A Comparative Study on Additive and Subtractive Manufacturing

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Abstract

The objective of this study is to effectively use Additive Manufacturing (AM) techniques (3D printing) and Subtractive Manufacturing (SM) techniques (CNC machining) and compare and contrast the process parameters and quality of parts produced. In particular, produce the exact same part on two different machines: MakerBot Replicator 2X (AM), and Roland 3D CNC Milling Machine (SM). The study provides details on the methodology of each manufacturing process, the actual processes used, the parts produced, and the measurements made on each produced part. The AM and SM were evaluated for the setup process of each method (number of steps and setup time), ease of use, printing/ machining speed, accuracy, surface finish, and percentage of material waste. Results obtained from students' hands-on projects were presented and discussed. Some of the difficulties encountered and the learning experience from the student team are also presented and discussed.

Keywords

Additive manufacturing, CNC, 3D printing, rapid prototyping, and process parameters.

Introduction

Additive Manufacturing refers to a process by which digital 3D design data is used to build up a component in layers by depositing material. The term "3D printing" is increasingly used as a synonym for Additive Manufacturing. The term Additive Manufacturing holds within such technologies like Rapid Prototyping (RP), Direct Digital Manufacturing (DDM), Layered Manufacturing, and 3D Printing. There are different 3D printing methods that were developed to build 3D structures and objects. The 3D printing technologies include: Stereolithography (SLA), Digital Light Processing (DLP), Fused Deposition Modeling (FDM), Selective Laser Sintering (SLS), Selective Laser Melting (SLM), Electronic Beam Melting (EBM), and Laminated Object Manufacturing (LOM)[1, 2].

Subtractive manufacturing is a process by which 3D objects are constructed by successively cutting material away from a solid block of material. Subtractive manufacturing can be done by manually cutting the material but is most typically done with a CNC Machine. Advanced CNC machines utilize multiple tools and cut around at least three (x, y, and z) axes such that they minimize the requirement for designers to flip the block. One of the principal advantages to subtractive manufacturing is the ability to machine an extremely thin piece of plastic into a living hinge. This kind of process is simply not yet possible in a 3D printer. For those prototypes that require living hinge components it is useful to produce certain parts using additive manufacturing while using the CNC machine for specialty components like a living hinge[1, 2].

The objective of this study is to effectively use additive (3D Printing) and subtractive (CNC machining) manufacturing process machines and compare and contrast the processes and parts produced. In particular, compare AM and SM technologies using low cost process machines available at Mercer University School of Engineering by producing the exact same part on two different machines: the MakerBot Replicator 2X 3D Printer (AM), and the Roland 3D CNC Milling Machine (SM). The methodology of each manufacturing process, the actual processes used, the part produced, and the measurements of each produced part are presented and discussed. The results of the measurements were compared for each process machine to determine which provided the most accurate and precise machining for a typical lab project. Other students' hands-on projects results were also presented and discussed.

Background Research

The Additive Manufacturing/Rapid Prototyping process allows the fast creation of products' prototypes eliminating considerable amounts of resources and time spent on the project when compared to traditional development design methods[1]. In Additive Manufacturing (AM), a model initially generated using a three-dimensional Computer Aided Design (3D CAD) system, can be fabricated directly without the need for process planning. Although this is not in reality as simple as it first sounds, AM technology certainly significantly simplifies the process of producing complex 3D objects directly from CAD data. This technology came about as a result of developments in a variety of different technology sectors[2].

The 3D printer is a machine allowing the creation of physical object from a three-dimensional digital model, typically by laying down many thin layers of a material in succession[3-5]. This is the main characteristic that distinguishes the 3D printers from other numerically controlled (CNC) machines where the production process is subtractive, meaning that the final object is achieved by removing the raw material using different mechanical tools[2, 6].

The 3D printer has become a good alley of Rapid Prototyping, because the process of this technology is easy to design, rapid to create, or replace[7, 8]. Manufacturers and product developers used to find prototyping a complex, tedious, and expensive process that often impeded the developmental and creative phases during the introduction of a new product and with this new term and the 3D printer, all this process has become easy to manage and fast to accomplish[8]. Laser-based rapid prototyping and other related technologies are also available for making 3D parts[9]. The 3D printers have been used to build and test products and prototypes in laboratory environments[10, 11].

Methodology

For the purpose of this study, a simple 3D model was designed using SolidWorks[12]. A simple model is used so that production is simple and measurements are easy to gather. The part is designed specifically with the idea of comparison in mind. The descriptions of the machines, software, and tools used for making the part are presented in the following sections.

Design and Modeling

SolidWorks[12]

SolidWorks is solid modeling computer-aided design (CAD) software produced by Dassault Systèmes SolidWorks Corp. The primary use of SolidWorks is for the production of 3D models and conversion to STereoLithography (STL) file format for use on the manufacturing machines.

STL File

STL files are derived from word STereoLithography which was the first commercial additive manufacturing (AM) process. STL files come in two formats: ASCII (text) and binary. ASCII format is less common and is primarily used for teaching or illustration. STL files consist of list of triangular facet with each triangular facet uniquely identified by three vertices or corners and a unit normal vector. An STL file will hold no dimensions and it is the user's responsibility to know what unit of measurement is being used (in this case, inches).

Manufacturing Process

MakerBot Replicator 2X[13]

The MakerBot Replicator 2X (Figure 1), manufactured by MakerBot, is a full featured desktop 3D printer with experimental dual extrusion[13]. The dual extrusion allows for two interlaced colors that print through aligned nozzles while not having to stop or pause during a print. The printer has a flat, heated aluminum build plate that allows for higher variance in the heating and cooling of the print surface. The printer features a six-sided, draft-blocking enclosure that prevents uneven cooling, shrinkage, or warping. The printer uses fused deposition modeling (FDM) to print and build parts.

Figure 1: MakerBot Replicator 2X

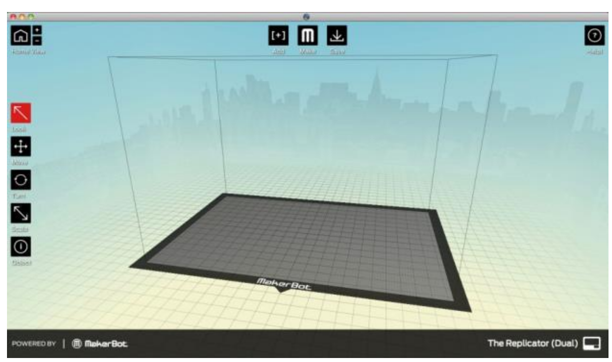


Figure 2: MakerWare Launch Screen

The MakerBot Replicator comes with MakerBot MakerWare (Figure 2), software provided by MakerBot. This is a free, easy-to-use, interface that allows one to move, rotate, scale, 3D models. The primary file type used is STL files and MakerWare takes these files and uses an algorithm to prepare the model for printing. The software allows for the use of "rafts", or stabilizing printed bases, that help ensure adhesion to the build plate and provide a better print quality and "supports", which are basic support materials that allow for printing of more complex models.

MakerBot also has a supplemental website, MakerBot Thingiverse[14], which provides user made models that can be quickly downloaded and printed using their software.

Roland 3D CNC Milling Machine MDX-40A[15]

The Roland 3D CNC Milling Machine (Figure 3 (a)) is a bench top CNC machine designed for rapid prototyping. This particular machine is a 4-axis machine that can handle a variety of materials, is G-code compatible, provides a smooth finish, and is relatively cheap[15].

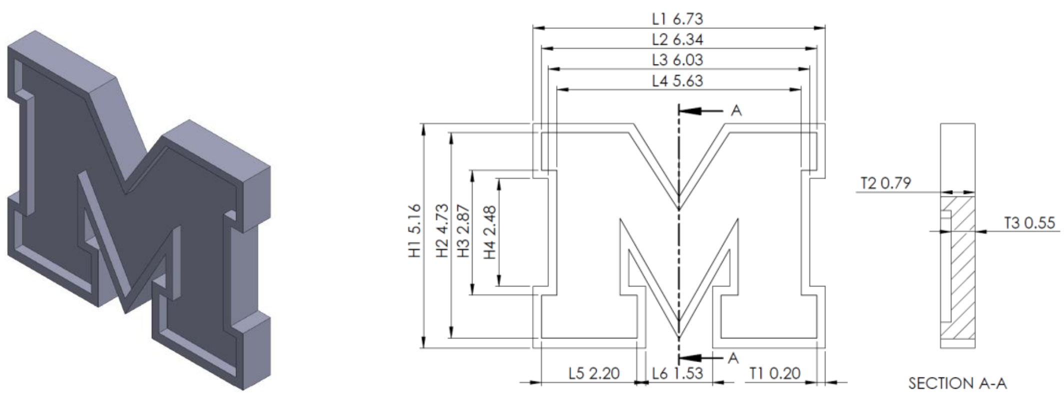
(a) (b)

Figure 3: (a) Roland 3D CNC Milling Machine MDX-40A; (b) Digital Caliper

For the majority of measurements, a digital caliper (Figure 3 (b)) was used. Digital calipers give a highly accurate and precise measurement of distance on small objects. These calipers allow for "zeroing" at any point along the slide, allowing for differential measurements.

Results and Discussions

It was decided to design a part with simple and easy to measure features. The logic behind this is that it is easier to measure a simple part and compare those specific measurements rather than a highly complex part (contours perhaps). The part that was designed is the "Mercer University M", as seen in Figure 4 (a). The part has varying thicknesses and lengths that will allow for easy comparisons. A dimensioned version of the file is seen in Figure 4 (b).



(a) (b)

Figure 4: Mercer University M

The part printed using MakerBot is shown in Figure 5. It has well defined features and finish. The CNC milling machine entails a much different process than the 3D printer. While the same files were used to make the part, the CNC machine requires supervision of the process. This is due to the removal of material during the process. A wax block was chosen to make the part. From previous studies[2] it is known that CNC machines did offer an advantage: a far superior finish than the 3D printer. The results indicate that it is true even with low cost CNC machine and 3D printer used in this study. As it is seen in Figure 6, the CNC did have problems with the small, inner crevice of the M. This was due to that specific dimension being so small and the tool size used. It is possible to change to a smaller drill-bit; however this adds difficulty to the process and increases machining time.

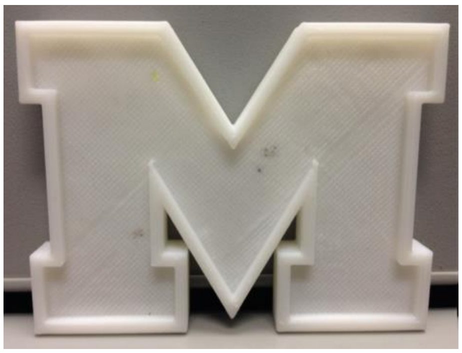


Figure 5: MakerBot "M"

Figure 6: CNC Milling Machine "M"

After the parts were manufactured, several measurements were taken and compared with the original model. It should be noted that due to size restrictions the models were scaled and the scale factor was used to make the comparisons based on original model dimensions. Several lengths were compared to each other to check for accuracy and precision and a summarized version of these can be seen in Table 1. Each dimension of the part made on the CNC machine came out slightly larger which is to be expected and preferable as a post process finish can remove excess material. The MakerBot produced part dimensions are slightly smaller due to shrinkage of plastic material after printing and cooling.

Table 1: Measurement Comparisons

Machine	Scale	L1	% Error	H1	% Error	T2	% Error	T3	% Error	Average % Error
SolidWorks Model	---	6.7300	---	5.1600	---	0.7900	---	0.5500	---	---
MakerBot	1:2.25	6.6758	-0.81%	5.1030	-1.1%	0.7845	-0.7%	0.5370	-2.36%	**1.24%**
CNC Machine	1:2.25	6.7489	0.28%	5.1615	0.03%	0.7925	0.32%	0.5630	2.36%	**0.75%**

After this comparison was done, a simple ranking system was made to give a numerical ranking of each process machine for comparison. 15 participants (14 students and a faculty) were involved in obtaining the ranking system using the Likert scale for quality with three-point scales[16]. AM and SM process machines can be compared using the following process characteristics [2]. The ranking criteria for comparison are:

- Setup – number of steps and setup time for each machine
- Ease of use – how easy is it to use the machine
- Machining speed – how quickly can the part be manufactured
- Material waste (%) – percentage of material wasted due to machining/printing
- Accuracy of measurements – how accurate the part is compared to the model
- Surface finish – smoothness of the part surface

As seen in Table 2, using scale 1-3 (1 = poor; 2 = good; 3 = excellent), the MakerBot performed better than the CNC Machine with respect to setup (number of steps and setup time), ease of use, machining/printing speed, and material waste (%); the CNC machine is better than MakerBot with respect to surface finish only. Overall, MakerBot performed better than CNC Machine.

Table 2: Machine Rankings

Machine	Machine Setup		Ranking System					
	No. of Steps	Time (min)	Software Ease of Use	Machining/ Printing Speed	Material Waste (%)	Accuracy	Surface Finish	Average
MakerBot Replicator 2X	8	7	3	2	2	2	2	**2.167**
Roland 3D CNC Milling	17	17	2	1	1	2	3	**1.667**

Similar results were obtained from other students' projects: captain's wheel and phone stand. The CAD design and the parts made using MakerBot Replicator 2X and Roland CNC Mill are shown in Figure 7. The measurements and results obtained from these parts made using the AM and SM process machines were compared and found to be consistent. Further studies are needed to validate the results using statistical methods.

Captain's Wheel

(a) (b) (c)

Phone Stand

(a) (b) (c)

Figure 7: (a) CAD Design; (b) MakerBot 3D Print; and (c) Roland Mill CNC Part

Conclusions and Recommendations

While the two machines representing AM and SM processes (MakerBot Replicator and Roland CNC Mill) can rapidly produce parts and are easy to use, they are not necessarily equal. They are both accurate enough for prototyping but also easy enough to use for a learning environment. Both processes have their advantages and disadvantages. It is hard to make a case for one type over the other as a broad recommendation. The recommendation really depends upon the application and the desired result. If the desired result is for a faster product and the ability to produce multiple parts simultaneously then the AM would be the most advantageous route. However, if the surface finish is the primary concern while minimizing the amount of post processing then the SM would be the desired route. The most appropriate solution would be a combination of the two methods. The AM should be used to create the part while the capabilities of the SM can be used to finish the product to provide a smoother surface. The overall recommendation is to use a combination of both methods for the highest quality part straight out of the machine. Through this study, the student teams were able to learn and understand two different processes (AM and SM), advantages and disadvantages of each one of them, and when to use them. The teams needed additional time to learn and use the CNC machine compared to that of 3D printer. It is recommended that further studies are needed using other types of AM and SM process machines to compare and validate the results of this study using statistical methods.

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