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Comparative Analysis of Additive and Subtractive Manufacturing Processes through the Fabrication of a Spur Gear

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ABSTRACT

The newest technology in the world of industrial production methods is additive manufacturing, commonly regarded as the 3D printing technique. In comparison to subtractive manufacturing methodologies, it is characterized as the process of joining materials to create structures from 3D model data, typically layer upon layer. In this research work, a comparative analysis was done to see how 3D printing fares against the common subtractive manufacturing processes. A sample product (Spur gear) was made of ABS (Acrylonitrile butadiene styrene) material using four manufacturing processes of Milling, Hobbing, CNC Machining and 3D printing. The comparative study between the processes was based on different parameters like surface roughness, dimensional accuracy, teeth profile formation. From the analysis, it was found that Additive manufacturing (3D printing) responded better than other three manufacturing processes due to the inherent process characteristics of layer by layer material addition. This has resulted in high precision process in fully automated manufacturing environment of a 3D spur gear.

Keywords: Additive manufacturing, 3D printing, layer-by-layer process, subtractive processes, spur gear

1. Introduction

Additive and subtractive processes are two different types of manufacturing processes in the manufacturing world. Additive process is the newest in this arena, and the Fused Deposition Modeling (FDM) or 3D printing process is one of them. Material is joined or solidified under machine control in the 3D printing process to generate a three-dimensional structure, usually applying the material layer by layer. An additive manufacturing method that belongs to the material extrusion family is Fused Deposition Modeling (FDM) or Fused Filament Fabrication (FFF). An entity is created in FDM by selectively depositing melted material onto a layer-by-layer pre-determined course. Thermoplastic polymers are the components used which come in a filament shape. Due to the number of printers available on the market, it is possibly the most common printing form. In contrast to other 3D printing technologies, FDM is an inexpensive 3D printing technique. 3D objects are created in the subtractive process by successively cutting material away from a solid material block, which is also known as machining.
In this research work, ABS material has been used. And it's a widely used material for 3D printing [1,2] work. Nowadays, this process is being used very frequently [3, 4, 5]. And the accuracy of this process is also tested [6]. Plastic gears were made using additive manufacturing process [7], and those work very well.
A spur gear is made using ABS material by additive and subtractive process both. To compare them and analyzing both processes by three parameters, which are Surface roughness, Dimensional accuracy, Teeth profile analysis. To date, metal gears have been substituted in different systems by thermoplastic or polymer gears. They have less weight, less inertia and function even better than their metal equivalents. They deliver toughness, resistance to wear and corrosion, decrease of noise, less vibration, minimum upkeep and low weight. Instead of metal gears, utilizing plastic gears eliminates weight and thus lowers power demand and improves performance [8]. ABS gear's real application can be in Automotive Industry, Food Processors, Windshield Wiper Drivers, Watches, Toys, Automotive motor fan, Lift gates etc. [9]
In many sectors, additive manufacturing is now replacing subtractive processes as part of the industrial revolution as it's proven to be more accurate. After studying some publications, it seems that there is hardly any study that shows how additive manufacturing fares against subtractive processes. In this paper, we will compare Fused Deposition Modeling (FDM) with other subtractive manufacturing processes by using various parameters.

2. Methodology

For a comparative analysis, a sample product was needed to be made by both additive and subtractive processes. Spur gears are industrial equipment to transfer mechanical motion as well as control speed, power, and torque. For this research project, a spur gear was selected from machine shop laboratories of Ahsanullah University of Science and Technology (AUST). Dimensions and specification are given below in Fig.1 and Table 1:

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Fig .1 Sample Spur Gear

Table 1 Dimensions of sample spur gear (measured)

Dimensions	Value(mm)
Outside Diameter	74
Pitch Diameter	70
Inside Diameter	65.2
Cutter Size	2
Working Depth	4.4
Number of teeth	35

For the additive manufacturing process, a 3D model is created in SolidWorks version 2019 to perform fused deposition modeling (3D printing). Solid works model is given below in Fig.2

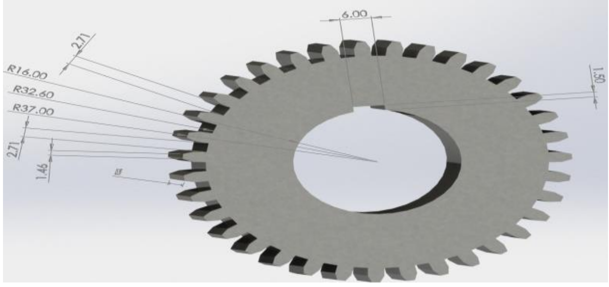


Fig.2 Solid Works Model

2.1 Material

Acrylonitrile butadiene styrene (ABS) material is used for both additive and subtractive manufacturing of the 3D spur gear. For the research work to be a success, such a material was needed which is machine able as samples need to be made through subtractive processes at the same time which has filament form for the FDM process. After studying, ABS material was found serves the above-mentioned purposes. To make the comparison justified and feasible, we needed a common material for all manufacturing processes to fabricate the gear with. We have used FDM process in which only thermoplastic material can be used. And so, we needed such a thermoplastic material which can be used in both additive and subtractive manufacturing processes. After studying, it was found that ABS is such a material and that is why it was selected as the comparison material. ABS is a common thermoplastic polymer. Its glass transition temperature is approximately 105 °C and obviously, it is machinable [10].

Formula: $(C_8H_8 \cdot C_4H_6 \cdot C_3H_3N)_n$
Boiling point: 145.2 °C
Density: 1.060–1.080 $\text{g} \cdot \text{cm}^{-3}$ [10]

The picture of spool for additive manufacturing and cylinder block for subtractive processes is shown in Fig.3.

Fig.3 ABS Material Spool and Cylinder Block

2.2 Processes

Fused Deposition Modeling (FDM)*:*

FDM process deposits material in layer-by-layer process in the printer with a spool of thermoplastic filament. The filament is fed to the extrusion head and into the nozzle where it melts until the nozzle has achieved the desired temperature. A 3-axis mechanism is connected to the extrusion head that enables it to travel in the directions of X, Y and Z. In thin strands, the molten material is extruded and placed layer-by-layer in predetermined areas, where it cools and solidifies. Often, with the usage of cooling fans connected to the extrusion head, the cooling of the substance is accelerated. Multiple passes are required to fill a region (similar to painting a rectangle with a marker). The building base falls down after a sheet is completed (or in some process configurations, the extrusion head moves up) and a fresh sheet is deposited. If the component is complete, this step is replicated [4].
Once designed, the 3D model (.STL file) was split into layers through a slicer named “Cura” before the parameters of the printing are chosen. The selected parameters are listed in Table 2.

Table 2 FDM Printing parameters

Parameters	Value
Infill Rate	100%
Layer Height	0.2
Outline Parameter Shell	03

Infill Rate: The volume of filament printed within the item is the infill density, and this specifically refers to the power, weight and length of printing. Since the other gears would be made by machining and fully solid, we needed a solid print. That’s why a 100% infill rate was given.
Layer Height: The precise height of each sheet of plastic extruded, cured or sintered by a 3D printer is the Sheet Height. Via a slicer software, this setting is changed and has far more implications on the final print than one would expect at first. With the correct setting, the quality can be improved in terms of tempo, resolution, and smoothness of printing.
Outline Parameter Shell: Shells are the number of layers that a print has on the exterior. For FDM shells, the first areas to be printed per sheet are often the first ones.

After the parameters were chosen, the printer began printing when the machined reached the desired temperature usually around 200°C. Then the material was extruded onto the platform according to the 3D model and the object was printed. Thus, the spur gear was fabricated by FDM as shown in Fig.4.

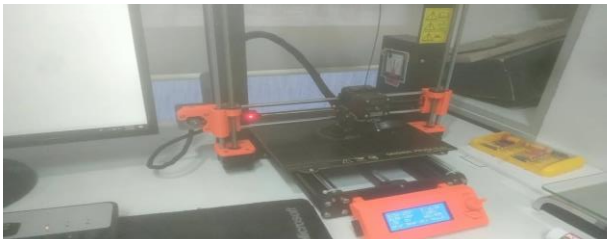


Fig.4 Printing of Spur gear in a Prusa I3 Mk3

CNC Milling:

The method of CNC milling uses computerized controls to run and manipulate machine instruments that cut and form stock material. A finished specification is exported to a CNC-compatible file format and translated into a CNC computer program by CAM software that drives the milling cutter motions. The designed model of Solid works was read in master cam X5 software to give input to the CNC machine. After automatically generating the code to complete the process, the command inputs were given to run the process. A 4mm Endmill cutter was used at first with RPM of 2000. Then, three more 3mm Endmill cutter was used to complete the whole process including finishing. The process is shown in Fig.5.

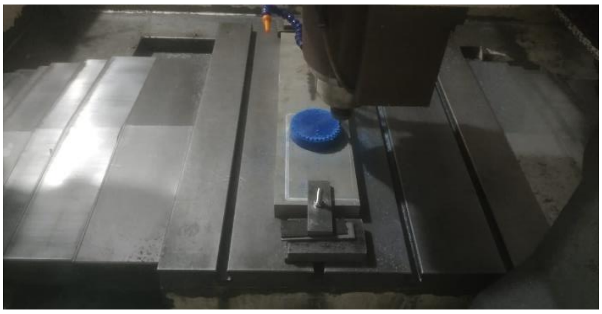


Fig.5 CNC Process

Milling:

Milling is the method of machining to extract content by advancing a cutter through a workpiece utilizing rotary cutters. To cut the tooth over the whole width of the gear, the motor moves along the axis of the work. The diameter rises steadily until the maximum depth of the tooth is achieved. The blank is indexed by means of the dividing head by a 1 / z revolution after one tooth space is removed, and the procedure is replicated before all the teeth are removed.

Here a horizontal milling machine is used for gear cutting. This is a manual milling machine, so indexing fixture was used. Indexing fixtures will disengage the drive worm and be connected to the handle of the system table (like a control feed) from an external gear train. The process being done is shown in Fig.6 and the operation parameters in Table 3.

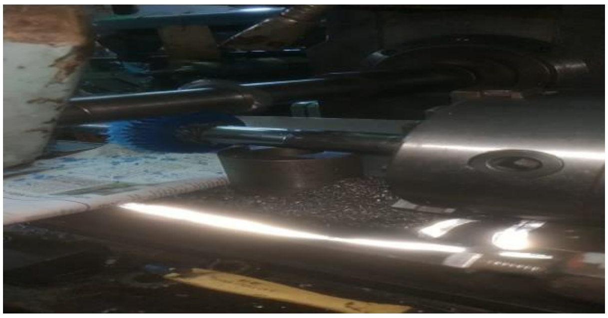


Fig.6 Milling Process

Table 3 Milling operation parameters

Parameters	Value
Spindle Speed	160 RPM
Mendel	15 RPM
Module	02
Cutter	HSS

Hobbing:

Hobbing is a machining method for gear grinding, grinding splines and cutting sprockets. A sequence of cuts created by a cutting instrument called a hob are gradually sliced through the substance by the teeth or splines of the Gear. The hob is rotated at a specific rpm and fed into the blank gear, which is rotated simultaneously. The velocities of the two axes are so aligned that with each full rotation of the hob, the blank rotates around one pitch. The gear hobbing process begins with the in-feed to the rotating hob until the appropriate depth of the gear tooth is achieved, or then the gear blank travels to the hob until the necessary depth of the tooth is obtained. The process is shown in Fig.7 and operation parameters in Table 4.

Fig.7 Hobbing Process

Table 4 Hobbing operation parameters

Parameters	Value
Spindle Speed	48 RPM
Mendel	24 RPM
Cutter module	02
Cutter material	HSS

3. Comparative Analysis

3.1 Teeth Profile Analysis

(a)Designed model of Gear (b)Fabricated Gear by FDM

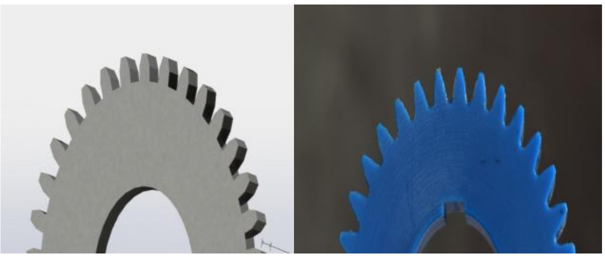
Fig.8 Optical teeth profile analysis between design and fabricated Gear by FDM

Hardly any variation can be seen in teeth profile between the design and actual product as shown in Fig.8. In case of 3D printed product, there is a small percentage of error when faring to the actual design which will be shown later in the paper. As 3D printing is done from inputting the actual design to the machine and the product is made layer by layer according to the design so the shape, size and teeth profile become mostly accurate. Very small deviation from the sample design is seen.

(a)Designed model of Gear (b)Fabricated Gear by CNC Milling

Fig.9 Optical teeth profile analysis between design and fabricated Gear by CNC Milling

CNC machining process, an automated process, removes material according to the design made in software. Over-all shape and size are nearly accurate. Still, CNC process has some mechanical limitations that were faced during machining. It was a three-axis CNC machine and it left 1 mm of round shape at the end of the endmill process as the cutter was round-shaped. But if focused on very small detail on the product then the variation is seen and the round shape left in the product is visible in the other face of the gear as shown in Fig. 9.



(a)Designed model of Gear (b)Fabricated Gear by Hobbing

Fig.10 Optical teeth profile analysis between design and fabricated Gear by Hobbing

Hobbing is an ideal process for producing Gear. Customized design is not possible using hobbing process. Few small details in the teeth are not as perfect as the design. In, hobbing, hob has a specific shape which is fixed and the teeth profile of the product would be the same as the hob. And so there can be seen some deviation from the original design in the actual product shown in Fig.10, especially the involute carve isn't as accurate in the fabricated one as it is in the design.

(a)Designed model of Gear (b)Fabricated Gear by Milling

Fig.11 Optical teeth profile analysis between design and fabricated Gear by Milling

In case of milling process, a rotation cutter removes material from the workpiece. As a result, customized design gear can't be fabricated. From Fig. 11, it can clearly be seen that there is a difference from the design. Involute carve in the design is absent in the actual product. Milling performs the straight cut operation, and so the involute carve isn't present in the product.

3.2 Surface Roughness Comparison

The calculation of the finely scattered micro-irregularities on the surface texture, which consists of three elements, namely roughness, waviness, and shape, is surface roughness. It is quantified by the deviations from its ideal shape in the direction of the usual vector of a real surface. The surface is rough if these deviations are large; the surface is smooth if they are minimal.

The surface roughness of the gears' teeth was measured using a DektakXT profilometer to show the roughness comparison. The face of the gear teeth over which the roughness was measured (both across length and height of the tooth) is shown in Fig.12.

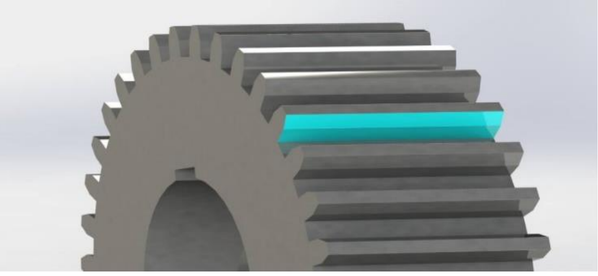


Fig.12 The Highlighted face (as gears mesh across this face) of the teeth over which roughness was measured

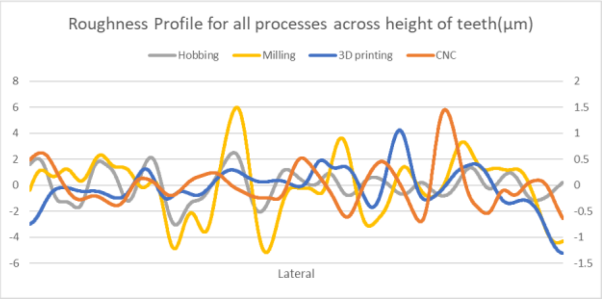


Fig.13 Roughness Profile of the processes across the height of teeth

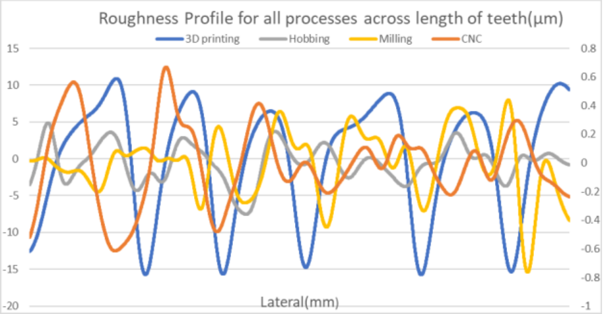


Fig.14 Roughness Profile of the processes across the length of teeth

From the roughness profile of Fig.13 and Fig.14, it can be seen that the fluctuations for 3D printing across length and height vary greatly. In the profile across the height, 3D or FDM's profile is minimal comparing to the other processes whereas across the length, it's completely opposite of that. The above roughness profiles show fluctuations across 1000 µm lateral for all processes indicating how the processes compare against one another. Across the height, after FDM, CNC has the least fluctuations followed by Hobbing, Milling. But, across the length, Hobbing resulted in minimal fluctuations followed by Milling, CNC and FDM. Usually, 3D printing or FDM process generates higher surface roughness as in this process material is stacked layer by layer meaning after one layer of material is deposited another layer is deposited on top of it and thus the process continues. Here when roughness was taken across the height of the teeth for FDM, it resulted in the lowest roughness among all the processes.

3.3 Dimensional Accuracy Comparison

Dimensional accuracy is the factor which shows how close the dimensions are of 3D model of product. In manufacturing, the accuracy of the product is very much important. Here, we are comparing the dimensional accuracy of the processes by showing the error percentage of the fabricated products. Five parameters(shown in Fig.15) of Spur gear according to dimensions have been taken to show the comparison of accuracy. They are listed below in Table 5.

Table 5 Dimension parameters taken to measure Dimensional Accuracy

Dimension Parameters	Original Value(mm)
Outer Diameter	74
Inner Diameter	32
Teeth Thickness	3.13
Involute Carve	2.01
Topland of teeth	1.46

After fabrication of the 3D spur gear of ABS, the average dimensions of the mentioned parameters were taken using a digital Vernier Scale. The values of the dimensions for the processes are listed below in Table 6.

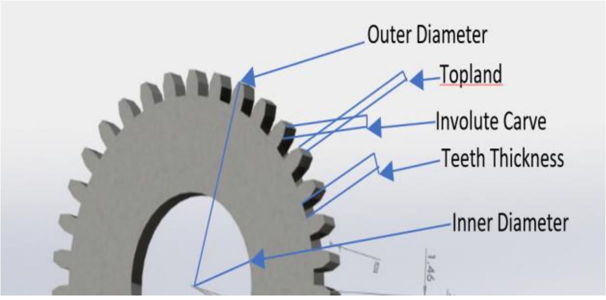


Fig.15 Dimensional Parameters measured

Table 6 Measured values of the dimensional parameters for each process (O.D.=Outer Diameter, I.D.=Inner Diameter, T.T.= Teeth Thickness, I.C.= Involute Carve, T.O.T.= Topland of Teeth)

Processes	Dimensions				
	O.D.	I.D.	T.T.	I.C.	T.O.T
Hobbing	74.05	32.81	3.06	1.94	1.063
CNC	73.88	32.55	3.22	2.27	1.36
Milling	74.35	32.7	2.97	-	1.57
3d	73.46	32.2	3.1	2.00	1.50

Percentage of error formula:

$$\frac{|\text{Measured Value} - \text{Original Value}|}{|\text{Original Value}|} \times 100\%$$

The percentage of error for all processes across all dimensional parameters is shown in Fig.16 altogether.

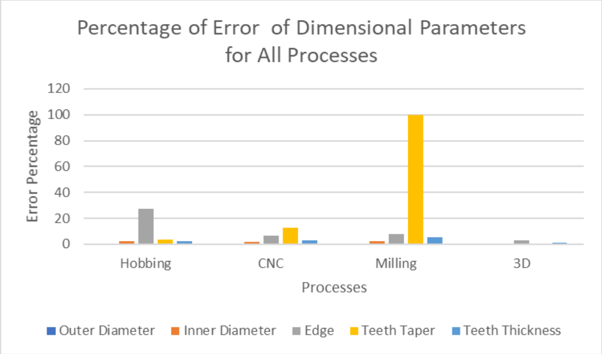


Fig.16 Percentage of error of Dimensional Parameters for all processes

Additive manufacturing seems quite an accurate process comparing to other conventional processes. In FDM, the material is deposited layer by layer according to the given design. Both CNC and FDM are automated processes. They work according to the specific commands given to them. As a result, their accuracy tends to be higher comparing to conventional machining. From the above-shown graphs, it's clearly visible that FDM has the lowest percentage of error, especially in the complex teeth profile section. This accuracy is expected as said above. CNC's accuracy is less, but still, it's quite close. The accuracy of Hobbing is quite close to CNC because Hobbing is a machining process for gear cutting, cutting splines, and cutting sprockets on a hobbing machine, which is a special type of milling machine. Compared to other Gear forming processes, it is relatively inexpensive but still quite accurate. Since Hobbing is a special gear cutting process, its accuracy is not so surprising. Milling has the most percentage of error. FDM has generated the most accurate result.

In this research work, additive manufacturing process is being compared against other subtractive machining processes to see how it fares against them. That is the goal, how it fares against the other processes. Accuracy is one of the basic parameters in any manufacturing process and so, using these errors, it is being seen which process has fabricated physically the most precise gear with respect to the sample gear/design. From Fig.16, we can get some idea about the accuracy of each process by seeing the error percentage and as the goal was how additive manufacturing process fares against others, here it can be said that it's the most accurate one among all the manufacturing processes.

4. Conclusion

- Comparing optical teeth profile analysis, FDM generated the best teeth profile according to the design.
- Milling produced the worst teeth profile as seen in the optical analysis, and as straight Milling was done, involute carve is absent in the fabricated Gear using Milling, which is visible in the optical analysis.
- FDM generated the lowest roughness across the height of the teeth but the highest roughness across the length of the teeth among all the processes. As in Gear meshing, the friction between two teeth would occur along the height, so in this case, low surface roughness results in better operation.
- FDM produced the lowest percentage of error in almost every dimensional parameter, implying its higher precision than the subtractive processes.

5. References

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