by using a laser scanning machine. The three dimensional model is loaded into a manufacturing software. This software then generates the g and m codes on basis of top surface of the part. To get the actual motion of a deposition nozzle, the 3axis milling simulator mode is chosen to generate the g and m codes. The diameter of the nozzle head is given as the size of the ball cutter.

Different software’s in the market may do this kind of output generation which is desired but they key is to get the correct data which needs to be used in deposition. To overcome this, the files may be stored in a similar extension which can be read or interchanged between two or three different software’s like STL, IGES, etc. The g and m codes help us to give the required co-ordinates of the surface points which can be then saved. The manufacturing software also gives a lot of instructions pertaining to the milling of the part which may not be exactly necessary in our case. To avoid any no movement phase of the machine, the parts not necessary for the rapid prototyping machine are removed from the text file. This file is then ready for the slicing program.

The term STL is derived from the name Stereolithography and is one of the most commonly used files in the field of rapid prototyping. A STL file is actually a part model which resembles a wireframe model consisting of triangles. A triangular mesh is used to represent a face or side of the part model. A STL file can easily be generated once the solid model of the desired part is ready. It can be hard to get point data as the stl file is mainly in a binary form. A MATLAB program is used to gather the coordinates of vertex of these triangles. The program then generates a surface data which is again processed in MATLAB and a STL output file is then created.

Parallel curved slices need to be developed after surface point data (text file) is obtained by one of the methods explained above. Bin Huang developed the vector method, by proceeding with two vectors first and gradually evolving towards a four vector approach [26]. These methods are briefly reviewed here for the sake of continuity.

Vertical surface offsetting algorithm - In this type of algorithm, the surface is offset to construct the sliced layers and the tool paths. A new layer made by lifting each point by a distance from its original location and same is repeated till the whole surface is generated.

Two vector cross product algorithm - Cross product of two vectors is employed for developing this algorithm. X and Y along with the Z co-ordinates of all the surfaces are changed. The direction of cross product vector is used as a basis for the co-ordinates of the new surface points and their locations. There was a mild improvement from the defects in vertical surface offsetting in this algorithm but it was deemed fit for similar thin parts only.

Four vector cross product algorithm - The four product vector is similar to the two product vector as in this, cross product of four vectors are employed to construct the algorithm. Even though it was an improvement from the vector surface algorithm and the two vector cross product algorithm, and may be used for similar thin parts only.

Modified four vector cross product algorithm - The modified four vector cross product algorithm is a variant of the four vector cross product algorithm in which an auxiliary vector and two vectors on the surface are used to construct the cross product vector. Because of its stability this algorithm was chosen to be a good solution for slicing of curved layer models.

The modified four vector cross product algorithm was chosen as the best for constructing slicing models, there were a few issues like self intersection and duplication of points which needed to be addressed. To overcome this, each surface point is to be provided with additional data. Different combinations of 1's and 0's in the extra information column would mean the different possible motions of the deposition head. Another drawback from the modified four vector cross product algorithm is that when two or more points on the deposition path are repeated. Due to this, the machine may tend to deposit more material in the repeated set of points assuming they are different set of points. To avoid this repetition of points a module check is developed which scans all points in each layer and compares it with coordinates of each pair of consecutive points. During this if two consecutive points are similar; one of them is dropped from the database.

2.4 Current method used for slicing and deposition

For the purpose of this research project, two models are chosen for producing curved layer parts and their testing. The first of these models is chosen to explain the concept of slicing procedure being used to print and test the part. The main part (Fig 2.13) and its support structure (Fig 2.14) are as follows:

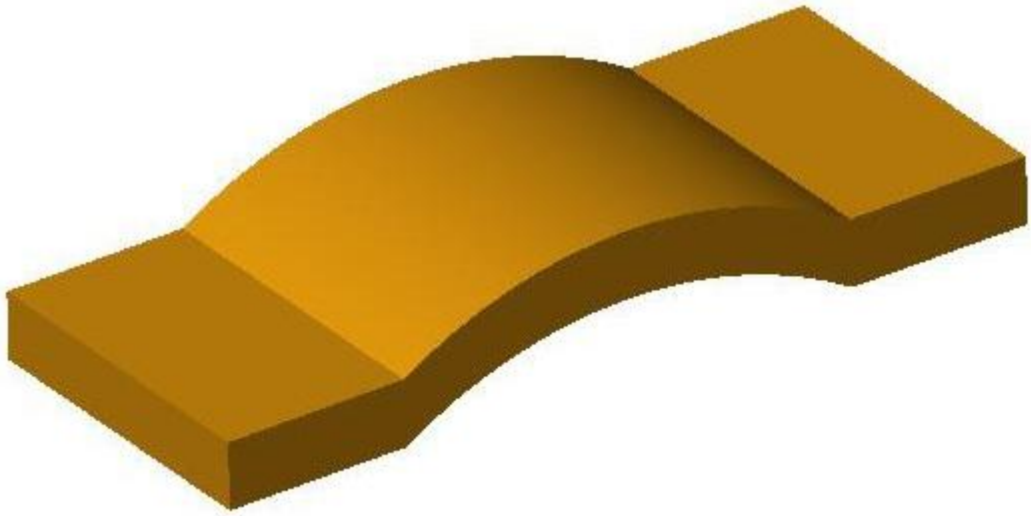


Fig 2.13 Main Part

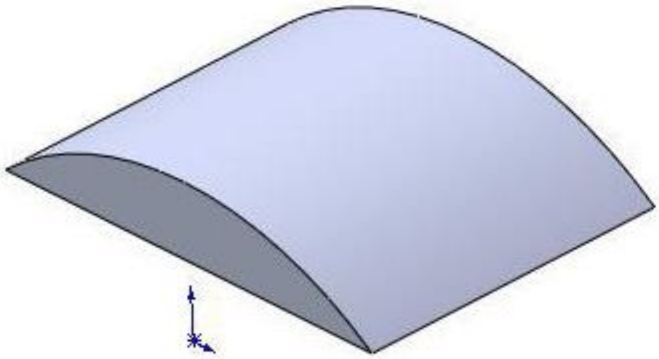


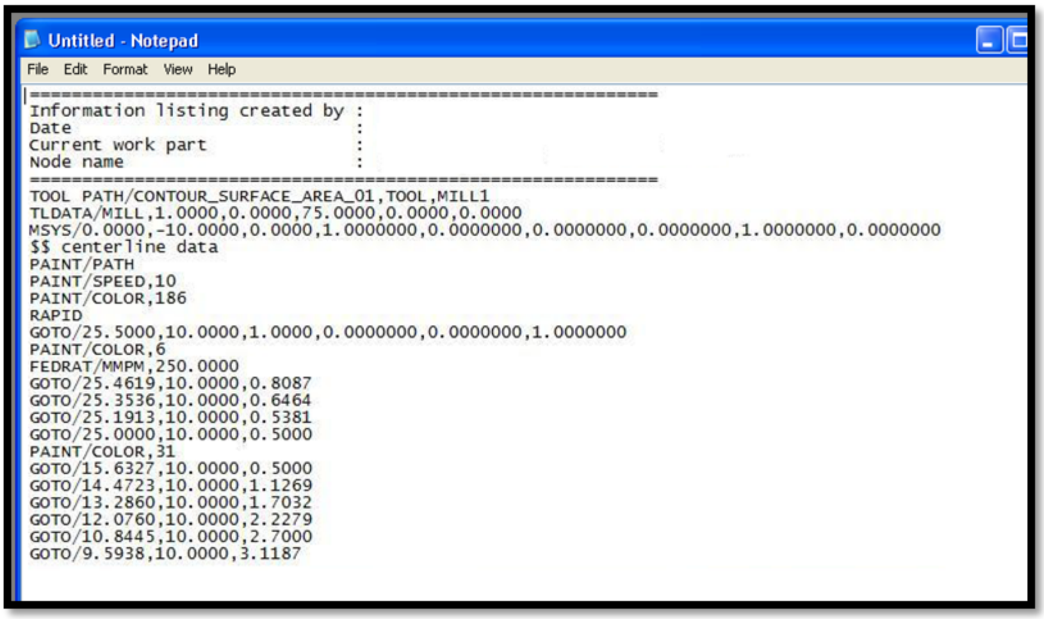
Fig 2.14 Support structure part

To print a part shown in figure 2.6, it is first modelled in Solidworks. The part has a hollow part in the centre of its body which means that it cannot be printed as a standalone part; because once the deposition is started the nozzle would be printing in air. And due to this reason a support structure for the part is to modelled and printed first. Once the support part is ready the main part can then be printed on top. A flat layer support structure can be printed for this purpose.

The flat layer support can be either printed by either slicing the bottom surface of the part or using STL files exported straight out of the modelling software. In this project both these methods are tried for statistical purposes. The later method of printing is fairly a straight forward approach in which the part is first modelled in solidworks as per the desired dimensions. This is then saved as a STL file – which is a feature included within all modelling software's. The STL file can be then imported into the user interface software of Fab@home machine. Once imported into the software, it is oriented in the right direction, machine is set for origin and home positions and it is set for printing.

2.5 Printing the Main part

Once the support structure is ready, the next step would be to print the main part on top. After the modelling, G & M codes of the model are to be developed using a computer aided manufacturing software. The milling operation with a flat cutter is chosen for this purpose as it's the closet choice available for our process of deposition. The diameter of the nozzle head is used as a reference diameter of the cutter. The program is run which generates the tool path data for the whole part. This is then recorded by the software and the output can be then exported as in Fig 2.15 below:



Untitled - Notepad

File Edit Format View Help

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============================================================
Information listing created by :
Date                           :
Current work part              :
Node name                      :
============================================================
TOOL PATH/CONTOUR_SURFACE_AREA_01,TOOL,MILL1
TLDATA/MILL,1.0000,0.0000,75.0000,0.0000,0.0000
MSYS/0.0000,-10.0000,0.0000,1.0000000,0.0000000,0.0000000,0.0000000,1.0000000,0.0000000
$$ centerline data
PAINT/PATH
PAINT/SPEED,10
PAINT/COLOR,186
RAPID
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FEDRAT/MMPM,250.0000
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GOTO/25.0000,10.0000,0.5000
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GOTO/10.8445,10.0000,2.7000
GOTO/9.5938,10.0000,3.1187
```

Fig 2.15 Cutter Path Data

As this text file is to be used with the Fab@Home machine, a lot of information in the file may not read by the machine and hence is not required. These are mainly the tool path, contour and speed data etc. This file may be edited by using “Notepad” or any similar word editor available in the Computer’s operating System. This file containing the raw coordinates of the part is now ready to be processed with the modified four vector cross product algorithm which was explained above. This is done with MATLAB – mathematical analysis software. Once the modified four vector cross product algorithm is run, the tool paths are tested and consecutive curved layers are found. The coordinates of all the surface points on the curved layers are obtained and the output is saved in .txt format which can be then used as input to the Fab@Home machine.

Chapter 3

Experimental Setup and materials

3.1 Fab at Home as a Rapid prototyping test bed

Fab@Home model 1 is a three axis gantry positioning system which is powered by stepper motors. It mainly consists of:

- Chassis
- 1-Syringe Tool
- 4-Axis Electronics
- Firmware
- Application
- USB Drivers
- Style options

These stepper motors are further attached to lead screws. The tool used for deposition is syringe based. Right on top of the syringe is a stepper motor which is responsible for the movement of the plunger and material deposition from the syringe. The electrical board provides 24 V energy to the four stepper motors. Along with this are two limit switches for each axis and an optional one limit switch for each of the axis. A microcontroller is used to control the positioning of the axes and is connected to the PC with a Universal Serial Bus connection. A graphic user interface comes with the software and also available on Fab@home's homepage establishes the user connection and allows the control of the machine to manoeuvre and operate the machine.

The main body, structure and components of the Fab@Home machine are made from acrylic sheets which have been laser cut as per the dimension desired as per design. It uses a t-nut style fastening method, high manufacturing tolerances improves the reliability of the machine. For linear motion of the positioning system, linear ball bearing blocks of half inch diameter rails are used. The deposition tool rides on the Y axis which rides on the X axis in a gantry configuration. The z axis moves the building platform independently to the other 2 axis, this helps in minimum movement of parts while they are being made. External polymer lead nuts are mounted to the axes carriage. Timing belt and pulleys are used to couple a slave lead screw to the motor lead screw to achieve a symmetrical drive in case of the x axis.

A microcontroller with a universal serial bus 2.0 peripheral, the Philips LPC-2148 ARM7TDMI is used with this machine which provides the main channel of communication between the machine and the user. It is a high performance 60 MHz, flash based micro controller with 512kb flash memory and 40kb of RAM. The large Random access memory available helps to buffer motion commands so that real time motion is not affected. The universal serial bus powers the microcontroller and so communications are intact even when amplifier electronics are not powered. A xylotex 4 axis stepper motor amplifier board is used to power the syringe tool stepper motors and the positioning system. This board provides switch mode current regulation for 4 stepper motors per board.

The microcontroller’s firmware was developed in C language using a software called Crossworks. The firmware provides some very important function like

- Configuration of limit switches (present/absent for each axis and direction)
- Communicating axes positions and other system status to the PC via the USB
- Controlling step and direction outputs for up to 6 axes.
- Receiving and syntactic analysis of packetized commands from the PC via the USB
- Buffering of motion path segments for fabrication paths
- Immediate execution of jog motion and emergency stop commands

3.2 Development of Fab@Home machine

The project begins with the procurement of the Fab@home kit from Koba industries, based in Albuquerque, US which essentially means that the kit contains everything required for the setup. The Fab@home machine can also be built by buying the fabber and the parts separately. Being an open source code machine and the design of the structural components and everything required is available and hence the body can also be cut to dimensions with a laser cutting machine. With a good amount of planning and pre-preparation the assembling of the fab@home machine can be relatively straight forward. The fab at home wiki website [27] is a good source of information in terms of the materials required and the whole method for assembly. Once all parts and tools required are available, the Fab@home can be put together in about three to six days depending upon the competency of the person putting together. The breakdown of steps required to put together the Fab@home machine is as follows –

- Get the required parts and tools
- Build the XY and Z Carriage
- Build the deposition head
- Assemble the chassis
- Build the cables and assemble with electronics and the machine
- Program the microcontroller with model 1 firmware
- Install the Fab@home model 1 software on the PC
- Commissioning and printing parts

The most important parts and assembling features are discussed below.

3.2.1 The Deposition Head

The deposition head, which is also known as the model 1 syringe tool is the main part responsible for the deposition of material and building a part or a support structure. It consists of a syringe barrel, tips and piston which houses the material used for deposition. The deposition head is shown in fig 3.1 below.

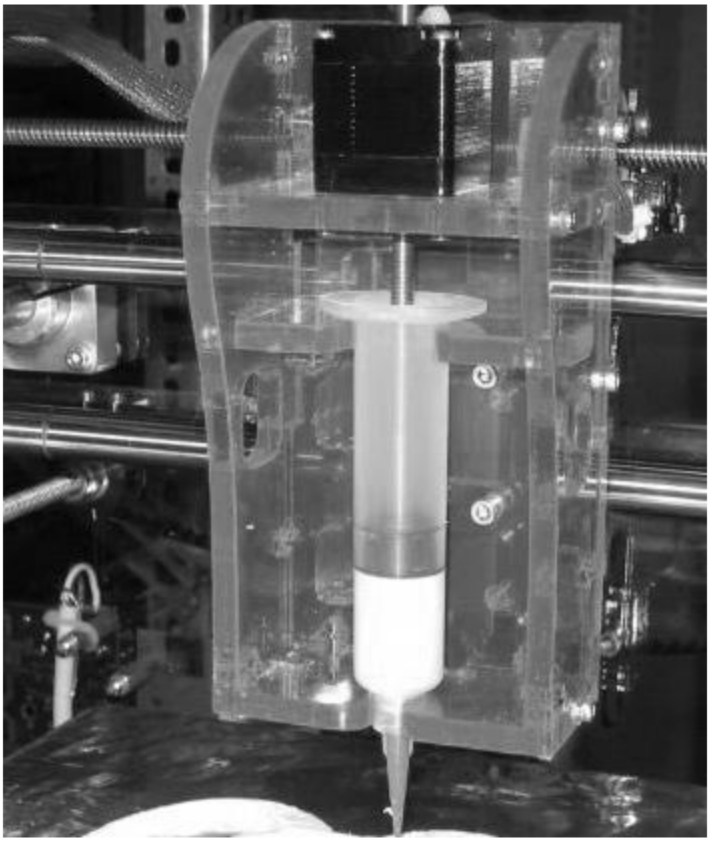


Fig 3.1 The deposition head

At the top of the syringe casing is an acrylic board on which the syringe stepper motor is mounted. The stepper motor is used for controlling the position of the syringe piston, which is the main reason for material flow. The body is then put together with the acrylic cut sheets available. This is done by fastening the sheets together with screws and nuts. A 10cc syringe barrel and tip from Nordson, EFD is used to be placed in this deposition head. The stepper motor is inserted with a lead screw at the end of which is a shaft collar and shoulder screw. This lead screw is driven by the motor which in turn pushes the material out the nozzle tip at the end of the syringe barrel.

3.2.2 Assembling the chassis

The chassis is the most important feature of the Fab at home machine, as it is the body and it contains a mixture of several sub assemblies:

- The machine base, which holds and encloses all of the other subassemblies

- An XY-Carriage which moves the deposition tool along paths within the XY-plane to build the layers of the part
- A Z-Carriage which positions the build surface vertically relative to the deposition tool

The carriage's mentioned above are assembled individually and these are put together to form the chassis for the fab at home model 1 machine. The chassis of Fab at home is shown in fig 3.2 below.

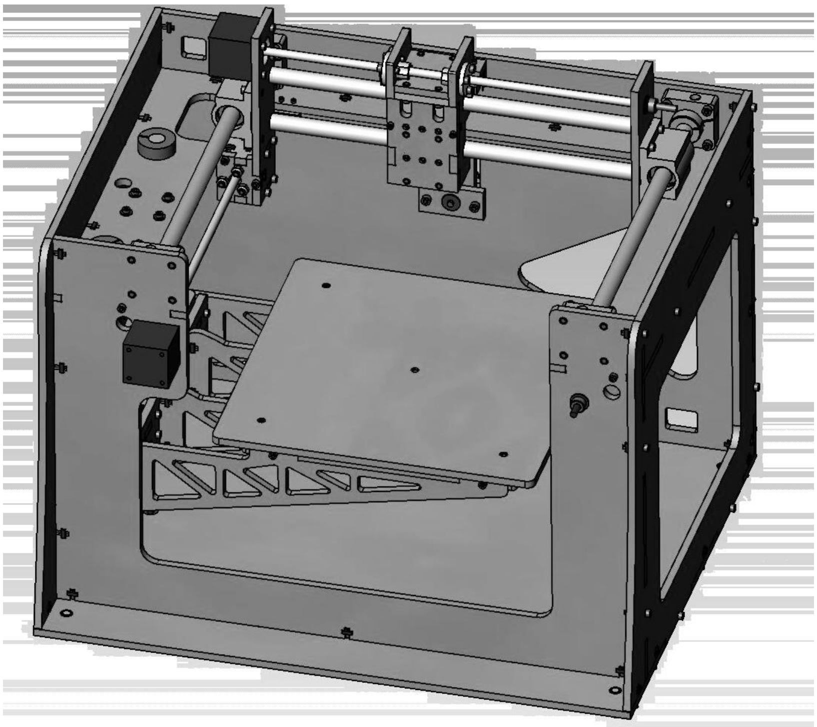


Fig 3.2 Fab at home chassis after assembly

The Z carriage is mounted on the bottom of the assembly and the XY carriage mounted on top of the base assembly. Threaded bass inserts are available on the base which facilitates the mounting of the carriages. Also fastened to the base are the stepper motors, which are placed at the end of lead screws and connected to the XY and Z carriages.

3.2.3 Assembling Electronics and cabling

The model 1 fab at home machine consists of the following electronic parts and components:

- Elpac MW4024-760-NC-WH 24VDC Power Supply
- AC Power Cord for Power Supply
- Olimex LPC-H2148 Microcontroller Board
- Xylotex XS-3525/8S-4 4-Axis Stepper Motor Amplifier Board
- Winford Engineering DB-25 Breakout Board
- Omron D3M-01K3 SPST-NC Limit Switches
- Limit Switch Cables
- Ribbon Cables to connect the LPC-H2148 to the other devices
- USB Cable to connect LPC-H2148 to the user's personal computer

Xylotex XS-3525/8S-4 4-Axis Stepper Motor Amplifier Board

The stepper motors of the deposition head and positioning system of the fab at home machine are given control signals and power with the help of this Xylotex stepper motor amplifier board. It is designed with a set of screw terminals to allow simple connection of devices to any auxillary input/output signals coming onto the board via ID26 connector.

These terminals are used to connect with limit switches, which will then travel to the olimex microcontroller board via the IDC26 to DB25 cable, through winford board and then over the ID26 cables to the microcontroller. This stepper board is a 4 axis pulse width modulated current controlled bipolar micro stepping controller with each axis driver having a +- 2.5A/phase at 35volt maximum continuous output rating. Each axis accepts direction and step signals and alongside is two jumper inputs to define micro steps per full step.

Olimex LPC-H2148 Microcontroller Board

Signals and instructions between the fab at home software and the hardware are interchanged with the help of the microcontroller board – Olimex LPC-H2148. This microcontroller is allocated with a large random access memory which enables for motion commands to be buffered.

There is a USB connector on one of the sides of the microcontroller which can be used to connect direct with a computer for the transfer of signals and information. To program this board a provision of connecting with a Jtag adaptor is also given.

JTAG adaptor cable, Programming the microcontroller and Firmware

A JTAG adaptor cable is mainly used to code software onto a LPC-H2148 microcontroller which works within a firmware development environment. The JTAG adapter is currently not a part of the standard kit set of the fab at home machine model 1. For programming the microcontroller, software called Crossworks is required which involves connecting it with the computer with the help of a JTAG connector. At the moment, Rowley crossworks is known to be compatible with only two JTAG adaptors; a) Parallel port to ARM JTAG adapter and b) USB to ARM JTAG adapter from Rowley. As the available options are not the best options available it was chosen to make one ourselves.

To program the microcontroller, the Rowley Crosswork for ARM chip support, Fab at home firmware drivers were downloaded and installed on the computer. To begin programming the microcontroller is first connected with the computer via the JTAG adapter.

Once connection is established, Crossworks software is fired up. Now the Fab at home firmware and the workaround dummy project are opened from the “file > Open solution” option on Crossworks. A few other steps are followed as per the fab at home manual procedures and the firmware is flashed onto the microcontroller. The microcontroller is now disconnected with the JTAG adapter and ready for working with the Fab@home machine.

The software which runs on the LPC2148 microcontroller is essentially called the firmware and is written in C language using software called Rowley Crossworks for ARM. The manufacturer of the microcontroller preloads a simple demo firmware which needs to be replaced with our Fab at home firmware. The main channel of communication between the Fab@home machine and the computer are through the firmware. It is used in receiving, transmitting information from the software which is then forwarded on to the Fab@home machine. This information is then used by the Fab@home machine to achieve the co-ordinates and positions as commanded by the user.

Winford Engineering DB-25 Breakout Board

The main function of the Winford Engineering Breakout board is to ease the communications between microcontroller and the stepper motor diver board. On any signal, the Winford Engineering DB-25 breakout board allows a maximum of 2.25A and two hundred volt maximum between any two signals.

The DB-25 Breakout board is used to connect the tow ribbon cables (which were prepared earlier) with the microcontroller and it also connects the DB-25 to IDC 26 Ribbon Cable with the stepper motor driver board.

Assembling the Electronics to chassis

The electronics mentioned above – Xylotex XS 3525/8S-4 Stepper motor driver board, Olimex LPC H2148 Microcontroller board, Winford Engineering DB-25 Breakout Board, ELMAC Power supply, AC Power cord, limit switches are connected all together with a help of a detailed schematic diagram given at Fab@home's wiki database. The boards are first mounted on to the chassis and using the available wires and the wiring diagram, the assembling is carried out. Once all the electronics are assembled as per the schedule it would look as shown in Fig. 3.3.

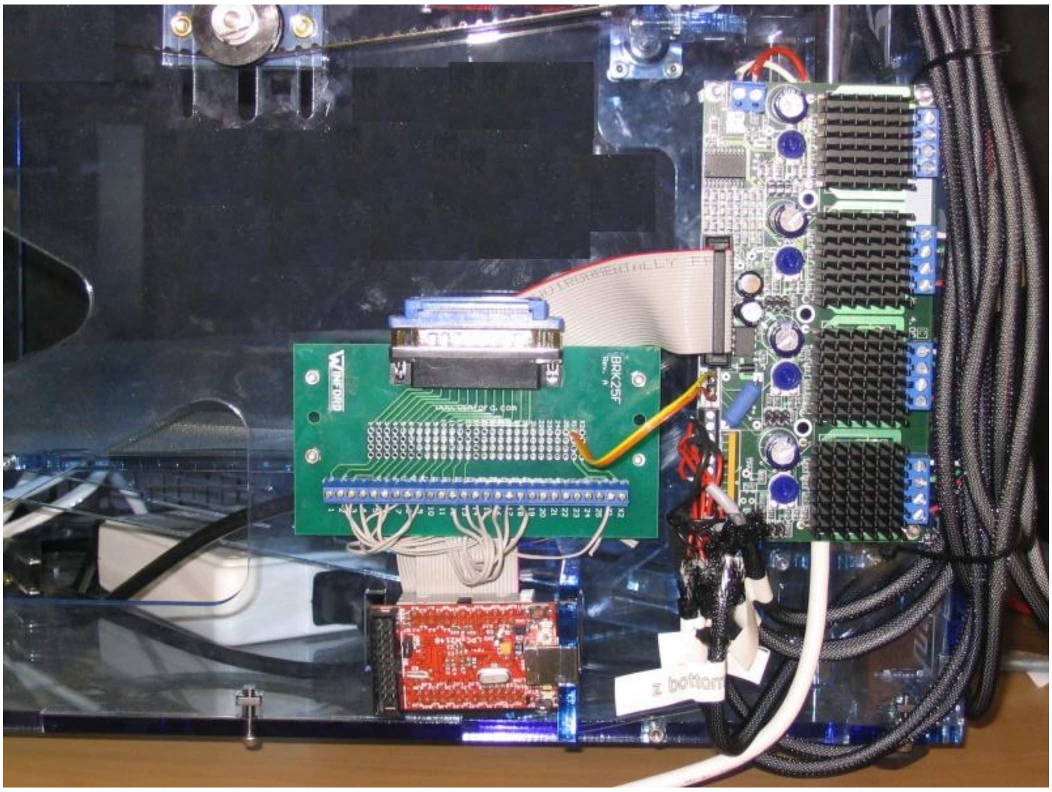


Fig 3.3 Electronics – Assembled view

3.3 Fab @ home Installation and commissioning

After all the parts of the chassis and electronics are fully put together, some final minor assemblies of the last stage are still left to be completed, some of which are – levelling the z table, adjusting the motor current, mounting the belt, truing the XY Carriage etc. To ensure that the two sides of the X axis are driven at the same speed, the belt is mounted. This is done so that perpendicularity between the X and Y axis is maintained at all times. Also, to ensure that X and Y rails are perpendicular to each other, X rails are parallel to each other, Y rails are parallel to each other, truing of the XY carriage needs to be done. To prevent the motors to be overheated the current passing through the motors needs to be regulated and hence the motor current needs to be adjusted. To allow the table to be in level with respect to the XY carriage, levelling of Z table is necessary. For the deposition tool to maintain a constant distance from the table during the deposition of material, it is imperative to have the XY plane parallel to the Z table.

The relationship between test points and potentiometers are derived from xylotex's website. The value of Motor current may be defined as equal to .69 times the value of voltage available.

3.3.1 Fab at Home Machine Driver and PC Software Installation

For the computer to accept the Fab at home machine as a new hardware and to run it, specific drivers and software's are required. The Fab at home wiki website is a good source were all necessary software and drivers are available and can be downloaded. A universal serial bus cable may be used to connect the computer with the fab at home machine. Once the machine is turned on, the computer detects that a new hardware was plugged in and requests for the location of the drivers, which is then given. Once all the required drivers are installed, the machine is set to be controlled upon by the user.

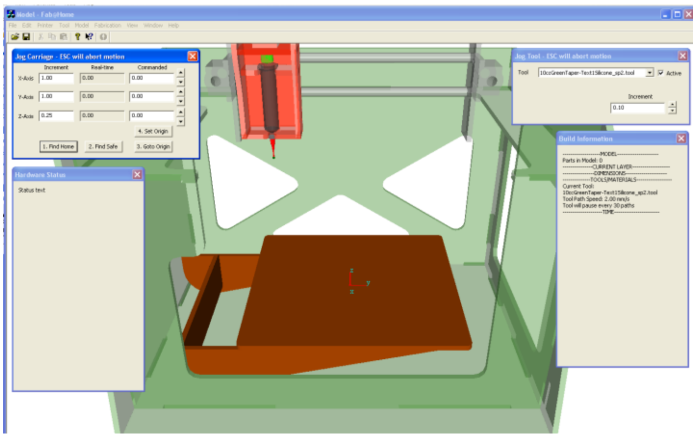


Fig 3.4 Fab at Home software – User Interface control

The fab at home graphic user interface shown above (Fig 3.4) is created using open gl graphics rendering which is initially written in c++ in Microsoft visual studio. Having been made in a windows environment, right now the software runs only in the recent Microsoft operating system family. This interface helps to paint the true physical motion of the fab at home machine at any time along with the synchronised motion of the graphics. The software communicates with the fab at home machine through a universal serial bus cable connected between the PC and the machine. The fab at home software has a provision for accepting .stl and .txt files which are the two main formats used to import cad models desired to be printed. Within the software, there are a lot of possibilities for manipulating the Cad file, like the alteration of scale of the output model or position of the model on the deposition table, etc. After the Cad file is imported, the tool and material properties are applied. The material is now ready to be deposited in the shape of the model desired to be printed on the deposition table. The fully assembled machine looks as shown in Fig. 3.5.

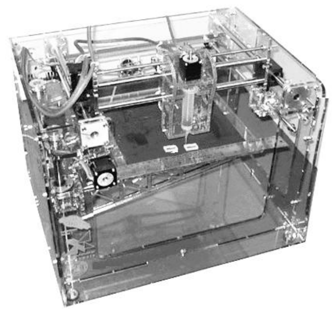


Fig 3.5 The fully assembled Fab at home in operation

3.4 Material characteristics for FDM

One of the main properties of a material to be used with the test bed like fab at home machine, is that material to be used has to be thixotropic, i.e in a semi solid state which will enable a continuous, uninterrupted flow through the syringe barell. The strength, mechanical properties of the end part is quite dependant on the bonding between the individual strands or filaments. An investigation was done by Celine et al [28] on the bond formation of parts made with a fused deposition modelling process. The FDM process is analysed thermally and dynamics of bond formation between filaments were evaluated by sintering. The results obtained from heat transfer analysis and experimental data from sintering was used to study the degree of bonding in the filament deposition process. It showed that the envelope temperature had little effect on the neck growth than the extrusion temperature did.

An investigation was conducted by Ker ching ang et al [29] to find out the bonding relationship and mechanical properties of structures formed by FDM processes. The team have basically studied the effects of the FDM processes and its direct impact on the mechanical properties and porosity of a scaffold structure made with ABS plastic. With the help of Design of Experiments, these parameters were examined by varying the main FDM parameters like build profile, raster width, air gap etc. A number of samples were printed and compressive strength and modulus data were collected. It was found that raster width and air gap were the most important parameters effecting mechanical properties of the scaffold structures.

A study similar to the above investigation was carried out to study the mechanical behaviour of ABS materials made with FDM processes. Jose et al [30] did this by dividing the experimental studies in two parts – first by finding out the mechanical properties of the feedstock material and the next by studying the mechanical properties of ABS materials with different mesostructures. Tensile, torsional tests were performed on the test specimens and it was found that the stress-strain response had quite an effect due the mesostructural influence. Voids and loss of molecular orientation during fused deposition extrusion were found to cause reduction in strength with fused deposition processing.

3.5 Materials and Deposition

Testing of Materials

For printing parts with the Fab@home machine, a number of materials were tried initially to check their response, flow rate, compatibility with the deposition style etc. For printing a part in the Fab at home machine, a number of factors are to be considered:

- Speed of deposition
- Granular size
- Material feed rate
- Path interval
- Fluidity of the material

After considering the preliminary requirements, and considering a number of materials which may have a flowy nature but harden when cured for a number of hours, RTV Silicone (Fig 3.6) was found to be a suitable candidate fit for this purpose.

Fig 3.6 RTV Silicone

The RTV silicone is basically a household sealant and an adhesive. It is a one part material which hardens to a certain degree when cured. The RTV silicone can be chosen in a number of colors bronze, beige, black, white and also transparent. Due to its nature it was found fit to be used with the deposition syringe and tip within the Fab@home machine. Silicone is chemically inert and can withstand high temperatures of up to two hundred degrees. It is usually fully cured within a day's time and is tack free in one to two hours per mm of thickness of material deposited. Once cured, silicone turns into a flexible rubber like semi-soft, stretch-able material. This property of silicone can be used to make different parts, moulds of desired shapes and sizes.

3.5.1 Silicone with other materials

Owing to silicone's suitable properties, it was used as the base material and a number of other materials were added to silicone to test if it would improve the properties of silicone and if it were fit for research and strength testing purposes. Various combinations are tried and a few of the results are as follows:

1) Silicone and Epoxy - Epoxy when added to silicone makes it denser but still maintains the ability to be deposited using the syringe in the test machine.
   Inference – The material cures faster than silicone when used alone but the end part created is still flexible and not fit for strength testing purposes.

2) Silicone and Epofix Hardener - Epofix came out to be very strong with silicone as the mixture hardened and it lost the fluid characteristics needed for depositing the material.
   Inference – The mixture hardened even before it could be put into the syringe and hence a part could not be made with the test bed.

3) Silicone and saw dust – Saw dust was powdered to best possible extent to get fine granules. They are then mixed with silicone. Initially it became hard but it was still fit to be used with the syringe for depositing the material.
   Inference – During deposition there were some patches when the material would get stuck at the tip of the nozzle due to the saw dust, but pressure from the plunger would keep the deposition going. On curing it was found that the hardness of the part had improved but it still retained the base properties of silicone and was a flexible rubber like material.

4) Silicone with grinding powder – Grinding powder was chosen as they are finer in their original state compared to saw dust. They are mixed thoroughly and filled into the syringe to be used on the test bed.
   Inference – After printing the part and left for curing the model turned out more or less exactly same as it would have with silicone alone. The powders

did not have any impact or made any difference to the end part as it was still rubber like.

5) Silicones, grinding powder, epoxy and epofix hardener – A combination of the materials tried above are chosen and put together with the base material, silicone.
   Inference – The mixture became hard quite quick and so it became a hard lump with no fluid properties required for the syringe. It was not possible to make a part through deposition and test it in this case.

6) Gypsum plaster and epoxy – A combination of plaster and epoxy are mixed together to be tried with the test bed.
   Inference – This combination gave good results on curing and it could be used to make small models and parts. However, these parts are not that hard for strength testing purposes.

7) Gypsum plaster, epoxy and epoxy hardener – Epoxy hardener was chosen to add to the above combination to check if epoxy hardener can improve the hardness properties we desire.
   Inference – Similar to the previous model, this model proved good for making small, temporary models but they were found to be too brittle and hence not fit for any mechanical testing.

From the detailed experiments shown above, it is found that silicone stays the same even when mixed with a number of materials and it does not lose its property. Any material when mixed with silicone will always end up retaining the properties of silicone and the resultant material is a rubber like, flexible material which is not desired for making parts or as an alternative to ABS plastic. Some materials when being mixed had very less curing time and so they lost the fluid property of a material required when being used in the machine and so they became quiet hard rubber like material. This is not good for any material expected to flow out from a small tip of a nozzle without any presence of external heat source, similar to what exists in the

Fab@home machine. Since our requirement was not fulfilled, the search for a suitable candidate for deposition and testing continued.

3.5.2 Fabepoxy

Fabepoxy is an epoxy based, light weight, two part material created by a company especially for the Fab at home machine. It has been formulated in such a way that it has a creamy paste like consistency, as this is a primary requirement for the standard deposition syringe and nozzle setup of the Fab@home machine. It has been designed to be thixotropic and has a good two – three hour time bracket before it starts to harden.

Fig 3.7 Fab epoxy tub and tube forms available for use with the Fabber.

Fig 3.7 shows different forms in which Fabepoxy is available. Fabepoxy is non sag, no solvent mixture which does not shrink during or after the cure. This gives a good amount of time if a syringe is meant to be fully filled with material for printing 2-3 parts at one stretch. As long as the part is in room temperature, it can take upto one full day to fully cure for the fabepoxy to become a rigid hard material. The curing time can also be fastened by increasing the temperature during curing.

Clearly as per the options discussed above, Fab epoxy and silicone are two materials which are best suited for printing considering all the limitations and properties desired for using with fab at home machine. They can be used for printing both support structure and the actual part as required but considering the price and availability, its chosen to use silicon for all support structure requirements and use fabepoxy for printing parts alone. These materials may not be the very best for printing materials to be used in places which require long life but are a very good alternative for testing, research and development purposes.

3.6 Printing of parts on the test bed

Once the Fab@home is all set and the materials are all decided, next step is to run demo prints of different parts and support structure. This helps to find out about defects in the machine or printing methodology, if any in advance. It will also help to optimize the working of the material deposition head and the positioning system. It will also help to verify if the material is being deposited as per the programmed tool path. This is very important as the software uses the .txt files to communicate tool path data with the machines which are used to print the part. Other important information like the rate of deposition, total no of layers, number of layers remaining to print, current position, approx time left to complete the print etc can be known from the deposition software.

Before starting to print the material all connections are checked and referred to with their schematic schedule – this helps to keep errors to the minimum. A universal serial bus cable is connected between the computer and the Fab@home machine. The machine is switched on, the desktop program is initiated and the machine's origin, safe and home location is first set before starting the deposition process. The .stl or the .txt file (depending upon flat or curved layer) is then imported into the machine software. The part is then oriented into the right position in the software and moved if required. Various other parameters of deposition head and the machine, the deposition cycle are checked. Once the stage is all set, the machine can then be given to start printing.

For the preliminary test and evaluation purposes, random models with different shapes and sizes are selected and are printed with the machine. The test models are printed using the two suitable materials – the silicone and the fabepoxy. Variation in their shapes and sizes gives an idea of the limitations, problems which may crop up during printing. Some test samples are shown below in Fig 3.8

Fig 3.8 Test samples printed with silicon and fabepoxy

3.6.1 Printing Flat and curved layer parts for testing

To print the flat and curved layer parts, a thin shell-like part shown in Fig.3.9 is selected. This requires a support structure to be printed as the shape chosen for the main part has a curvature in the middle beneath which is a hollow semi circular area. If we were to print this part straight without the support, when the deposition tool raises in Z axis to meet the curvature required for the model, the material coming out from the nozzle would hit the deposition table straight and so the desired shape cannot be produced. The main part remains the same for both flat and curved layer deposition as these two methods of printing, their differences in properties and strength are to be compared. The shape being the same, the support structure for the main part is the same and can be printed in either flat or curved layer style printing as desired. The main dimensions is 50mm L x 20mm W x 8mm H.

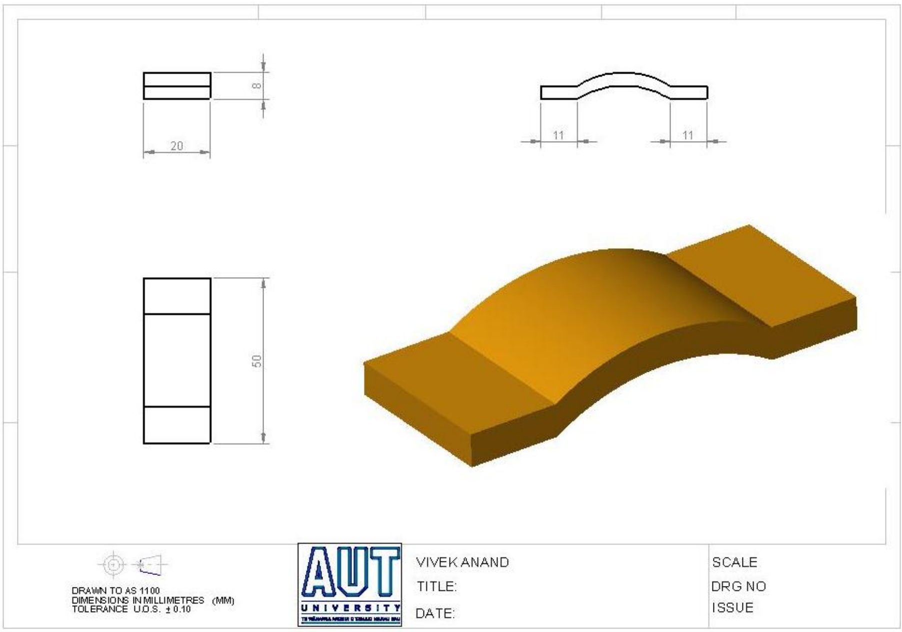


Fig. 3.9 Main Part structure

The first and the most important part of the whole part is the support structure (Fig 3.10) which acts as the foundation of the main part. The part is a small curved section, over which the main parts are to be printed.

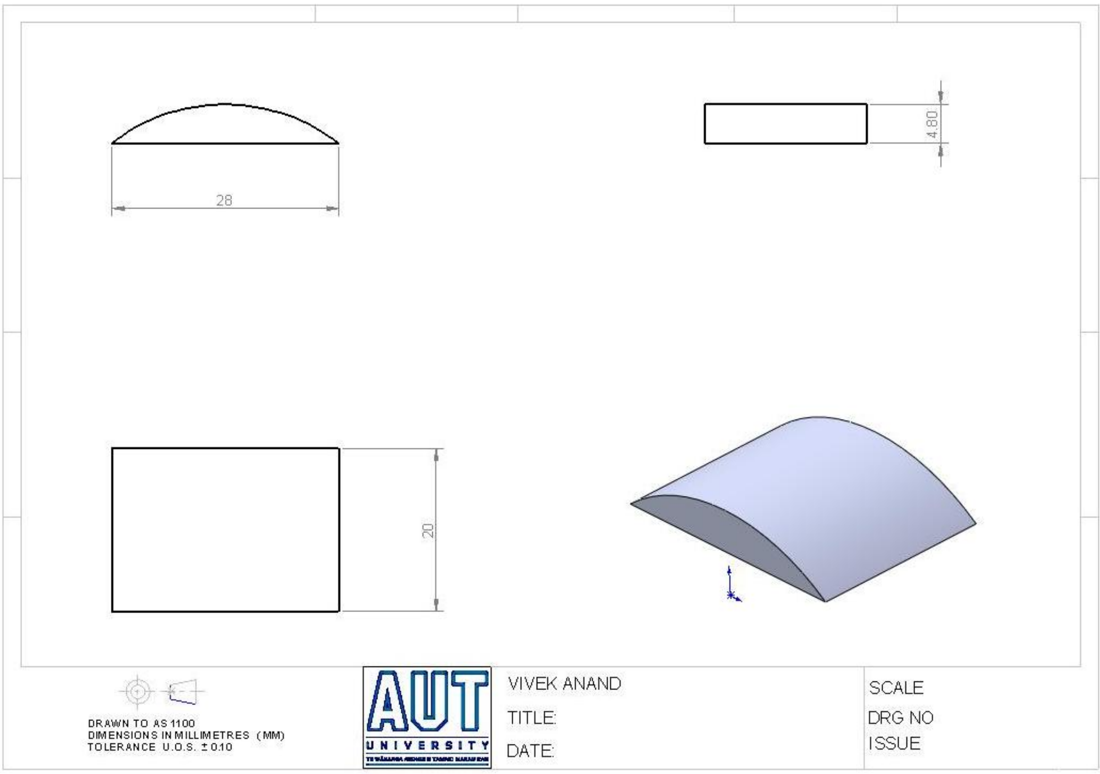


Fig 3.10 Support structure dimensions

The support structure’s dimension is 28mm L x 20mm W x 4.8mm H. Under strict parameters and quality control, the parts are printed in the fab at home machine using silicon and the output result is shown in Fig. 3.11.

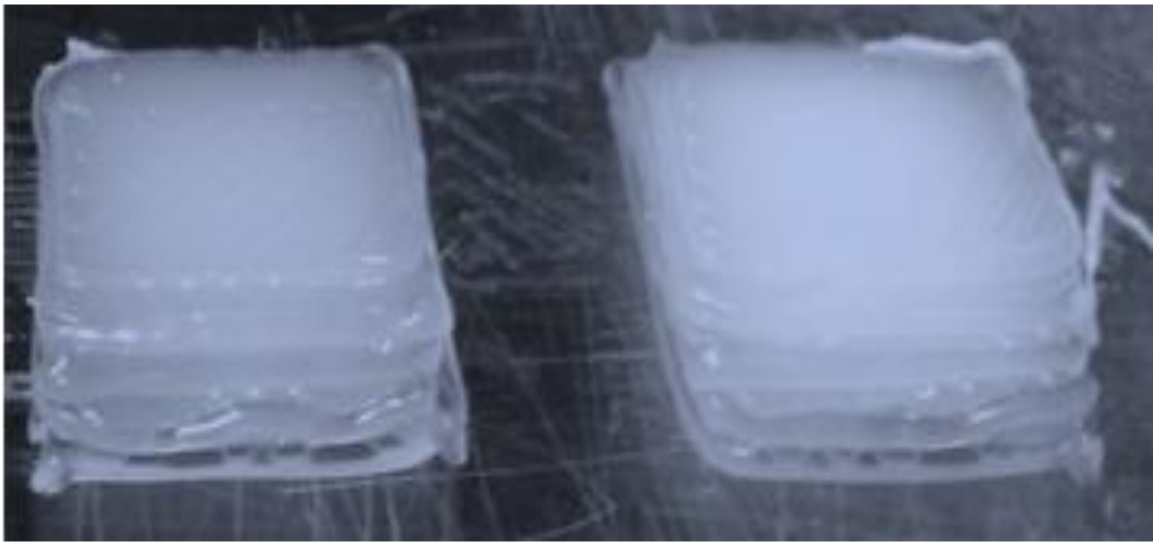


Fig 3.11 Support structure printed with Silicon

The same support structure would be needed for both curved and flat layer and a number of parts would be required for testing the strenth, hence a good number of support parts may be printed at a stretch, side by side so that they are ready to go, to be used for printing on top. Once the desired number of support structures are created, they are left to cure overnight so that main parts can be printed the next day. The main part which would be used in this research paper to compare the strength, needs to be printed under the same strict conditions and quality control the material is to be printed. The material for the main part would be Fabepoxy, which is to be prepared first.

Fab epoxy comes in tubs of two – a epoxy and a hardner. Equal quantities of epoxy and hardener are taken, measured and then mixed together in a mixing bowl. The epoxy and the hardener are first in pure white and dark brown color respectively to start with, and they are nicely mixed till they reach a light brown to pink color. It is also made sure that the material is in fluid / paste composition which can easily flow through the nozzle attached at the end of the syringe. In case when the material is still thick when mixing the two parts, it implies that the white part – the epoxy may be needed more in the mixture and it may be added as desired. This mixture which is now ready to be put into the syringe and printed in the fab at home machine. Flat and curved layered parts are then printed one by one on top of the support structures printed earlier. A flat layer part being printed in Fig 3.12.

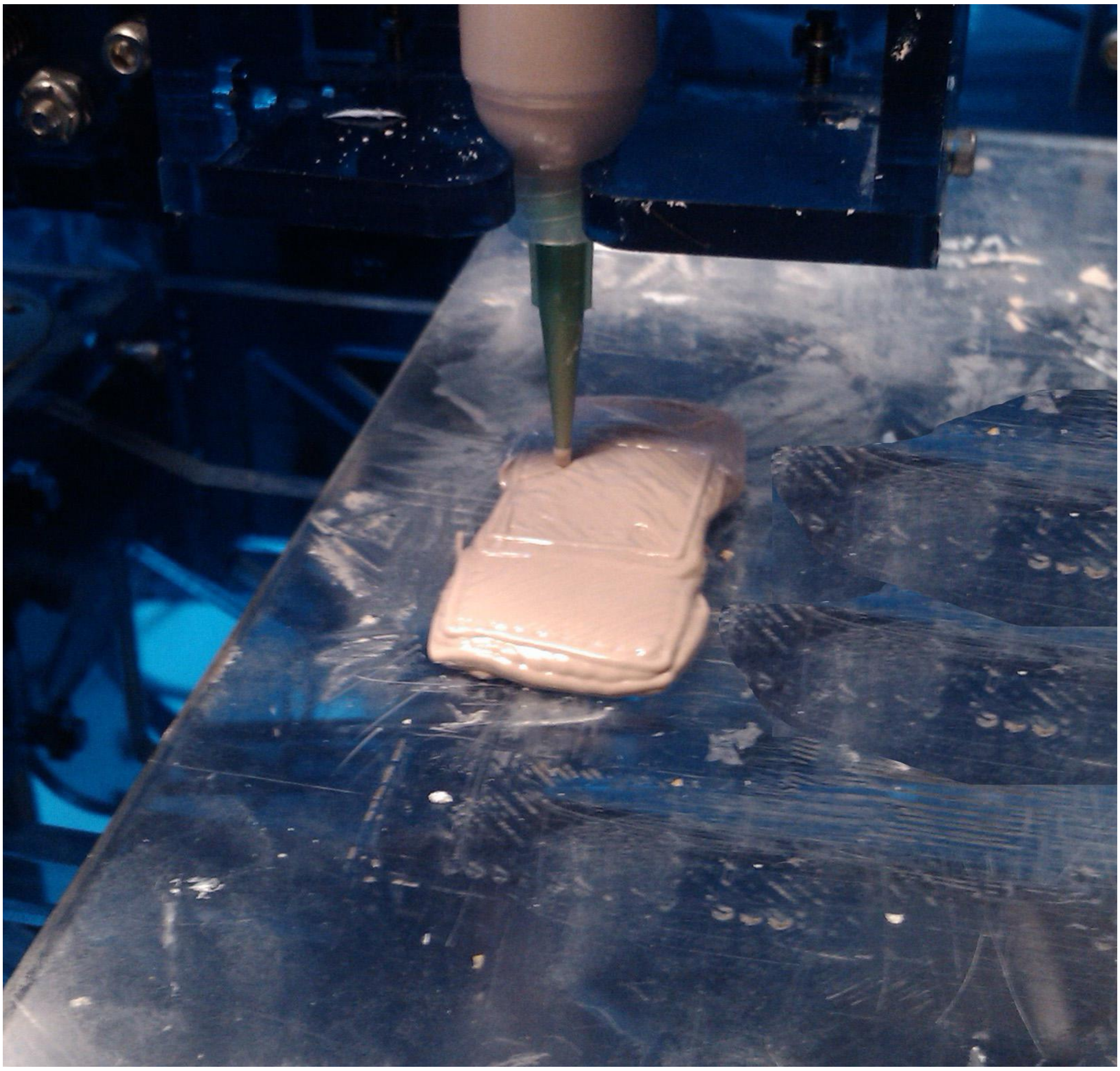


Fig 3.12 A flat layer part being printed on the Fab at home machine

Flat and curved layer models are then printed on alternative support structures while modifying speed of deposition. Sample flat and curved layer printed parts shown in fig 3.13.

Fig 3.13 Flat and curved layer parts being printed side by side on the Fab at home machine

As a variation to the standard part, and for statistical analysis the curvature of the main part is increased slightly creating a second part, Model 2 with height 11mm. The length, width of the new part is kept the same as Model 1. A change in curvature would mean that there would be an increased gap between the bottom surface and the top surface of the main part and hence a new support structure model is created to support this change. Fig 3.14 shows main and support structure model of Model 2.

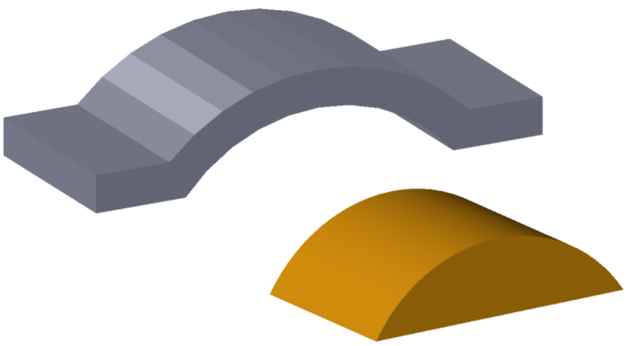


Fig 3.14 Model 2 – Main part and support structure model

Similar to the previous model, support structures are prepared first and the main part is then printed over them by changing parameters like style of deposition – flat or curved layer, speed as per the statistical design which will be covered in detail in the next chapter.

Chapter 4

Experimental evaluation of CLFDM

4.1 Experimental conditions

The main aim of this research is to find out the characteristics and behaviour of the parts printed with the FDM test bed, mainly when they are printed in two styles of deposition: flat and curved layer. Two parts (model 1 and model 2) are chosen and support structures as required for each model is printed and kept ready for both the models. The support structures can be printed with either silicon or fabepoxy. Silicon was chosen as the material for support structures in all experiments as this is the least expensive material available to be used with the current FDM test bed. Another major advantage of using silicon is that it can be removed easily from the main part without much difficulty and any adverse effects on the structure of the main part.

After the support structures are ready, the main parts are printed on top with varying conditions of deposition style and speed. Once all the parts are printed, they are then cured for nearly two days and then tested for their ultimate stress for varying conditions. For the second part structure, model 2, a curing time of nearly two weeks is given before they are tested in the Hounsfield Tensile testing equipment. This test will give clear representation of strength qualities of parts when printed in flat and curved layer style of deposition. Testing of model 2 in the same process will also give results for strength comparison as well as tell if curing time has any effect on the strength of the part.

The number of experiments is statistically planned by Taguchi L8 design. Three input parameters namely curvature, speed and deposition style are selected for the investigation. Curvature is represented by the two models 1 and 2 which are used for this purpose. Speed of deposition can be changed from the tool information file, a part of the Fab@home software. Two speeds of deposition are chosen and the deposition style is the most important parameter in these experiments as it is either Flat or curved style of deposition. A brief review of the need for statistical design of experiments is treated next before presenting the actual experimental design, methodology and analysis of results.

4.2 Design of experiments

There are a number of ways to design a statistical experimental investigation, out of which the most commonly used and thorough approach is the full factorial experiment. There are 2^k possible combinations for any full factorial experiment that must be tested (where k is the number of factors, each at two levels). Since the number of factors become too high, it becomes very difficult to carry out investigations. To reduce the number of tests required, fractional factorial experiments (FFEs) were developed. Fractional factorial experiments allow only a portion of the total possible combinations to estimate the main effects of factors and some of their interactions [31].

The determination of factors to investigate depends upon the product or process performance characteristics or response of interest. The customer who uses a product expects or needs some function from a product. If during initial development stages of a product the function is not provided or consistently provided, the performance characteristic will have to be improved. Different methods are useful for determining which factors to include in initial experiments. These may be discussed as follows [32].

Brainstorming

This involves bringing together a group of people related with particular problems and soliciting their advice concerning what to investigate. Here it is very appropriate to bring in product or process experts and statistically oriented people to discuss the factors and the structure of the experiment.

Flowcharting

Flowcharts are useful in determination of factors affecting the process results. The flowchart adds some structure to the thought process and thus may avoid the omission of important factors. All factors that are thought to influence a performance characteristic should be included in the initial round of experimentation. It is better to have many factors from contention and find those important few factors that do contribute to a product problem or contribute to product quality improvement.

Cause effect diagram

The structure for a cause effect diagram begins with the basic effect that is produced and progresses to what causes there may be for this effect. Primary, secondary and tertiary causes are branched off the main trunk of the “effect” tree. Ishikawa provides several suggestions for developing cause effect diagrams. After factors are selected, any interactions that are of interest should be noted. Experimental design is a universal knowledge that can be applied to a wide range of products and processes.

The current investigation however, will also have to consider the limitations in the experimental facilities, before making the final decision on the experimental factors and their levels. One of the major influencing parameters in the current experiments could have been the material for the test parts. In spite of several attempts on different materials as discussed in Chapter 3, there was only one material that could successfully be used on the experimental setup to print test parts by fused deposition. While fabepoxy was a successful candidate, all other materials failed to provide part that can be mechanically tested. This meant, dropping one of the most important factors.

Further, filament size was considered to be an important factor, considering the influence it would have on the inter-road diffusion and the overall meso-structure. These inter-road and inter-layer diffusion characteristics were found to have significant influences on the mechanical properties of FDM parts [30]. However, when it comes to practically implementing this, there were numerous problems. When the filament size is reduced, the total number of deposition paths would change. For example, the number of roads will be doubled when the filament size is halved. Though this could be easily implemented using the software solutions made available for this work, the total time of deposition was also doubled, and considering the manual attention needed on the machine, it became practically impossible to control the quality of the printed part. After a number of trials, and considering the inconsistencies, it was decided to drop this factor also altogether.

Considering a simple test part as shown in Fig 3.9, which is a typical thin shell type part, the curvature of the shell is considered as a geometrical parameter. This is significant in influencing strength and surface quality of parts, a varying slope of the surface results in different levels of stair-step effects and continuous fibres, as in the case of curved layer deposition and might lead to significant improvements over the flat layer counter parts. The speed of deposition is a process parameter, and could have significant influence on the part characteristics, as the material processing scheme in FDM is a thermo-mechanical process. Any new road, immediately after exiting from the nozzle would be at a relatively high temperature, and as it is deposited, the temperature drops [33]. Subsequent mechanical behaviour of the road and its ability to fuse into adjacent roads will depend on the thermal conditions. The higher the speed of deposition, the better is the sintering process between adjacent roads, considering a better thermal situation. Normal FDM machines would have a heated chamber in which the actual deposition takes place, and the envelope temperature is maintained at above the glass transition temperature. However, in the present case, the test bed does not support a controlled envelop temperature, and hence, the speed of deposition becomes a significant parameter. Deposition style, whether flat or curved any way is the main aspect of interest in the current research, and is implemented through a proper control of the test bed.

It is finally conceived to analyse the influence of these three fused deposition modelling parameters with the help of L8 orthogonal array as suggested by Taguchi. It was also assumed that there is no interaction between the factors considered in experiments. The final input parameters for the fused deposition modelling with the test bed are as follows:

- Curvature
- Speed of deposition
- Deposition Style

A brief introduction to Taguchi methods follows next, before presenting the actual experimental design

4.3 Taguchi methods

There are two types of factors in parameter design that affect a product's functional characteristic: control factors and noise factors. Noise factors are primarily response for causing a product's performance to deviate from its target value. Taguchi developed a family of fractional factorial experiments matrices which eventually reduce the number of experiments, but still provide sufficient information. The conclusions can also be associated with statistical levels of confidence. In Taguchi's methodology, the factors affecting the process quality can be divided into two types: control and noise factors. Control factors are those set by the person conducting the experiments and are easily adjustable. These factors are expected to have a significant influence over the quality of the product. Noise factors, on the other hand, are those undesired variables that are difficult, impossible, or expensive to control, such as the ambient temperature, humidity, and the aging of parts.

The major steps in the application of Taguchi's method in an experimental investigation are:

- To identify the factors / interactions
- To identify the number of levels of each factor
- To determine the values of the level of the factors
- To select a appropriate orthogonal array
- To assign the factors / interactions to the columns of the orthogonal array
- To conduct experiments
- To analyse the data and determine optimum levels
- To conduct the confirmation of experiments

The Taguchi approach has been successfully implemented in research and several industrial organizations to change their perspective on quality management [34]. Taguchi philosophy is to design quality built into the product rather than to have it inspected after its production. Quality improvement must start at the very beginning i.e. during the design stage of the product development and should continue through the production process. Dr Taguchi observed that any amount of inspection could not put quality back into the product and it only treated the symptom, therefore he presented that quality concepts should be based upon and developed around, the philosophy of prevention.

The Taguchi Method is a multi-stage process as follows:

- Systems Design,
- Parameter Design, and
- Tolerance Design.

Systems Design: The centre of the systems design is about finding out new ideas, concepts to provide new, improved products to customers. It includes designing and testing systems based on the scientist's understanding of selected materials, parts and technology. It also involves innovation, creativity from different fields of sciences and technology.

Parameter Design: Parameter design searches to determine the factor levels that make the best performance of the process under study. It aims to improve the uniformity of the product which could be done at no additional cost to the company. The nominal condition was chosen so that the effect of uncontrollable noise factors causes the least variation of system performance. Noise - Performance Statistics (NPS) are used to identify 'Control' factors. Signal-to-Noise ratios are also used to evaluate the effect of 'Noise' on the system. An unreactive system will have a high Signal to noise ratio.

Noise Factors: The 'noise' factors can be classified on the basis of being either internal or external to the system, as either inner or outer noise. Inner Noise is the type of variation from specification, which can be described as product noise. Outer Noise is the variation which is imposed by circumstances, for e.g., temperature, humidity, wear and tear effects.

Tolerance Design: Tolerance design is a way to perfect the results of the parameter design by squeezing the tolerance of factors with prominent bear on the product.

Such steps usually identify the need of innovation and identification of better machinery, parts etc.

Taguchi methodology stresses the importance of the middle stage in the total design process, which is often neglected in industrial design practice. The methodology involves recognising the parameters which are under the control of the scientist, and then the setting up of a series of experiments to find that subset of those parameters which has the most influence on the variation and performance of the design. The scientist is hence able to point out the aspects of the design which most influence the result of the design process.

Another aspect of the Taguchi methodology is the "Taguchi loss function" or "quality loss function" which says that there is an increasing loss from the ideal or target value of any design parameter. A larger deviation from target implies the greater loss. The idea of loss being dependent on variation is long established in design theory, and at a systems level is related to the benefits and costs linked to dependability. Variability unavoidably means waste of any kind - but it is impossible to have zero variability. Thus if performance falls anywhere within the range, it is regarded as acceptable, if it falls outside that range it is not acceptable.

The Taguchi methodology guides that a more realistic function should used based on the square of the deviation from the ideal target, i.e. that customers get more dissatisfied as performance varies from ideal. The Taguchi loss function strategy stresses for reducing variability and to strive for a process mean that is equal to the nominal specification. Companies using the basic methodology of examining main specifications and striving for a mean of measurements equating to nominal specification values, along with a reduction in data variability, can expect to produce products that are expected by customers to have higher, more consistent quality. Taguchi recommends two-level factors for an initial experiment. If the factors and their interactions are less than 7, a possible matrix is an eight-trial orthogonal array, which is labelled as an L8 matrix.

4.4 Taguchi L8 design

The Taguchi L8 design is a statistical plan for conducting eight experiments with a maximum of seven input factors set at two levels and arranged in orthogonal arrays. In this method, each factor is assigned a column and each row represents an experiment with a unique combination of factor levels. The maintenance of orthogonality between columns ensures that, for every factor, four tests would be carried out at one level, while the remaining four would be performed at the other level. This allows the simultaneous evaluation of the effects of several factors with the minimum number of experiments. The disadvantage is that there is considerable “confounding” or overlapping of factor and interaction influences due to the drastic reduction in the number of experiments from a full factorial design of 128 experiments.

The Taguchi method makes use of a tool called linear graphs to assign parameters and interactions to various columns of an orthogonal array. Linear graphs represent interactions between pairs of columns in an orthogonal array and makes it easy to plan experiments involving interactions. Taguchi provides associated standard linear graphs for each the tabulated orthogonal arrays. Linear graph made up of three parts

- Dots
- Number assigned to the dot
- Line Segments

4.4.1 Signal to Noise ratio

The control factors that may contribute to reduced variation can be quickly identified by looking at the amount of variation present as a response. All past analyses have addressed which factors might affect the average response, but now there is interest in the effect on variation as well. Taguchi’s main focus is producing products at optimal levels with minimal variation. So Taguchi recommends the use of a statistics called the signal-to noise ratio, denoted S/N as an aid in reducing variation. There are three types:

Smaller is better

$$S/N_{SB} = -10\log_{10}\left[\frac{\sum_{i=1}^{n} Y_i^2}{n}\right]$$

Nominal is best

$$S / N_{NB} = -10 \log_{10} [S^2]$$

Larger is better

$$S / N_{LB} = -10 \log_{10} \left[\frac{1}{n} \sum_{i=1}^{n} \left(\frac{1}{Y_i^2} \right) \right]$$

n is the number of size of a sample and S^2 is the variance of that sample. A signal to ratio is calculated for each treatment combination. Taguchi claims that treatment combination with largest true average signal-to noise ratio produces the least variation in the response variable. This can identify the factors that can reduce variation.

4.5 Experimental design for CLFDM experiments

Based on the extensive research done above, Taguchi's L8 design was selected to come up with a strategic design for the series of experiments. While the basic part for the experiments is the thin shell type part as already stated, the experimental design includes curvature of the part, speed and style of deposition as critical factors. The design matrix is built based on the Taguchi L8 orthogonal array considering each of these factors at two different levels. The design matrix is shown in Table 4.1.

Table 4.1 Taguchi L8 design for CLFDM

Trial No.	Curvature	Speed	Deposition Style
1	1	Speed 1: low	1 - Flat layer
2	1	Speed 1: low	2 - Curved layer
3	1	Speed 2: high	1 - Flat layer
4	1	Speed 2: high	2 - Curved layer
5	2	Speed 1: low	1 - Flat layer
6	2	Speed 1: low	2 - Curved layer
7	2	Speed 2: high	1 - Flat layer
8	2	Speed 2: high	2 - Curved layer

4.6 Methodology

A total of sixteen parts (8 parts x 2 batches) were printed as per Taguchi's L8 design, repeating each of the trials shown in Table 4.1 twice, but during printing a number of difficulties sprung while printing with the FDM test bed at hand. Some of these are presented as follows:

- Limited capability of the machine to accept a broad range of materials. Materials had to be semi-solid and viscous in state which would enable easy flow through the syringe.
- Maintaining consistency of fabepoxy compound; Mixing of the epoxy and hardener had to be very accurate in 1:1 ratio to ensure smooth flowing material desired when the two materials were in tub form. The company KraftBiz, which manufactured this compound later, introduced a gun barell system which would then push out fab at home with the exact 1:1 composition of epoxy and hardener straight into the syringe.

- Control of material flow – The lead screw which pushed the material from the top of the deposition head at times would not be good enough to maintain a continuous deposition. To overcome this, the lead screw was rotated at times with hand to ensure that material was always being deposited when the Fab@home software was running.
- The Fab@home software would refuse to connect to hardware at times for no reason. Repetitive trials of plug and play would set this right.
- When the Fab@home software was paused in the middle of a deposition, and then restarted back on again it would at times go to the wrong location and not start from the place it was paused at.
- When changing to print between different models / different conditions, Fab@homeat times would go to print at a wrong location on the machine. To avoid this, software was closed and started back on again to avoid any wrong printing.

In spite of all these difficulties, all parts are printed as per the design specifications, however, with some minor errors in some of the parts. One set of parts printed to the specifications in Table 4.1 are shown in Fig. 4.1. Some disturbance and discontinuity of fibres may be evident in a couple of the samples. Otherwise, the specimen parts have some distortions on the sides due to the spreading of the polymer under its own weight. For this reason, the samples are polished on the side faces, after sufficient curing and the finished samples of flat and curved layer specimens are shown in Fig. 4.2.

4.7 Results and discussion

The specimens are then subjected to 3-point bending tests on the Hounsfield tensile testing equipment in materials testing lab of AUT University. A typical specimen under 3-point loading is shown in Fig. 4.3. The maxim compressive force before fracture of   is recorded in the case of each sample, and the final data obtained for all samples is presented in Table 4.2. All the test samples are cured for about 48 hours in this case. It was observed that curing time is a critical factor in the case of fabepoxy, and the more the curing time, the better the part strength.

Fig 4.1 Series of parts being printed as per design of experiments

Fig. 4.2 Flat and curved layer polished parts

Fig 4.3 Parts being tested with Hounsfield Testing equipment

Table 4.2 Maximum compressive load after a curing time of 48 hours

Trial No.	**Curvature**	**Speed**	**Style**	**Strength1**	**Strength2**	**Average**
1	Low	Low	Flat	112	124	118
2	Low	Low	Curved	136	164	150
3	Low	High	Flat	88	116	102
4	Low	High	Curved	131	93	112
5	High	Low	Flat	117	147	132
6	High	Low	Curved	138	218	178
7	High	High	Flat	180	300	240
8	High	High	Curved	147	209	178

The S/N ratios for the results in Table 4.2 are calculated and are shown in Fig. 4.4. It is clear from these graphs that the larger curvature, higher speed and curved layer deposition style are the most favourable in terms of achieving the maximum response, in this case the maximum compressive load the curved components can withstand. This is a clear indication of the superiority of the curved parts. Though a few other responses could be developed based on the calculations of 3-point bending tests, the current results are discussed just based on the maximum compressive load values, as the main aim is to establish the relative merits of curved layer deposition.

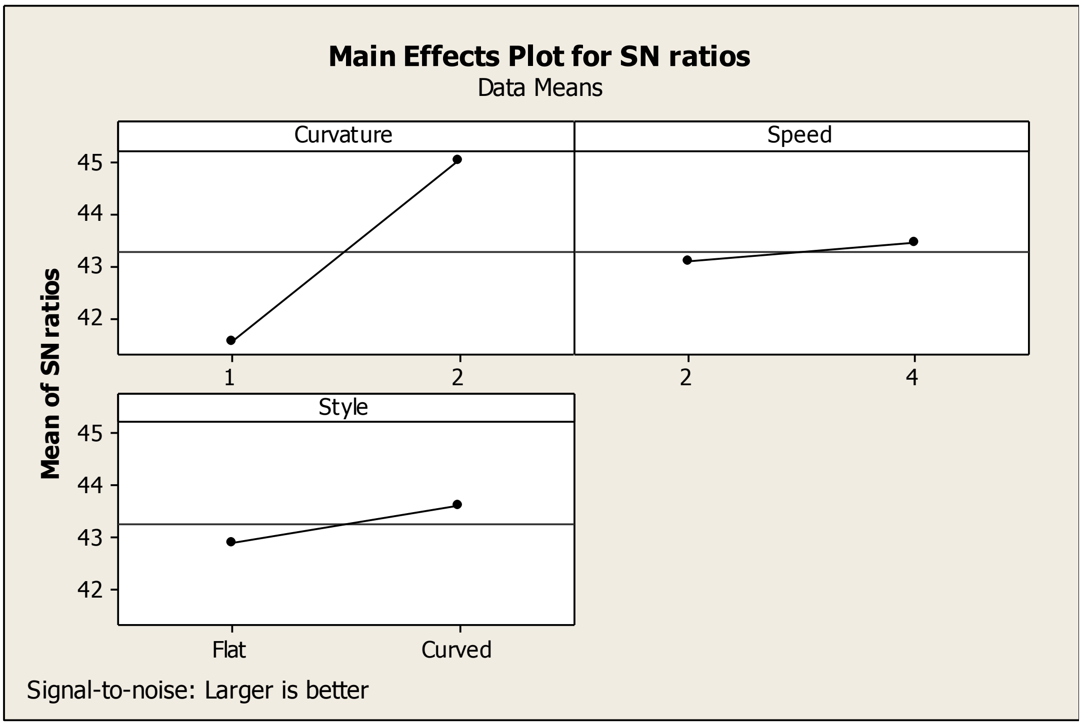


Fig. 4.4 Main effects plot for SN Ratio's

Table 4.3 ANOVA: Experimental set 1

Source	DF	SS	MS	F	P
Curvature	1	7564.5000	7564.5000	29.958	0.032
Style	2	505.0000	252.5000	0.151	0.864
Speed	4	6682.0000	1670.5000		
Total	7	14751.5000			

It was clear from the experiences of these experimental trials that the curing time of the epoxy is quite significant in controlling the final characteristics of the parts, and the actual curing time of the epoxy being unknown, another set of components is printed according to the same conditions as before, and left curing for a couple of weeks. The results are quite astonishing in that the maximum compressive load values in all cases are almost double that of the corresponding trials in the first set of experiments, as is evident from the results data shown in Table 4.4. Subsequent S/N ratio calculations, as shown in Fig. 4.5, depict the larger curvature, lower speed and curved layer deposition as the most favourable combination for the best maximum compressive load. ANOVA calculations in this case, as shown in Table 4.5 reveal that curved layer deposition is the main effect that has significant influence on the overall strength of the parts, at above 95 % confidence level.

Table 4.4 Maximum compressive load after a curing time of more than 3 weeks

Trial No.	Curvature	Speed	Style	Strength1	Strength2	Average
1	Low	Low	Flat	227	273	250
2	Low	Low	Curved	386	574	480
3	Low	High	Flat	218	232	225
4	Low	High	Curved	272	338	305
5	High	Low	Flat	286	334	310
6	High	Low	Curved	264	316	290
7	High	High	Flat	302	368	335
8	High	High	Curved	268	332	300

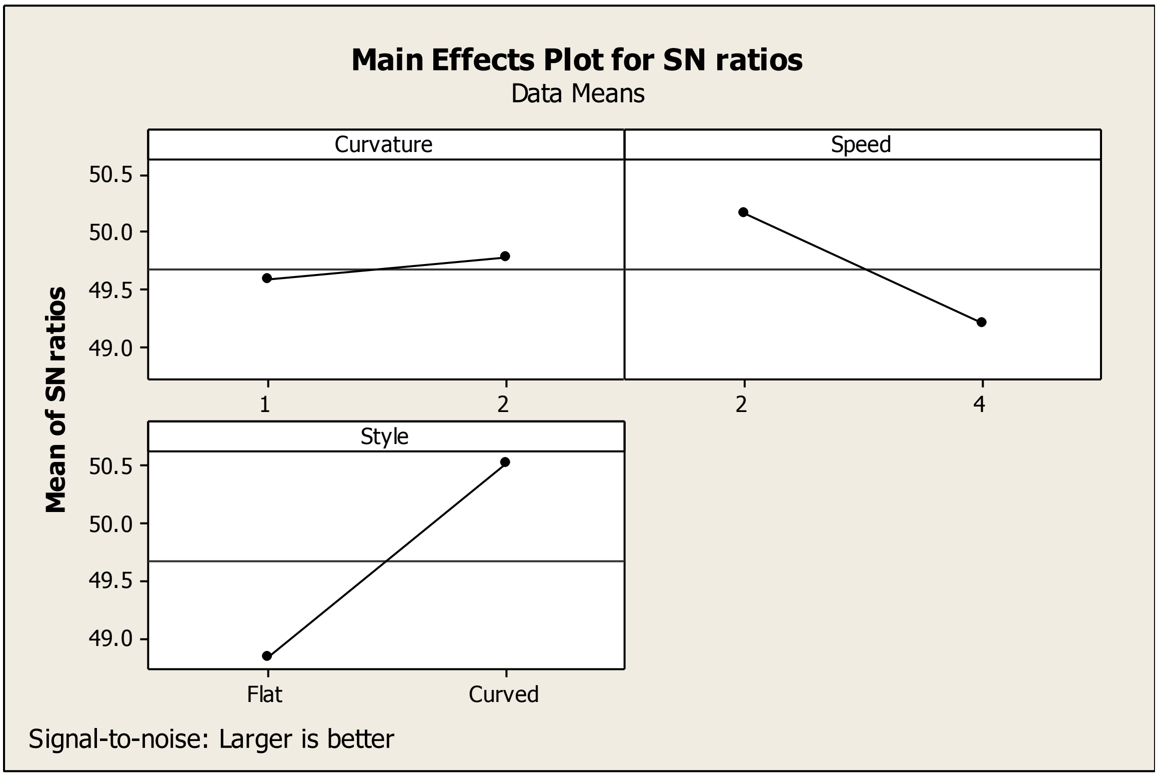


Fig. 4.5 Main Effects for SN Ratios

Table 4.5 ANOVA: Experimental set 1

Source	DF	SS	MS	F	P
Style	1	25878.1250	25878.1250	7.604	0.110
Speed	2	6806.2500	3403.1250	0.829	0.500
Curvature	4	16412.5000	4103.1250		
Total	7	49096.8750			

Overall, the results are interesting and contradicting also in some cases from one set of experiments to the other. For example, in set 1, the most significant factor is the curvature at above 90% confidence level. Whereas, the deposition style came out to be insignificant. The second set of experiments with more curing time, however, gave the style of deposition as the most significant factor, at above 95% confidence level. The other parameters were insignificant. A closer examination of the strength values obtained in experimental set 1 reveal that the curved layer parts are always of higher strengths compared to their flat layered counter parts, except in one case. This was mostly reversed in the case of experimental set 2. The probable reason for this is the typical nature of the epoxy used in the investigation

It was observed that the epoxy remains as a semisolid with considerable amount of fluidity for a considerable length of time, as no external heating is used. This resulted in a thorough fusing of the material across adjacent roads and also due to self weight, across different layers. A gross distortion of the shape in the vertical direction also was observed and the net result was a thoroughly fused flat layered part, which when given with sufficient time such as the two week curing time as in the case of the second set of experiments, resulted in stronger parts. However, this much of inter layer fusing might not happen in the case of normal FDM, due to the short duration of sintering of the polymer across roads or layers. In such a case, curved layer FDM is likely to give better strength to parts, as against flat layers, as is evident from the first experimental set. However, these results are only indicative, and a more comprehensive investigation using regular FDM materials and a more reliable experimental setup is essential to establish the true significance of curved layer FDM.

Chapter 5

Finite Element Analysis of flat and curved layer FDM

5.1 Finite Element Analysis of FDM

Finite Element Methods were first introduced by Courant (1943) and from the 1950s to the 70s they were developed by engineers and mathematicians into a general method for the numerical solution of partial differential equations. Though the initial growth was slow, with the proliferation of computational facilities, FEA gained more and more popularity, and methods to formulate stiffness matrices, discretisation of solid models, and solution of large sets of equations were all made possible. Current applications of FEA encompass thermal, electromagnetic, fluid, structural and other engineering fields. The basic approach in any finite element analysis begins with a governing differential equation that defines the variation of the functional within the problem domain. In addition, a set of boundary conditions usually accompanies the control equation. In order to obtain a solution for the variable satisfying all these conditions, the domain is sub divided into a number of elements, with continuity at inter-element boundaries.

Each element being represented by a set of nodes, a mathematical processing follows next that will allow nodal equations to be generated in terms of the unknown quantities, whether displacements or temperature etc, depending on the problem being analysed. Various approaches such as nodal force equilibrium, minimisation of potential energy etc are used as mathematical techniques to develop the set of simultaneous equations. The contribution to a particular node from all adjoining elements are then assembled and structured in an overall stiffness matrix, The set of simultaneous equations is then solved making use of the boundary conditions to obtain nodal values of the functional. The variation of the functional within an element is obtained through approximation schemes. Once the distribution of a basic quantity is established, other derived quantities are calculated using constitutive equations.

The finite element method has had a great contribution to the advancement of computational methods, and is still widely used in industry today. The FEM provides cheap and simple solutions to solving problems, and this is apparent by the amount of software readily available that is cheap and reliable. Almost thirty years of uninterrupted development, it can be said that the finite element method has now reached the stage where no additional breakthrough may be expected. However, the potential of the method attracts renewed applications as new processes are developed with time. For example, the development of rapid prototyping technologies, and in particular, the rapid manufacturing approaches, where end use parts are produced directly from CAD files, necessitate the use of advanced techniques such as the finite element methods in order to be able to understand the process attributes thoroughly. This has naturally attracted the attention of some researchers into using FEA to better understand both micro and macro characteristics of several RP processes.

Mostafa et al [35] conducted 2D and 3D numerical analysis of melt flow behaviour of a representative ABS-iron composite through the 90-degree bent tube of the liquefier head of the fused deposition modelling process using ANSYS finite element package. Main flow parameters including temperature, velocity, and pressure drop have been investigated. Filaments of the filled ABS have been fabricated and characterised to verify the possibility of prototyping using the new material on an existing FDM machine. The results of the analysis were found to be in good correlation with experimental data and the flow behaviour was sufficiently predicted.

Non-random porous ceramic material structures are fabricated by fused deposition and a novel technique is presented to model the compressive strength behaviour of such materials [36]. Elastic interactions between pores have been considered and the finite element method is used to numerically evaluate the same for the stress fields developed. The FEM results are found to correlate quantitatively with uniaxial compression experimental data of non-random porous ceramics of different porosities. Variable volume fraction porosities were achieved by varying horizontal pore-pore interactions for constant pore shapes and sizes. Effective elastic interactions between pores have been considered between interacting micro-pores and the finite element method is used to numerically solve for the stress fields that are developed. A two-pore system is presented to represent the multiple pore material system.

Augmented scaled bone replicas were built using FDM based on micro-computed tomography data and the geometric accuracy of the model was evaluated by comparing experimental tests with the replicas to the finite element solution based on the same micro-CT data [37]. A new version of the large-scale FE solver was developed to incorporate orthotropic material properties. This allowed the experimentally measured properties of the rapid prototype material to be input into the FE models. The modified FE solver was reported to have predicted the experimental stiffness within less than 1%.

A finite element analysis was proposed by Zhang and Chou [38] considering coupled thermal and mechanical phenomena and an element activation function to mimic the additive nature of FDM. In a further study [39] the FEA model was used to evaluate the distortions of a part. A parametric study, with three factors and three levels is performed to evaluate the effects of the deposition parameters on residual stresses and part distortions. Prototype models with larger sizes are fabricated, measured, and compared with the simulations. The commercial FEA software ANSYS was utilised to develop the simulation codes. The simulations were conducted in a stepwise thermo-mechanical manner. A rectangular parallelepiped element capable of both mechanical and thermal analyses was chosen. The scan speed was the most significant factor affecting part distortions, followed by the layer thickness. The road thickness alone was insignificant but its interaction with layer thickness was significant. Residual stresses were found to increase with layer thickness.

It is evident, most of these examples of the application of the finite element analysis in FDM either allow modelling of the flow of the individual filament or calculate the overall part characteristics. There is very little work done in terms of using the capabilities of FEA to model the influences of different deposition styles. However, Anna and Selcuk observed indeed that the road shape and the road-to road interaction as well as the trajectory of deposition strongly affect the properties and performance of finished FDM parts [40]. This implies that determination of the build strategy will have a pronounced effect on the properties and ultimately the performance of the finished product. Dimensional stability, resulting from process-related thermal stresses and the interactions of different parts of the built shape would also be influenced by the deposition strategies. Possible influences of the curved layer deposition on the mechanical behaviour of a simple thin shell type part are investigated in the current research. Part geometry, finite element modelling strategies and results are presented in the following sections

5.2 Solid modelling of flat and curved layer FDM parts

The part selected for the finite element simulation of the curved layer and flat layer fused deposition is the same simple thin shell type part used in the experimental analysis presented in Chapter 4. The solid model of the part is reproduced in Fig. 5.1 for the sake of continuity.

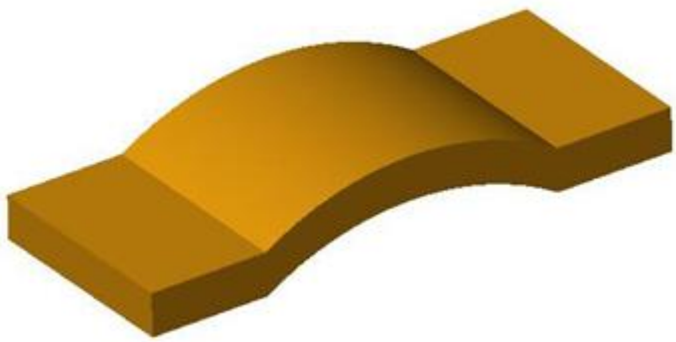


Fig. 5.1 Thin shell-type part considered for the FEA

Creation of the solid model and conversion of the same into a finite element mesh for the consideration of the boundary conditions would have been relatively simple and straightforward, had the material structure been continuous and homogeneous. However, the material structure in FDM parts is inferior due to the porosity generated from an insufficient fusing of adjacent roads and layers. The overall properties of the prototype can be modelled by the lamination theory, at the macro level. At the micro level, the properties of each lamina are functions of the properties of the filaments, the quality of bonds between filaments and void density [28].

The formation of bonds in FDM process is driven by the thermal energy of semi molten materials. FDM prototypes are composites of bonded ABS filaments and voids. The bonding quality among filaments in FDM parts is an important factor in determining the integrity and mechanical properties of resultant prototypes. A sintering mechanism was proposed by Longmei et al [41] first idealising the cross sections of filaments as circles. The first step of the process is the establishment of interfacial molecular contact by wetting. The molecules than undergo motions toward preferred configurations to achieve the absorptive equilibrium. Molecules diffuse across the interface, forming an interfacial zone, and react to form primary chemical bonds across the interface. The randomisation can be reached only after extensive inter-diffusion of chain segments under critical conditions. The magnitude of the neck formed between the filaments gives a partial indication of the quality of bonding. This way, a certain amount of distortion of shape of each filament takes place and depending on the thermal and other conditions, adjacent filaments fuse together to different levels, and finally assume a continuous network of distorted cross sections. A dimensionless sintering neck growth is calculated as the ratio of neck radius with cylinder ratio.

Rodriguez et al [42] measured void densities on the principal material planes and the extent of circumferential fibre to fibre bonding as a function of fibre to fibre gap, flow rate and processing temperatures. It was found that a slightly negative gap minimised the voids and maximised the extent of bonding. Further, Rodriguez et al [30] also studied the mechanical properties of the FDM1600 feedstock material and the mechanical behaviour of unidirectional FD-ABS materials with three different mesostructures. The mechanical behaviour of the ABS mono filament and the FD-ABS specimens were found to be different, with a substantial reduction in both stiffness and strength for FD-ABS, influenced by the mesostructure. Some reduction in strain at yield could be observed, and the FD_ABS specimens were found to fail in two different modes. A relatively tough response was exhibited by the longitudinal specimens with fracture surfaces normal to the load direction and surrounded by a highly whitened region. The transverse specimens, on the other hand exhibit brittle behaviour with failure occurring at the maximum load and along the fibre-to fibre interfaces.

Considering all these developments, the current models also assume a 25% of fusion of all filaments into the surrounding filaments. The distortion of the cylindrical shape, however is neglected, considering the modelling difficulties at such a micro scale. The mesostructure assumed for the development of both flat and curved layer models is shown in Fig. 5.2.

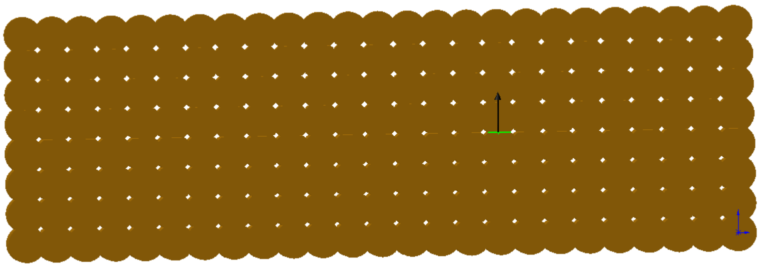


Fig. 5.2 Mesostructure of the cross section of the solid model

Based on this mesostructure, the solid model representing the flat layer component is developed by extrusion and the model looks as shown in Fig. 5.3.

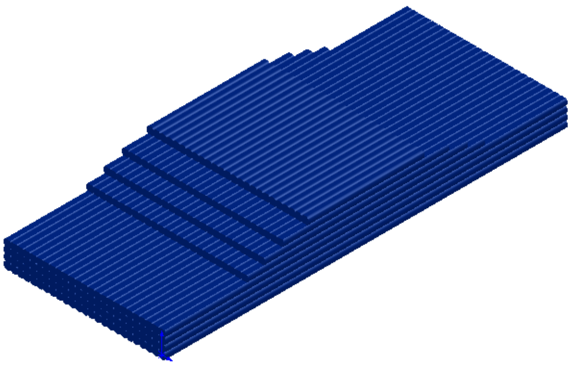


Fig. 5.3 Basic shape of the flat layer model

The overall dimensions of the part and the filament sizes considered are similar in proportions to the first model discussed in the previous chapter. The thin shell type part is then developed by removing the unwanted portions of the material and the final shape of the model simulating the flat layer FDM part looks as shown in Fig. 5.4.

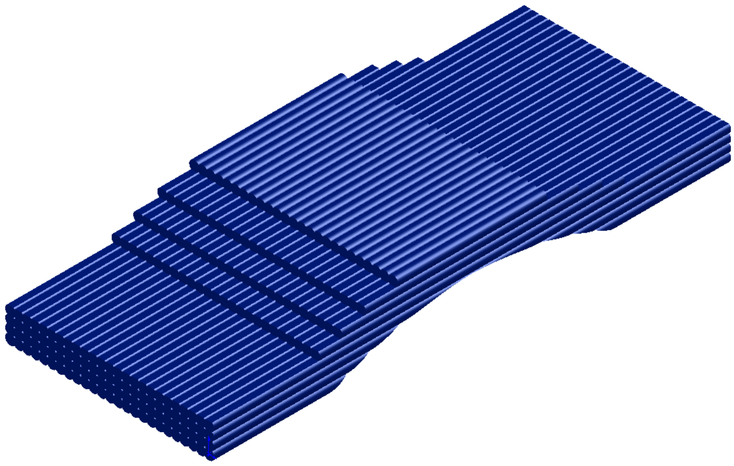


Fig.5.4 Solid model simulating the material structure of the flat layered FDM part

In the case of the curved part, the basic shape is obtained by directly extruding the mesostructure along a curved path generated in accordance with the shape of the side view of the finished part. The final solid model simulating the curved layer FDM part is as shown in Fig. 5.5, and the structure of continuous strands is clearly visible.

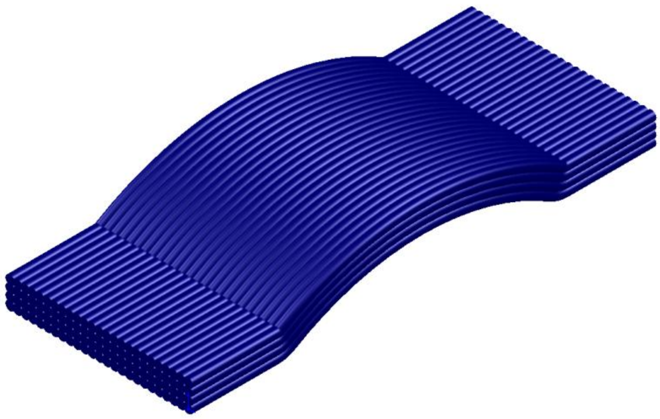


Fig. 5.5 Solid model simulating the material structure of the curved layer FDM part

Fig. 2 (a) is the thin curved part simulating the flat layer deposition, while Fig. 2(b) simulates the curved layer deposition. Both parts are first created as full solids initially, considering cylindrical filaments extruded from a selected mesostructure as shown in Fig. 3. Once the solid models are created, the next step is to develop the finite element mesh using the FEA software available, which is Abaqus in this case.

5.3 The FEA tool; Abaqus

There are many commercial packages for the FEA of various engineering problems, ANSYS and Abaqus being the most common for general use. While most of them have almost similar capabilities, there are subtle differences in that the user interface and the modelling for the geometry, and procedures for simulating the boundary conditions may vary from one system to the other. Abaqus is used for the current analysis as the package is readily available at AUT university for research purposes. Abaqus FEA is a suite of software applications for finite element analysis and computer aided engineering. It consists of four core products for computer aided engineering, computational fluid dynamics, general purpose FEA and special FEA analyser for highly nonlinear problems.

Any finite element analysis consists of three stages: Pre-processing, processing and post-processing. The pre-processing stage involves the development of the basic model of the domain to be analysed and modelling the boundary conditions to be satisfied, together with selection of appropriate finite elements. Though the basic finite element algorithms are taken care of by the code supporting the package, considerable amount of skill and expertise is still needed in developing appropriate boundary conditions that bring the problem conditions close to the reality.

Processing involves the solution of the simultaneous equations generated based on the geometry, mesh structure and boundary conditions. Most calculations during this stage are usually taken care of by the powerful solver algorithms of the code running behind the graphical user interface. However, the mesh structure, element continuity and appropriate scheme of boundary conditions generated during the pre-processing stage are paramount to achieving and effective solution.

Post-processing stage involves developing graphical display of results. Functional values such as displacements or temperatures are only evaluated at the nodes of the finite element mesh based on the calculations of the solver during the processing stage. A graphical display of results however needs continuous plotting of variation of a parameter in the form of 2D contours or 3D surface images. This needs appropriate interpolation schemes, and the size and distribution of the finite elements and the complexity of the problem domain will have direct influences on the ability of the package to capture representative profiles.

5.4 Preprocessing in Abaqus

The first step in the process of analysing the stress fields on the two components under study is to develop solid models of the two components to be investigated. This is done using the pre-processing Part module of the Abaqus software. There are two methods of creating a part geometry in Abaqus. One is to directly create the model geometry using the sketcher tools of the Part module. However, considering the relatively complex geometries of models under investigation, this may not work. The other method is to directly import solid models created using other software packages. Both flat and curved layer models developed using Solid Works are imported into the Abaqus Part module. For compatibility however, the solid models need to be saved in the IGES format initially.

The next step is to create the material properties, for which the Material module of Abaqus is used. It is necessary, first to develop the material property data Fabepoxy, the experimental material for the current analysis is not a very common polymer, and being a propriety material, there is only limited data made available. The following are the details obtained from kraftmark.bz

Table 5.1 Property data: Fabepoxy

Mixed Color	Tan
Shore "D" Hardness ASTM D2240	65
Viscosity Resin	Paste
Viscosity Hardener	Paste
Specific Gravity, Resin	.91 (7.59 lb/gallon)
Specific Gravity, Hardener	.82 (6.8 lb/gallon)
Tensile strength	610psi
Elongation, Compressive strength, Maximum use temperature:	<6%, 20,000 psi, 250F

The modulus of elasticity of the material is not available in the literature. For this reason, a tensile specimen is cast using Fabepoxy and allowed to cure for a week. The cured sample is then tensile tested using a Hounsfield tensile testing machine at AUT University. The load-deflection graph obtained is as shown in Fig. 5.6. This data is further used to calculate stress-strain data and the stress-strain plot shown in Fig. 5.7 is drawn.

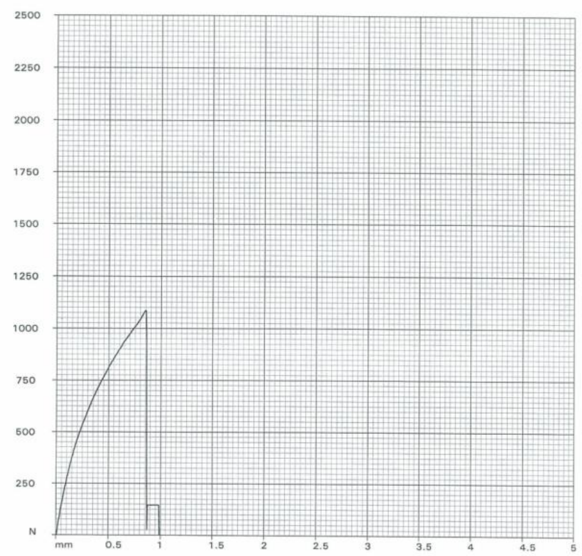


Fig. 5.6 Load-Displacement diagram of Fabepoxy

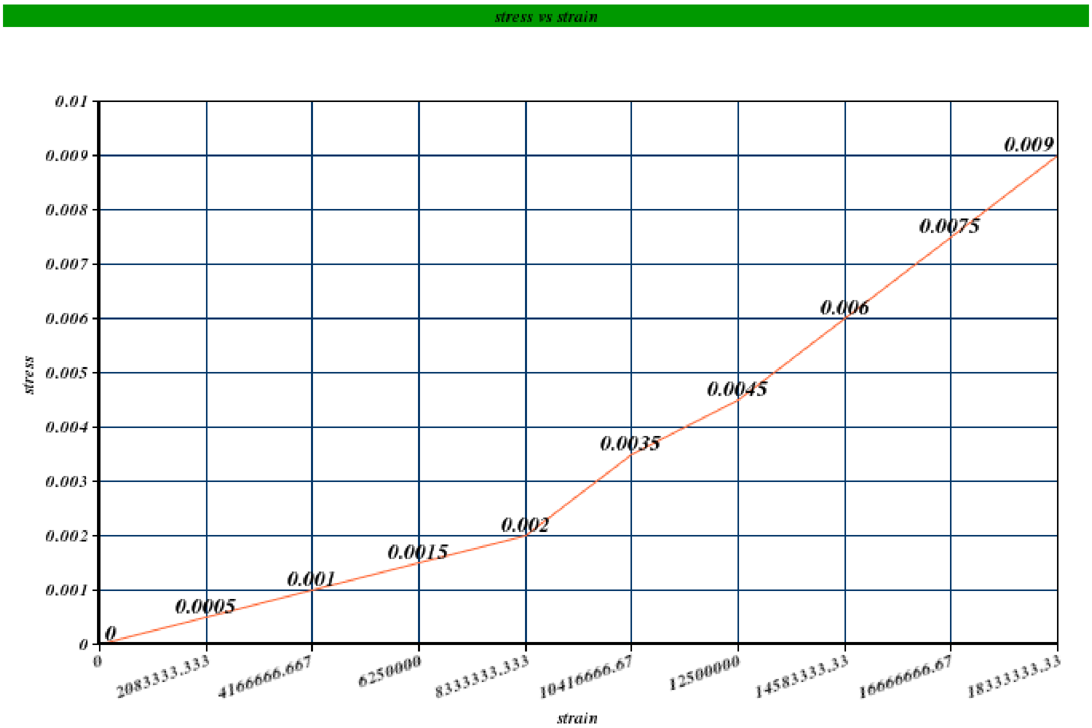


Fig. 5.7 Stress-strain diagram of Fabepoxy

From the stress-strain graph of Fig. 5.7, the modulus of elasticity is calculated as the slope of the straight line portion, which is equal to 4.1 GPa. It is difficult to establish the exact value of Poisson ratio, but generally, ABS polymer, the other common material is reported to have a Poisson's ratio of 0.4, and the same value is used in the current trials. All the relevant property data is assigned to the Fabepoxy material created in the Abaqus software. A section and an assembly of each of the test part are then created and the material properties are assigned to the part.

The next stage is to discretise the problem domain with finite elements. Thee tetrahedral elements for transient elastic stress analysis are selected from the Abaqus element library. There were problems encountered while meshing, considering the relatively complex geometry arising out of the mesostructure with characteristic gaps. Very fine elements were necessary to be able to fill the entire volume with continuous elements. The global seeding option is used for this purpose and many trials with different size of global seeds were made before finalising the optimum number. The final finite element meshes generated for the flat and curved layer models are shown in Fig.s 5.8 and 5.9 respectively.

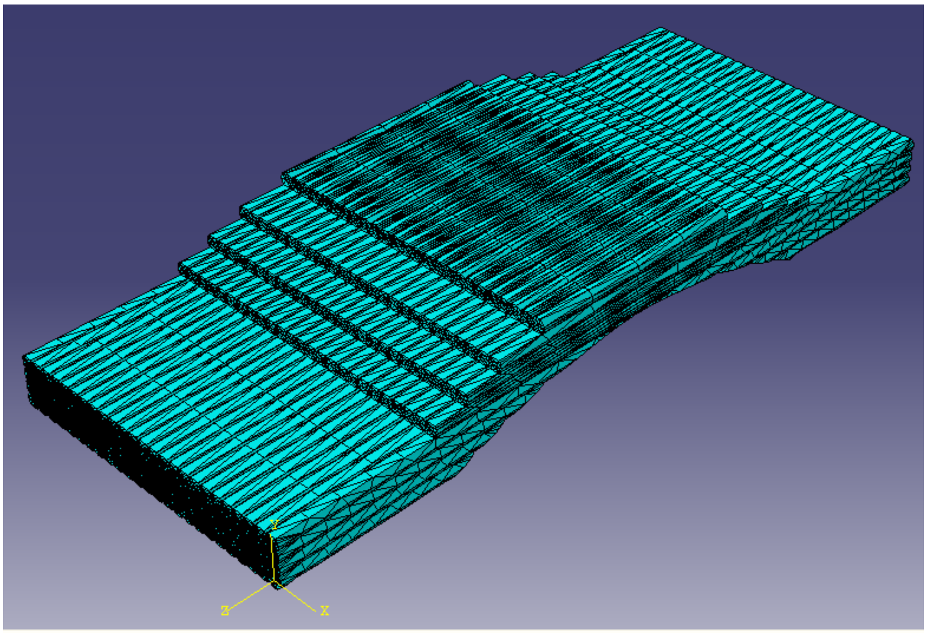


Fig. 5.8 The finite element mesh used for the flat layer model

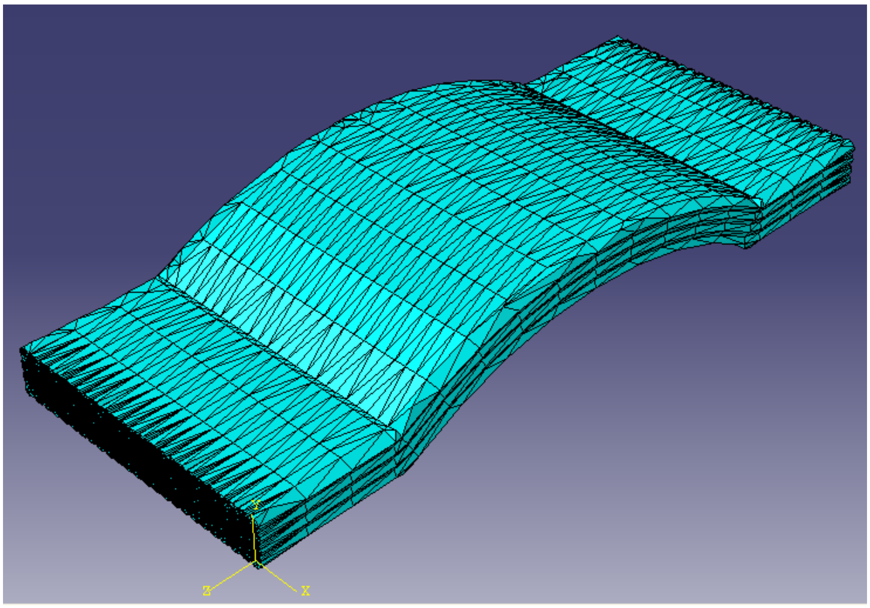


Fig. 5.9 the finite element model used for the curved layer model

5.5 Analysis procedure and boundary conditions

A transient elastostaic analysis is planned to assess the influence of the deposition scheme on the mechanical characteristic of the final shell type parts. Each model is partitioned into two parts, so as to create 25 points on the top surface, for the specification of the compressive load, simulating the three point bending conditions. The load is equally distributed at the nodes on the top of the curvature, as shown in Figs 5.10 and 5.11 in the case of flat and curved layer parts respectively. The load vales at each node increases during the selected time interval, from 0 to -30 N, thus allowing for the total load to vary from 0 to -750 N. All the nodes on the bottom surfaces of the flat portions are fixed in the vertical direction. All these conditions allow the three point bending experimental conditions to be simulated closely.

The total number of elements and nodes being high, each of the analyses takes considerable amount of computational time. Field output requests and history of field outputs need to be specified in Abaqus, so as to be able store and retrieve data for postprocessing and recording the results for further discussion.

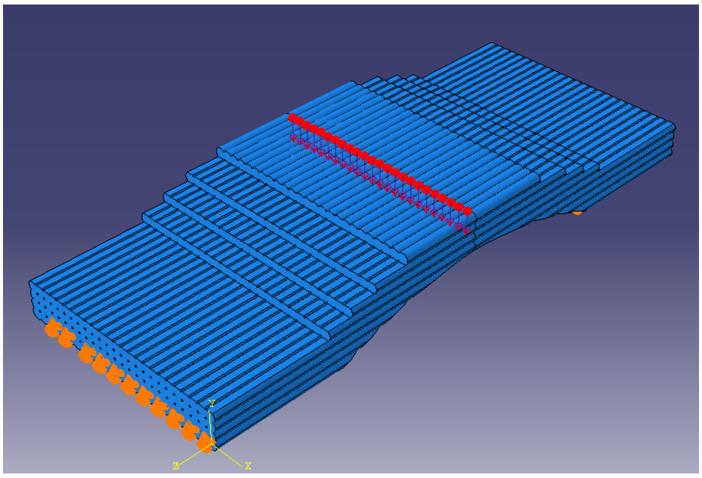


Fig. 5.10 Load and boundary conditions in the case of the flat layer FDM model

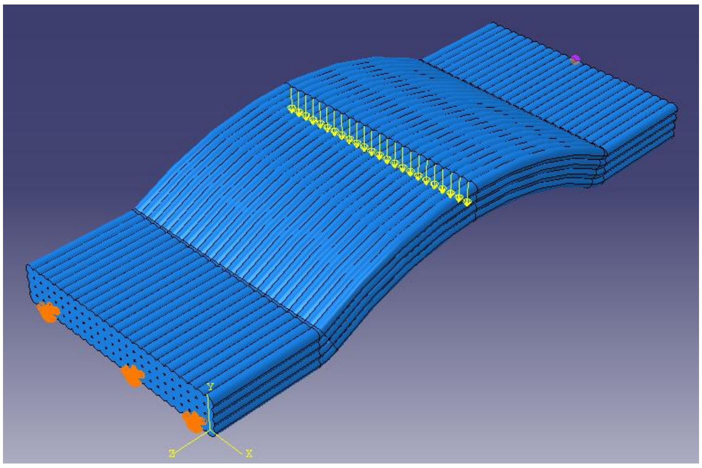


Fig. 5.11 Load and boundary conditions in the case of the curved layer FDM part

5.6 Results and discussion

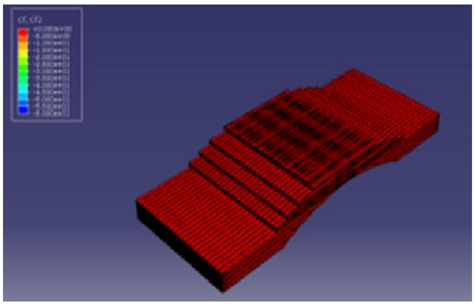
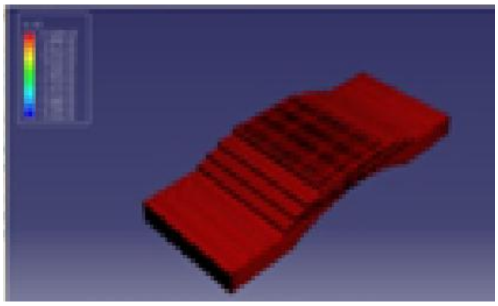
A lot of data is generated from the finite element analysis of the stress fields of the two parts in terms of displacements and various stress components. However, the finite element results are mainly considered to compare the maximum displacement values with the maximum allowable displacement of the material as generated by the tensile test conducted on the raw material and presented in the load-displacement diagram of Fig. 5.6. The reason for this is a lack of experimental data on other parameters. The distribution of the stress components will also be used, but mainly to assess the stress patterns generated in different material deposition schemes.

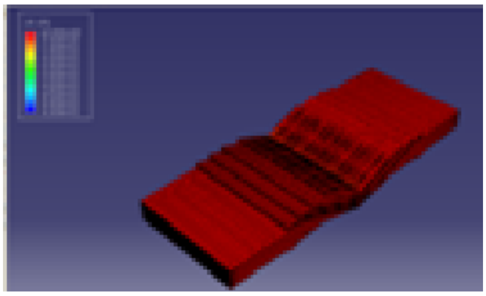
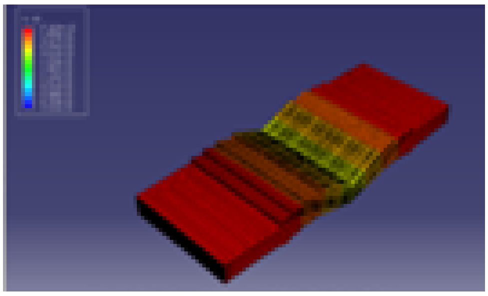
Each of the model is analysed for a time dependent variation of the applied loads. Fig. 5.12 presents a series of screen shots showing the gradual increase in the applied load and the corresponding variation in the displacement. There is a peculiar problem observed in the case of the flat layer FDM model, the applied load is concentrated at a few points, in a very narrow zone. The component assumes a completely distorted shape, and to reach the target load of 400-500 N overall, it was necessary to increase the total of nodal loads beyond 900 N. The model was tested a number of times, with all load and boundary conditions repeatedly checked, but the end result was the same. It was finally concluded that the relatively weak interaction between the flat layers, in particular at regions, where the part bends into a curved shape from the flat portions leads to an early failure and the strands are almost disconnected and the part has no consolidated shape to be able to take the increasing load. This needs to be verified against the behaviour of the curved layer FDM part.

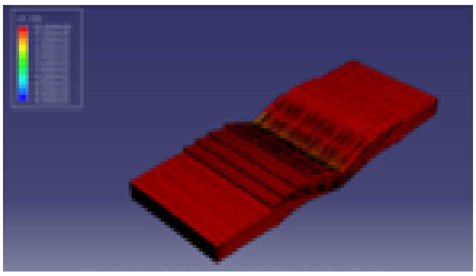
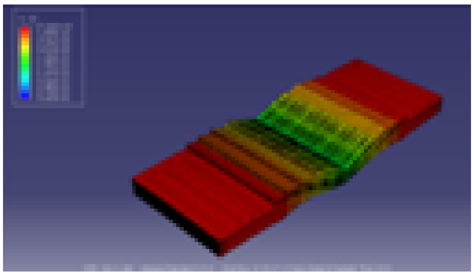
The target displacement to decide on the yielding of the material is 0.2 mm as obtained from an observation of the load displacement diagram obtained from the tensile test on Fabepoxy and shown in Fig. 5.6. The flat layer component seems to have attained the target displacement, suggesting the initiation of plastic flow and subsequent failure of the component at a relatively high overall load, but due to the anomaly stated above, the actual nodal force is much lower, and as already hinted, the components seem to be failing at very early stages of loading. This is attributed to the weak interlayer bonds emanating from the flat layer structure.

The curved layer FDM model on the other hand, produced a more meaningful result as expected. As shown in Fig. 5.13, the load pattern was distributed around the region at the top central regions of the part, though there is a concentration of the load around the top partition line, as it was originally applied only at those loads on this line. There is a gradual increase in the load as time passes by, as shown in the figures on the left side of Fig. 5.13. The corresponding vertical deflection diagrams on the right column also show a gradual increase from the top to bottom. Finally, the target displacement of 0.2 mm is attained at some portions at the top, when the overall load is around 500-600 N. This is a bit of an over estimation compared to the experimental result from the three point bending, giving a failure load of around 400 N in general. However, the finite element simulation is not very far from the experimental value, given the lack of accurate property data. Further, the mesostructure with a 25% deformation of each strand is a gross simplification, which in actual practice would be a continuously varying phenomenon.

The maximum principal stress in the vertical direction is plotted as shown in Fig. 5.14 for the curved layer FDM part. It is evident that the maximum stress is first reached at the bottom potion of the arch, suggesting the initiation of plastic deformation, crack formation and subsequent tearing apart of the part occurring around this area. The results from the three point bending confirm the same result. Finally, a look at the overall deflection pattern of two specimens under investigation presents a marked difference in the mechanisms of deformation between the two.

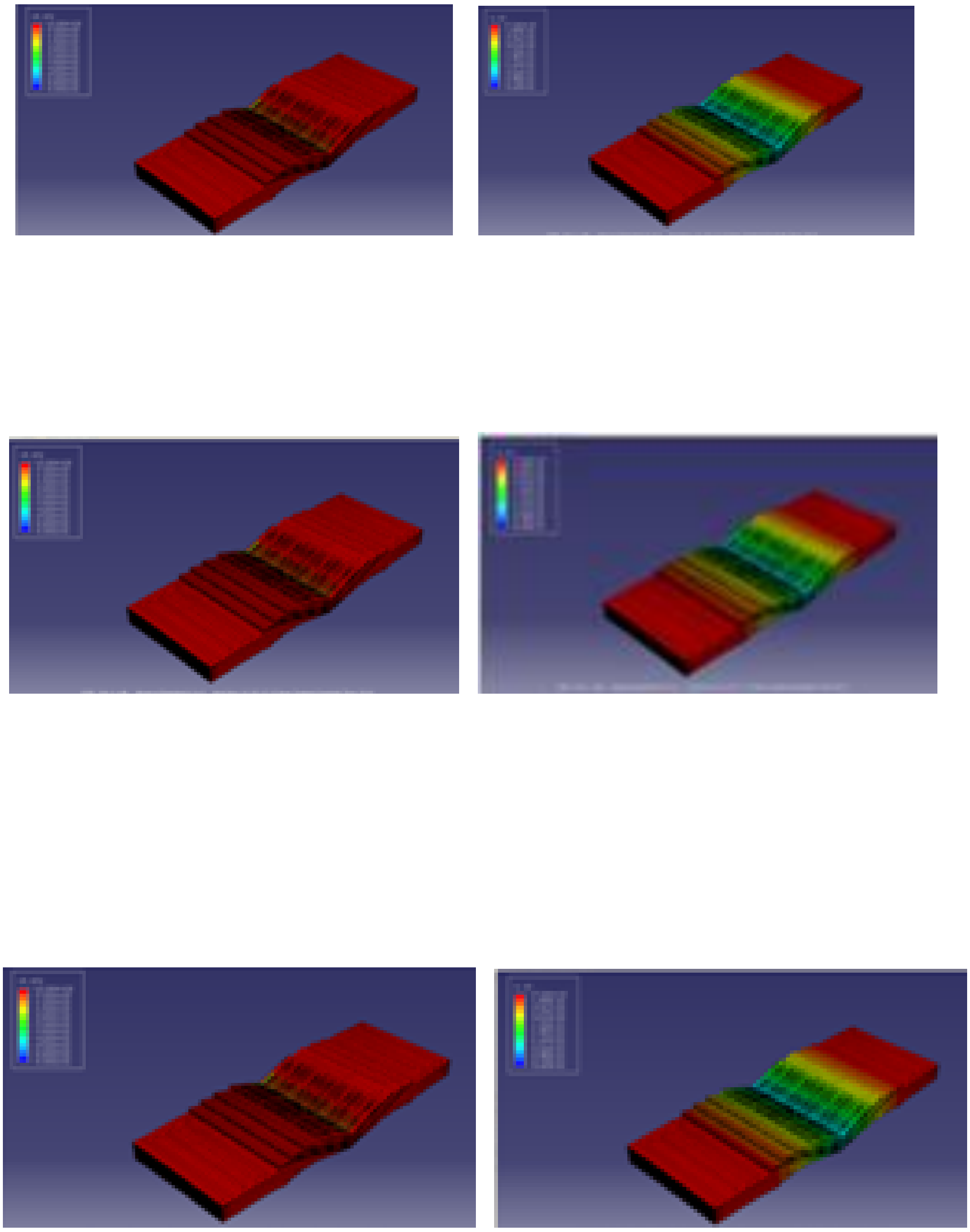


Fig. 5.12 Time dependent variation in load and vertical displacement in flat layer FDM model

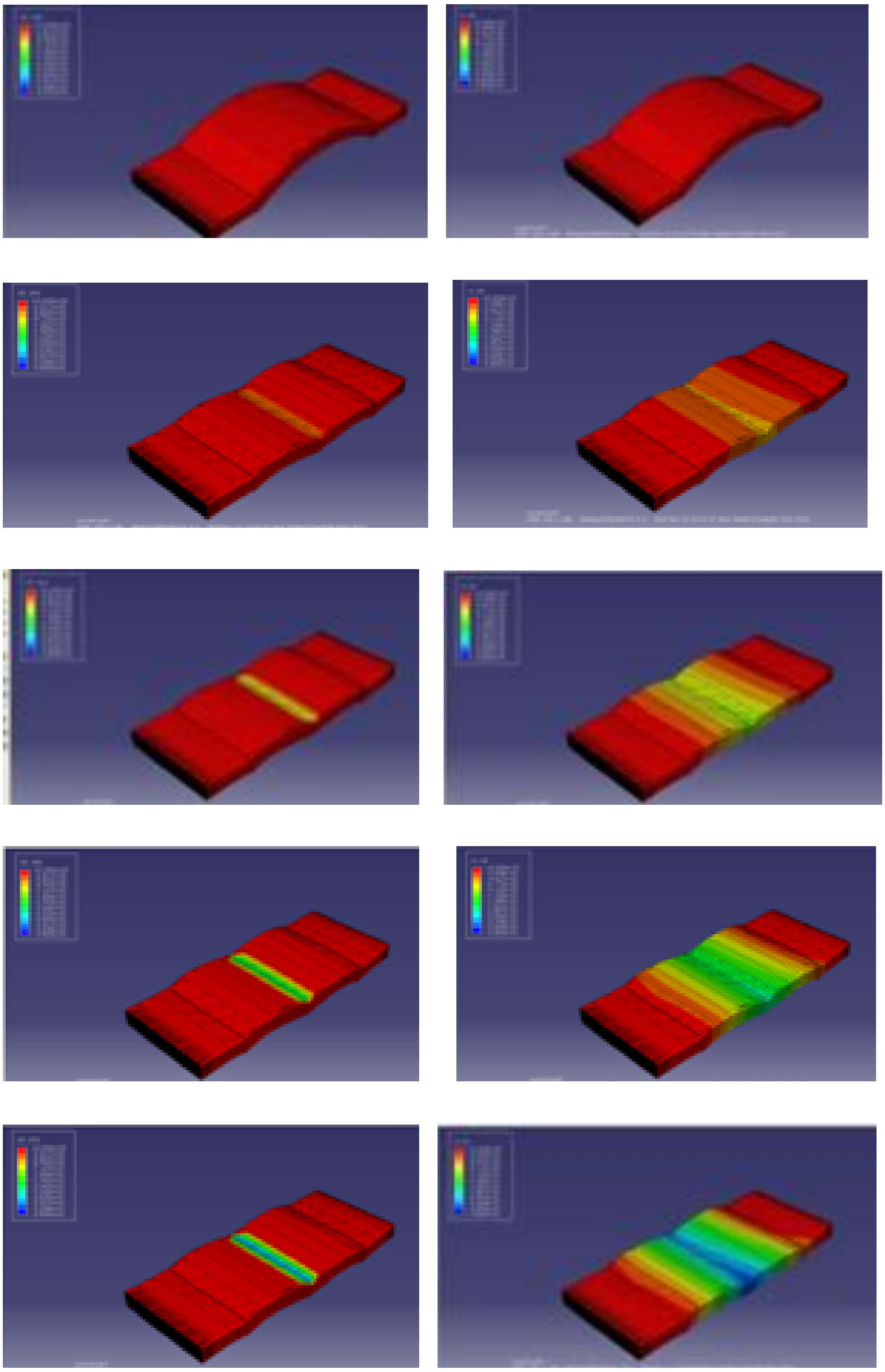


Fig. 5.13 Variation of compressive load and vertical deflection with time: curved layer FDM model

(a) Full view *(b) sectional view*

Fig. 5.14 Distribution of stress component in the vertical direction: Curved layer FDM Model

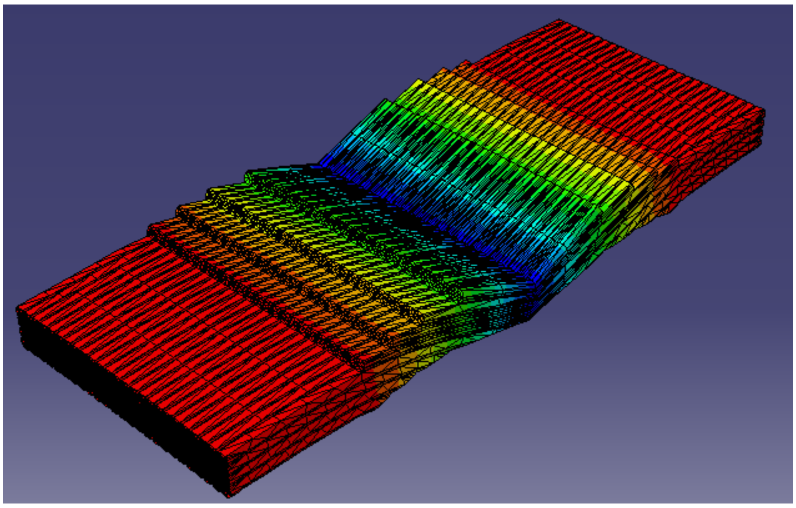


Fig. 5.15 Overall deflection pattern of the flat layer FDM model

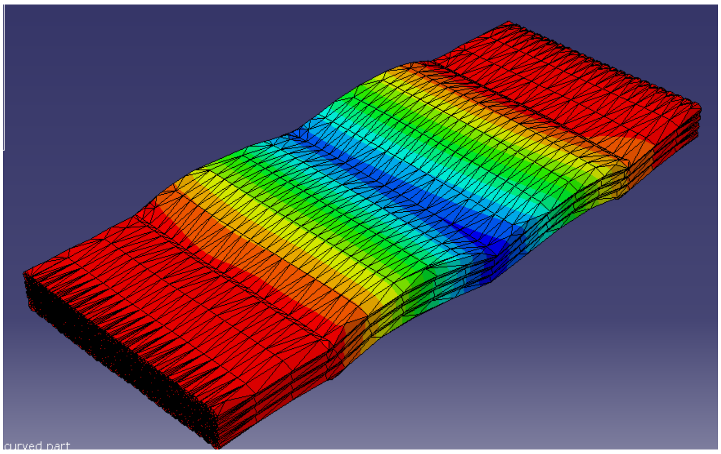


Fig 5.16 Overall deflection pattern in curved layer FDM Model

Fig. 5.15 shows the overall deformation of the flat layer FDM part, which is, as already indicated the result of a gross failure of the strands to stay together. It appears, the flat layers would slide against each other, the moment, and the weak interlayer connections are snapped. This results in large deformations along the length of the part, leading to an early plastic failure of the part. The curved layer FDM part on the other hand, clearly shows a better fusion between individual strands, as is evident from Fig. 5.16. The strand structure remains intact till the end and the part deflects and assumes the wavy shape as depicted, due to the central down ward load and the upward reactions on either ends of the part. As the load gradually increases, the central portion is bent, the upper strands are compressed and the lower strands are subjected to tensile loads. Finally, the part fails, when the crack initiated at the bottom reaches the top, tearing apart the shell like part. The failure mechanisms observed on most samples of the curved layer FDM models subjected to three point bending load confirmed the same.

Chapter 6

Conclusion

The main objective of the project is to establish the effectiveness of the curved layer FDM process through experimental and numerical investigations. A practical set-up and suitable mathematical models were necessary to be procured for the purpose of developing a test platform for FDM. The Fab@home machine is adopted for the purpose of the test platform, and essential mathematical models for CLFDM are reviewed from literature. A working software-hardware system is developed from existing models for the practical implementation of the CLFDM process.

Several material options were tried for being used in the investigations leading to the establishment of the significance of CLFDM. However, there was little success with most material combinations due to the multidimensional requirements of the material for FDM. Final experimental and numerical investigations were carried out using fabepoxy as the candidate material. Statistical design of experiments using Taguchi L8 orthogonal array was used and the influences of geometrical and process parameters were investigated. Numerical models were generated using the finite element methods in Abaqus, for modelling the mechanical behaviour of curved and flat layer FDM. The following are the main conclusions:

- Commercially available Silicone is a suitable material for FDM using a syringe type deposition head.
- Reinforcement of silicone with powder and other forms of composite ingredients does not yield satisfactory results in terms of producing FDM parts for mechanical testing.
- Fab@home as a FDM test bed is reasonable, but poses several problems while printing parts of consistent quality for experimental evaluation.
- Curved layer FDM gives better part characteristics, but the actual influence is dependent on the nature of the material and experimental conditions.
- The speed of deposition appears to have a negligible effect overall, considering the nature of the material used for FDM.

- The effectiveness of the deposition style is confounded with the geometry of the part.
- Finite element simulations clearly depict a marked difference in the deformation characteristics of parts produced by flat and curved layer FDM.
- Flat layer parts fail at inter layer links, which are the sources of weakest points.
- Once the weak links give apart, the part distorts due to a shear sliding of flat layers relative to one another.
- Curve layer part on the other hand withstands compressive loads until the final stages.
- The final failure is due to the formation of a crack at the bottom layers of the curved part at its peak, and the propagation of the same across part, towards the upper free end.
- This fracture and mode of the CLFDM part resembles the brittle fracture mode, as was also observed with a few curved layer FDM samples.

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