Fused Deposition Modeling (FDM)

MAE 298 – Rapid-Prototyping

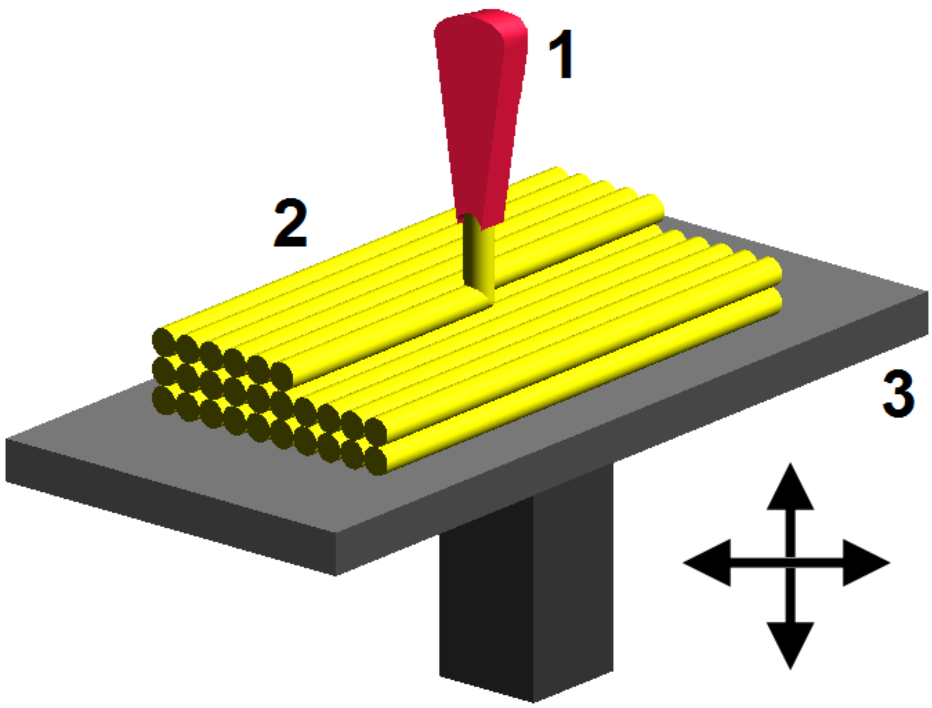

Figure 1: Fused Deposition Modeling Simplify [16].

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1 ABSTRACT

This research will explore the beginning of Fused Deposition Modeling (FDM) from its initial stage to final production and patent. We will explore the advantages of the FDM over other Solid Freeform Fabrication (SFF). We then move on to current research on FDM and its future potential. We will suggest a possible innovation for the FDM such as the Curved Layer Fused Deposition Modeling (CLFDM) with conductive materials. With this suggestion we will explore how this process is achievable alongside with the possible technological revolution this technology hold for circuitry and parts integration.

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2 List of Acronyms

Symbols	*Descriptions*
3DP	3-D Printing
ABS	Acrylonitrile Butadiene Styrene
CAD	Computer Aided Design
CLFDM	Curved Layer Fused Depositon Modeling
FDM	Fused Deposition Modeling
FFF	Fused Filament Fabrication
LENS	Laser Engineered Net Shaping
LOM	Laminated Object Manufacturing
PCBs	Printed Circuit Boards
RP	Rapid-Prototyping
SFF	Solid Freeform Fabrication
SLA	Stereolitography Apparatus
SLS	Selective Laser Sintering
STEP	Standard for Exchange of Product Model Data
STL	Stereolitography (file format)

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5 INTRODUCTION

In recent years, the technological leaps in the field of Computer Aided Design (CAD) and rapid-prototyping have given engineer designers tools to generate prototype models from computer models. With Rapid-Prototyping (RP) technologies growing tremendously and becoming commercially feasible for the general public, Fused Deposition Modeling (FDM) have become more popular recently. Due to the popularity of FDM, this research paper will try to explore the various aspect of fused deposition modeling from its initial prototype to possible future improvement.

- FDM history and initial finding
- Building processes
- Advantages and disadvantages
- Future improvement

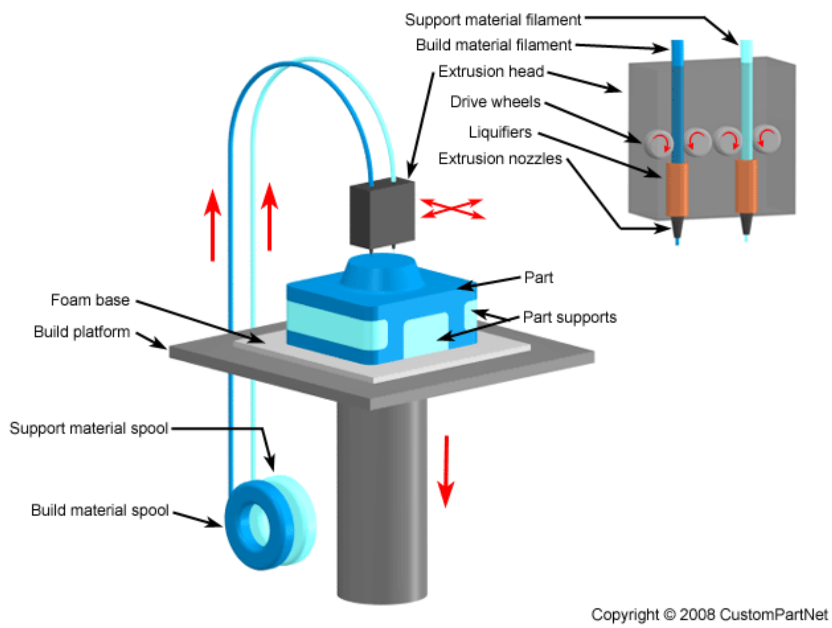

Figure 2: FDM concept model [1].

The general public normally group all solid freeform fabrication (SFF) as 3D Printing. Apparently 3D printing is actually a specific type of machine created by Emanuel Sachs and is a type of SFF. SFF is a general name for all the computer driven machine that does additive manufacturing of solid parts or models. FDM also fall under the SFF categories as does many other desktop manufacturing machine.

6 FDM BACKGROUND, HISTORY, AND PRINCIPLE

The development of FDM like all SFF was developed in the late 20th century due to many advancement in RP developments. FDM was developed by S. Scott Crump in the late 1980s and then patent in 1989 with his wife Lisa Crump. Mr. Crump originally automated design with AutoCAD for his job while at the company IDEA. While at IDEA, Mr. Crump developed a solid freeform fabrication machine to solve the problem of his difficulties getting prototypes to test new product designs. This development lead him to develop the fused deposition modeling machine that used thermoplastic.

It is say that the FDM originate from ideas similar to inkjet printing. The similarity for its design can be seen in the moving ink output nozzle. Both the inkjet printer and fused deposition modeling printer used a nozzle head to output ink or plastic with. This nozzle in both inkjet and FDM design is a moving nozzle that moves to the correct position before depositing its ink material. The hot glue gun would be the most similar in design if computer control is added to control glue location and output position.

The fused deposition modeling fall under the category of fused filament fabrication (FFF). FFF is an additive manufacturing technology that deposits a filament of same material on top or beside the same material to join. FFF is coined by members of RepRap to avoid legal issued of FDM patent and naming. This section will go over the main process of the FDM from initial file import to final part produced.

FDM came into production after Stereolithography Apparatus (SLA); therefore, stereolithography (.STL) format become popular and FDM at that time were force to used .STL file input format. This lead to many FDM machine input format file for printing to be .STL. The new push for format is Standard for Exchange of Product Model Data (.STEP).

With the input file out of the way the main process of how the FDM machine works is to be described. FDM basically build three dimensional parts by heating material to its flow point and advancing the material forward through a computer controlled extrusion head. The outcome of this is a finely produce part that is ready to use.

6.1 *FDM and its Part Production Process*

The main process of the FDM machine to produce three dimension parts can be broken down to these following main steps: create build file, prepare FDM machine, build CAD parts, and remove support materials. The process below is an example process flow of a FDM machine from file input to part production.

6.1.1 Create Build File

The initial step is to import the .STL format file (unless newer machine accept more advanced standard like .STEP). Once open, some machine will let you orientate part, select material, color, and slice thickness [1].

Once inputted the machine will will check for possible build error, etc. and build support material. If nothing comes up the CAD model and support material is then sliced into layers [1]. The computer also create toolpaths for both the parts and support structures. The computer then output the build file with all motion control paths, sliced, and properties defined.

6.1.2 Prepare FDM Machine

Depending on machine but both support materials and part material cartridges need to be in place before the machine starts [1]. Clean any previous debris as necessary from previous part production. Wait for the machine to heat the printing material to optimum temperature or flow point.

Once heated to the flow point the machine may start printing the desire parts along with the support materials [1].

6.1.3 ***Build CAD Parts***

The Z stage or support stage for the part rises to the starting position (in some machine). Some case the nozzle may be moved instead. Either way, once directly above the support stage the heated material is extruded. Normally a few layer of support material is deposited to produced foundation for the part [1]. The extrusion head will move in XY direction to deposit and join the materials together [1]. The nozzle extrude and lays down a ribbon of materials continuously to complete each layer and switch out nozzle between support and part materials.

After completing each layer the stage is moved down by the desire thickness or layer thickness and the nozzle continue to lay down ribbon of materials to produce the next layer. The same thing is done for the support materials as well. Part material and support material extrusion head are alternated as necessary to produce the desire part feature.

In FDM process, each layer is heated and deposit on the previous layer. The layer instantly fuse to the previous layer or the stage (stage mounting is for the first layer of support material).

6.1.3.1 Detail of the Extrusion Process

The extrusion process of FDM accuracy and precision comes from the coupling of both the extrusion head motion and material feed rates. Both the feed rate and extrusion are computer control to give the right output and thickness.

Drive wheels in this process push material filament into the hot liquefier section of the nozzle tip. The pressure forces the heated material through the tiny tip which is then output. When the head accelerates and decelerates through its different location for depositing materials the drive wheels adjust its pressure to change the material flow rate as necessary [1]. This result in the detail of the extrusion process for creating the support material and part material layers.

Figure 3: FDM part production (no support material is shown) [1].

6.1.4 *Remove Support Materials*

After the part is finished and cooled down the part can be removed for post processing. In this step support are to be removed. There are two way to remove the support material for this FDM process and they are to either place the whole part in soluble liquid or manual removal of the support material.

6.1.4.1 Soluble Support Material Removal

The soluble support materials may be place in a tank of liquid and left for automatic support material removal [1]. Some liquid may just soften the material to make manual removal simpler. Solution vary depending on the concentration and type of support materials.

6.1.4.2 Manual Support Material Removal

This process require manual labor to remove the support materials. This process may prove to be more dangerous to the part if careful handling is not done correctly. This process require twisting, breaking, tearing, and scraping support materials from the part [1].

7 FDM Advantages, Disadvantages, and other Printer Comparison

FDM when compare to other machine has price range that makes it the most affordable. The cheapest cost a few thousand dollars and is desktop friendly compare to many other machine in the SFF categories. The aspect that stand out for FDM is its feasibility and office friendly properties that make it stand out over 3DP, LENS, LOM, SLA, and SLS.

7.1 *Basic Comparison with 3DP, LENS, LOM, SLA, and SLS*

The other machine is either too costly or not as office friendly as FDM. When compare to 3DP the powder handling is not as convenient so this makes the FDM more advantageous [2]. 3DP may offer better finishing when baked and polished with more diverse part in term of materials if powder form is obtainable. The drawback for 3DP is its post-processing and handling of powder in office environment may not be as friendly as FDM [3].

LENS is capable of producing fine parts including metal parts which FDM part is incapable of doing [4]. The drawback of LENS is that it is pricey and definitely not office friendly for the general public. The high power laser also is a draw back and normally only corporate companies can afford such laser and machine for RP testing. For smaller application and functional parts FDM can produce them without much difficulties.

When compared to LOM, FDM can produce better parts in term of functionality and details. LOM produced parts lack functionality and surface finishing is poor. LOM so far do not have wide application [2] that make it more advantageous than FDM. The part produce by LOM are only static parts. Parts cannot be made to move and functional like FDM. The benefit of LOM is its capabilities to produce large parts that can be used as model display at low production time [5]. But on the other hand FDM can produce functional RP parts for testing at low price that makes it more advantageous in feasibility and functionality.

SLA when compared to FDM have advantages in finer finishing and better feature size. The major drawback for SLA process is the cost of the machine. It is one of the most expensive machine out of the all the SFF machine available with one of the finest finishing and quick time production. SLA can print the part within 24 hours [5] but FDM can do the same thing with lower surface finish quality.

SLS have the advantage to produce strong metal parts with good functionality over FDM. The production can be used for more rigorous testing and demonstration. The drawback of the SLS comes from the price and operation environment. This machine cannot be operated in an office workspace as it will emit toxic fumes. Functionality and surface finish wise SLS have the advantage after post-processing. FDM, on the other hand, require little or no post-processing beside support material removal and can produce cheap functional parts in an office space.

7.2 *Advantages and Disadvantages*

There are various advantages and disadvantages in FDM. The key features that makes FDM stand out for to the general public may be its capabilities to create function parts, cheap price, and office friendly properties. The follow table listed below will list out more advantages and disadvantages of the FDM process either in comparison to other SFF or traditional manufacturing.

FDM can produce parts using the following materials: thermoplastic, wax, polycarbonate, and polysulfone materials. Some research materials for FDM includes the following: ceramics, metals, high performance thermoplastic composites, and metal polymer composites. With the growth of material variety through research FDM could definitely continue to improve in the material area as more method are developed.

Table 1: Advantages and Disadvantages Chart [16] [5].

<table>
<tr><th>Advantages</th><th>Disadvantages</th></tr>
<tr><td>Produce Functional Parts</td><td>Limited to lower temperature materials</td></tr>
<tr><td>Cheap pricing for FDM machine</td><td>Slower build time for large parts</td></tr>
<tr><td>Office friendly size and operation</td><td>Output orientation changes overall strength</td></tr>
<tr><td>Various color parts</td><td>Limited in mass production of parts</td></tr>
<tr><td>Low production time</td><td rowspan="2">High temperature operation of produced part is not possible</td></tr>
<tr><td>Clean production and good finishing</td></tr>
<tr><td>Wide range of low flow point materials</td><td rowspan="2">Function parts are not as good as SLS and LENS</td></tr>
<tr><td>Dimensional Stability compare to other SFF</td></tr>
<tr><td>Simple post-processing of support material removal</td><td>Rigorous testing like parts made in SLS is not possible</td></tr>
</table>

8 FDM Major Vendors and Applications

Within this recent year many vendors are now offering feasible FDM machine. FDM was initially commercialized in 1990s by Stratasys. Now FDM machine can be brought from many companies and vendors due to its wide variety of applications. Some vendors for FDM includes Makerbot, Solid Concepts, Stratasys, 3DSystems, etc. Some major application FDM have imprint itself in are concept models, functional prototypes, manufacturing tools, and finished goods [1].

8.1 *Concept Models*

In early design production FDM can provide good example models for review and testing. This will provide possible updates on final design base on identified flaws. Reprint, analyze, test, and updates are made possible with FDM quick printing time. FDM can accelerate the development of model design and reduce the cost of the development time for a product [1].

In the medical field FDM can also provide cheap 3D sample model of specific patient after scan. This will give doctors quick access, visualization, and practice model for better understanding of specific patient's internal structural design. FDM in this field have many advantage when production time become crucial to producing model parts. Further modification will enable FDM to make biomedical devices.

Figure 4: Concept Models [1].

8.2 *Functional Prototypes*

FDM also have a strong application in creating functional prototypes. FDM can make prototypes ready for performance test and rigorous engineering assessments to help avoid possible flaw and reduce development time [1]. The FDM functional prototype will give the developer parts that can function when tested and help reduces time to market and maximizes product development and performance.

Figure 5: Functional Prototypes [1].

8.3 *Manufacturing Tools*

FDM can also provide quick way to produce a manufacturing tools for a company. FDM can quickly produce fixtures, gauges, jigs, patterns, molds, and dies at low cost for the companies [1]. Cost to fabricate mold and cast can be reduced tremendously with FDM. More complex shape

Figure 6: Manufacturing Tools [1].

for mold and cast could be created with FDM than conventional method while reducing production time at the same time. One great example is to create part for investment casting or sand casting out of wax. Then once the imprint have been made the FDM printed wax model can be melted away.

8.4 *Finished Goods*

FDM can produce finished goods at low cost for production run of a few thousands. In traditional manufacturing producing a few thousands would not be feasible for any profits, but with FDM the low production of finished goods is made feasible. FDM will provide the feasibility for aerospace companies, medical device makers, and visionary entrepreneurs the possibility to produce low production parts [1].

Figure 7: Finished Goods [1].

9 Research and Improvement Issues

Some features for research and improvement in FDM includes strength of produced parts, multiple nozzle design, and medical application.

9.1 *FDM Produced Part Tensile Strength*

When testing produced parts for FDM they discover that there are many implication for possible future production. When Smith and Dean tested the polycarbonate material in a tensile test they found out that face-up provided the largest ultimate tensile strength. This imply that depending on orientation during FDM part production the structural strength of the part will change [6].

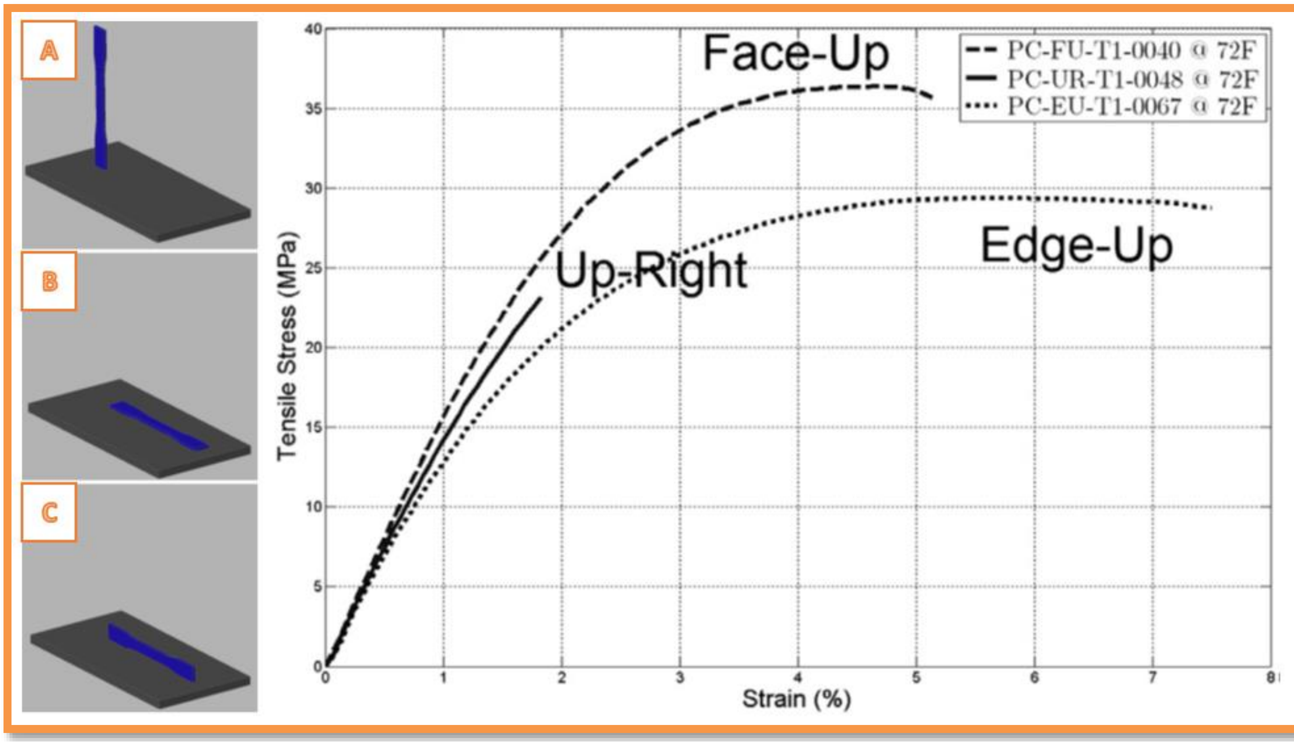

Figure 8: This figure feature 3 different positions for the tensile test. (A) Up-Right (B) Face-Up and (C) Edge-Up position [6].

It seem that depending on extrusion direction of the nozzle that the material strength will change as well. This recent research done by Smith and Dean shows that repeatable measurements can be made of ultimate tensile strength and elastic modulus of FDM manufactured parts. This imply that future manufactured part can be predictable with research and improve design and application can used FDM parts. By understanding the strength of FDM parts specific standards can be achieve for parts and better production requirement guideline can be imposed. These guidelines will pave a way for better creation of part strength and standards. Though further research is still needed to better understand the different produce parts in FDM as they tend to be weaker than the bulk material properties in strength.

9.2 *FDM and Biomedical Microdevice Application*

FDM research expand across many field including the biomedical field. Current research on FDM include modification of FDM ABS parts to make RP of biomedical microdevices [7]. Some research on FDM include creating techniques that is suitable for building microdevices that can interact with biological molecules and cells in water permeable and biofouling environment.

There is research in modifying the surfaces of ABS FDM rapid prototyped devices with microstructures channels and other features to render the part water impermeable, hydrophilic, or biocompatible [7]. The changes recommended includes acetone based sealing method to minimize the effect of surface roughness and structural reliability [7]. McCullough also suggested photo-induced graft polymerization functionalities onto surface of the ABS to increase hydrophilicity and resistance to protein adhesion. By changing the surface morphology of the FDM produced parts water contact angle and adhesion of protein will change and therefore improve biocompatibility.

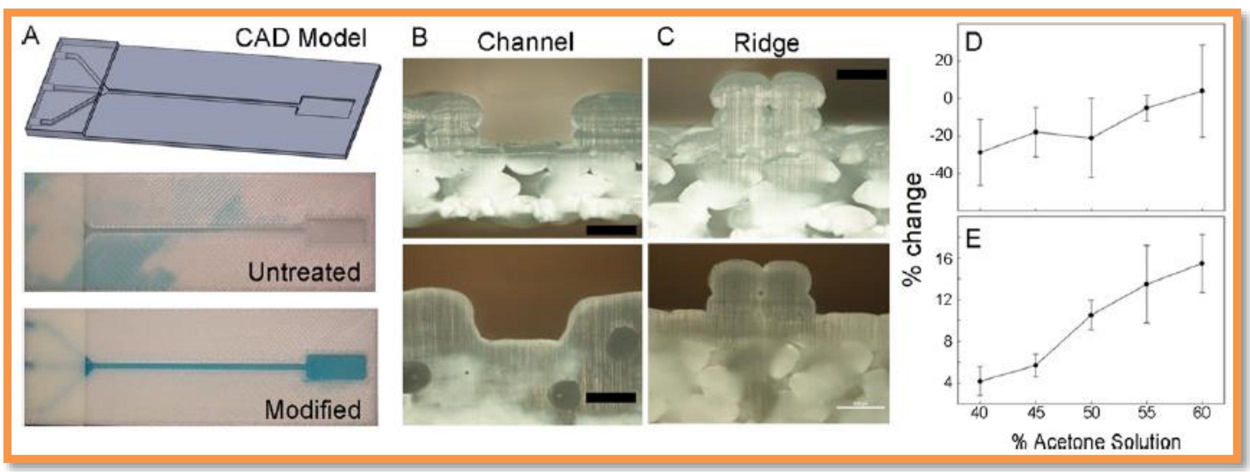

Figure 9: (A) Microchannels permeability before and after treatment of FDM parts. (B, C) Before and after treatment of FDM parts. (D) Percent change in ridge radius of curvature (E) Channel wall incline angle vs. acetone solution concentration. [7].

10 IMPROVEMENT AND REINVENTION FOR FDM

The development of FDM have been moving onward tremendously due to many of its advantages in RP. In this section we will discuss and uncover many other possibilities for the improvement of FDM and its applications. Some of the discussed possible future development for FDM includes the following:

- Curved Layer Fused Deposition Modeling (CLFDM) with Conductive Polymer Additive Manufacturing
- Composite material or multi-material manufacturing with computer chips, circuits, or other materials

10.1 *CLFDM with Conductive Polymer Additive Manufacturing*

The idea of CLFDM is to print components or parts with integrated conductive polymer electronic circuits. This technique can have tremendous application to robotics and mechatronics field. By integrating the electronic circuitry into complex part that can be produced through FDM, wire can be eliminated, design aesthetic can be improved, and complexity can be avoided. By making CLFDM possible better integration of wires can also be achieved as well. CLFDM is suggested alongside conductive polymer because existing FDM methods is incapable of continuously laying out circuitry without being interrupted.

10.1.1 Curved Layer Fused Deposition Modeling (CLFDM)

CLFDM is a relatively new and currently in testing phase in a few universities. Two working CLFDM systems were developed one at the National University of Singapore (NUS) and another at Auckland University of Technology (AUT) in New Zealand [8]. Both test have provided promising results in the possibilities of CLFDM. Feasibility and production of CLFDM have not been made clear though as there are still more research to be done on CLFDM.

Two CLFDM machine produced by NUS and AUT are still prototype design with curve layer algorithm to make it possible for curve layer designs. They have produce curved layer parts as described. The manufactured part is still at a beginning stage but making curve three dimension part is now possible with this new technology.

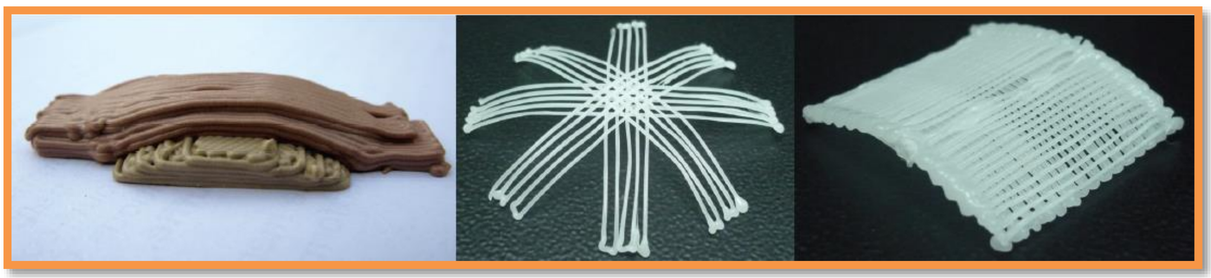

Figure 10: CLFDM parts made by the two universities [8].

Figure 11: CLFDM prototype machine made by two universities [8].
A) Two left images made by NUS: Screw Extrusion System B) Right image made by AUT: Fab@Home.

The new CLFDM still have many drawback as its mathematical algorithm for the curve layer is more complex. The CLFDM require better algorithm controls of the stage and extrusion nozzle; therefore, making this design difficult to produce. The design for CLFDM geometric advantage also add complexity to finding the ultimate tensile stress. In flat layer extrusion of FDM parts the ultimate tensile strength is much more predictable compare to the CLFDM part.

The layering effect and algorithm cam be sample in the Matlab figure below. The part first produced would be the support materials necessary to make the curved surface on. Once the support is produced the curved extrusion can then be fused onto the support surface. The whole process of CLFDM is in general similar to the FDM procedure as previously mention but with added complexity in the computer numerically control nozzle and stage.

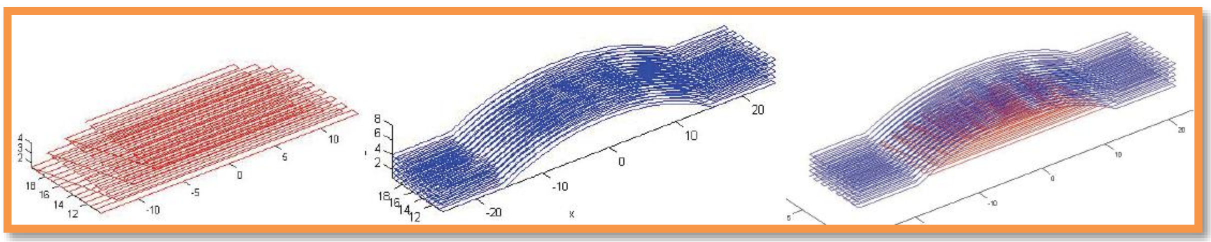

Figure 12: Matlab representation of support and part material path tool generation [8].
A) Support material B) Part material C) Support and part material actual placement.

The figure above show how support materials can be first produce for CLFDM. The support material in this design is produced in the same way as FDM. The main difference comes in when the part material is produced. The part is directly extruded on the support material with changing Z-elevation as necessary to produce the curved outline as desired for the part.

With this technology more advance circuitry and housing design can be made as describe in the next section. CLFDM also hold major possibilities in complex part design. The main problem is if the CLFDM can be made more economical, feasible, and advantageous enough over other possible new SFF design.

10.1.2 Adding Conductive Polymer to CLFDM

Existing flat layer additive manufacturing, like FDM, currently does not let circuitry be place continuously without being interrupted so CLFDM is suggested [8]. With CLFDM technology it opens up new possibility of building complex plastic parts that contain conductive electronic tracks within the plastic part [8]. CLFDM holds the possibility for creating continuous filament in three dimension making complex fitting for conductive circuitry.

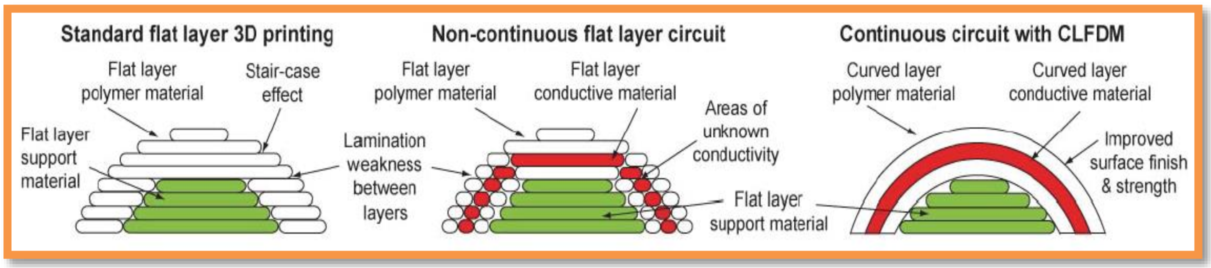

Figure 13: This figure feature the advantage of CLFDM over FDM [8].
A) Standard flat layer FDM B) Non-continuous flat layer circuit and C) Continuous circuit with CLFDM.

The figure above show that with the flat layering method circuitry will be discontinuous making conduction for part difficult. With CLFDM continuous layering, circuitry becomes possible. The idea here is to produce parts that integrate the housing and electronic circuit into one part rather than conventional separate part.

The creation of CLFDM with conductive polymers could possibility eliminate or integrate printed circuit boards (PCBs) into one design. CLFDM could become the printed circuited boards instead if it became the housing for the circuitry as a whole. CLFDM with conductive polymers could revolutionize the product design field as a whole if constrains are removed from having to design around flat PCBs and wiring.

This field of CLFDM with conductive polymer can change the way direct digital manufacturing works. Costs and size for packaging of many electronics components can be completely revolutionized if part is completely printed as part of the housing. The housing in this case will serve as the product and packaging for the electronic parts. This can spark innovated changes toward the field of robotics design if the information signal through the circuitry become one with the bodily parts, rather than just and outer exoskeleton of the robot.

10.1.3 Multi-material manufacturing with Integrated Circuits

With circuitry integrated into the FDM process we created housing parts that has electronic properties. But by adding integrated circuits the produced part could have digital control and communication with the outside world. For example by incorporating thermomistor materials and wireless information signal capabilities temperature could be read from the inside. This does not include only temperature, moisture sensors, frequency sensors, and other indicators can be incorporate if circuitry runs through the FDM parts. Even if the parts is not made from CLFDM then the part could be an integrated circuit at the single layer with the same but limited capabilities. Recent research in materials for FDM includes: ceramics, metals, high performance thermoplastic composites, and metal polymer composites. With these new materials being research for FDM part production, FDM may hold potential for future smart materials with electronics integration.

11 DISCUSSION

The recent decade of development in RP and computer aided design have made many SFF available. With the cost of some SFF becoming feasible for the general public SFF is becoming more well-known and popular. We found out that some FDM are very feasible SFF machine out there costing a few thousand at the lowest price. FDM being a flat layer thermoplastic extrusion process makes it office friendly and produce goods that are easy to handle.

For this we learn that FDM have many application in various field ranging from engineer design to biomedical. Application for FDM includes concept models, functional prototypes, manufacturing tools, and finished goods. I believe FDM will continue to develop in this field as it now have a strong foot hold in producing small batch production where bulk tradition production are not unfeasible.

Current research and application of FDM can lead out to new technologies like CLFDM and integration of circuitry in the parts. Making electronic housing possible and possibility remove electronic components packaging in some case.

12 Conclusions

Our research here have shown that FDM have many future applications either in the design and prototype field or biomedical field. FDM provide CAD designer and visionary entrepreneur with a feasible way to produce products with FDM. Future application of integration for FDM in materials and circuits also seem very promising as research have shown CLFDM is possible. Now just by laying out a wire along the curve path will make conductive FDM part possible. FDM could revolutionize our field by making the design part and circuit integration housing possible, creating material parts capable of collecting data, analyzing data, and communicating the collected data to external sources.

13 Acknowledgements

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15 APPENDICES

Refer to References for any information.