Design &Manufacturing of Spur Gear Using Fused deposition Modeling

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Abstract - *Fused Deposition Modeling (FDM) process can be used to produce the rapid tooling directly or indirectly. While rapid tooling drastically reduce the product development cycle time however, still it not been widely used due to the fact that these are more costly as compared to other tooling method. In this research we will study the feasibility of using rapid tooling and compare the tooling cost with other tooling methods.*

Key Words: Fused Deposition Modeling, Silicone Rubber Moulding, Rapid Tooling, Feasibility of FDM Tooling.

I. INTRODUCTION

In today's modern manufacturing industry the cycle time taken to produce the product is important along with the part quality. 'Rapid Tooling (RT)' is one of the prominent applications of Rapid Prototyping. RT is an attempt to make the tools rapidly to produce the parts from these tools. The rapid tools like "molds, patterns and inserts etc." are produced using additive processes which reduces the time and cost drastically. The application of this new technology reduces the number of design iterations as well testing trials required before introducing a new product in to the market. The rapid tooling can be mainly divided into two types i.e. Direct Tooling and Indirect Tooling. In direct tooling the pattern or mold is made directly from CAD data and used for actual production of the parts where as in indirect tooling patterns are made from CAD data and are used as master pattern to produce molds through which actual production of the parts is achieved as in silicone rubber molding and epoxy resin molding etc. The silicone rubber molding is widely used as indirect tool in Investment Casting(IC).The IC is one of the most economical ways to produce quality and complex parts. The quality of IC parts mainly depends on quality of master patterns produced by rapid prototyping process. So it has become necessary to study the quality behavior of tooling produced by various rapid prototyping processes.

Out of the available RP processes, FDM (Fused Deposition Modeling) RP process has become more popular because it has benefits like stronger parts; clean, easy and economical process etc. But surface roughness in FDM parts is more due to the stair case effect, which is the main limitation in its use as tool.

In literature various researchers have carried out several studies to improve the surface finish, in one of such studies the authors[1] have applied metal paint on surface of the FDM tool but it was observed that the metal paint cannot cope with wax pattern temperature above 80ºC even though it has shown good thermal conductivity. Similar research [2] was carried out to improve surface of FDM tools by using thin coat of polymer solution followed by providing light sanding using abrasive paper. In this method light sanding using abrasive paper was carried out manually and requires skill. One more study [3] the authors of this present study had applied post processing technique i.e. optimized chemical treatment process technique to improve surface finish of FDM parts. The authors [4] have applied different methods to improve surface finish of FDM parts. It is also necessary to evaluate performance of rapid tooling fabricated from various rapid prototyping processes. Most of such studies have proved that master patterns fabricated from rapid prototyping can be burnt out without any significant residual ash for investment casting. One of such methods is direct tooling method in which the authors have evaluated the quality characteristics of various RP patterns that were fabricated by various RP processes such as 3D Printer (3DP), Fused Deposition Modeling (FDM) and Multihued Modeling (MJM). Their results showed that FDM and MJM processes were superior in terms of mold cleanliness since no residual ash was observed during the burn out stage. Significant oxidation of ceramic powder was observed on the molds of the 3DP patterns which need to be removed manually from the molds. So they had recommended that FDM and MJM are only suitable RP process for master patterns to be burn out. Another study on investment casting using FDM made patterns, the authors [5] have used two types part building methods i.e. Hollow and Solid. They have compared both the methods with respect to dimensional accuracy, collapsibility and distortion characteristics of FDM built parts. Results of their study revealed that the hollow pattern built parts are much better than solid pattern built parts in terms of dimensional accuracy and collapsibility point of view. The solid pattern built parts are much better than hollow pattern built parts while considering less distortion aspects i.e. the hollow pattern built parts show 33.11% higher distortion than solid pattern built parts. This study also proved that ABS-P400 material was more feasible to be used as an investment casting pattern material.

In RT, all of the forming stages influence the dimensional accuracy of the die. The forming stages include slicing the CAD model to the STL file, making the prototype using an RP machine and obtaining the ceramic mold and transforming the ceramic mold to a metal die.

In an attempt to study the dimensional accuracy of the rapid tool, the authors [6] developed nonlinear coupled thermo-mechanical analysis for solidification process of transforming the ceramic mold to a metal die. In [7] the authors further automated the RT process by avoiding preparation of CAD model, instead of preparing CAD model they have used direct 3D digitizing which a reverse engineering (RE) method and obtained point cloud data. This point cloud data was used directly to prepare RP tool and also they analyzed RP tool for by finite element analysis (FEA), to assure the metrological accuracy of tooling geometry and optimization of foundry process parameters.

This project concentrates in the viability on using fused deposition modeling 3d printing as a manufacturing method for functional spur gears. This report contains information of the fast growing additive layer manufacturing methods, the present applications and research being performed. Discusses about the materials that are being used and experimental new materials, presents future advancements and the probable impact that this innovative technology will have in the manufacturing industry. The design of the spur gear is explained. Finally the process to elaborate the components is discussed, presenting the final results of each of them. The final product was tested for functionality and advantages, disadvantages where analyzed of the manufacturing of functional 3d printed gearboxes.

1.2 Problem Definition

This project concentrates in the feasibility of using fused deposition modeling as a method for manufacturing functional tooling for manufacturing spur gears. We will also consider using 3d printing as direct manufacturing process for spur gear. Since cost of 3d printing materials can be very high for large scale manufacturing hence we will also compare manufacturing cost and feasible batch size with existing injection molding process.

1.3 Objective

For applications where only a small number of units are required injection molding may not be a viable option. Due to the fact that initial cost of tooling design for injection molding is very high thus the method is only cost effective when very large numbers of parts are required to be manufactured. The objective of this project is to make a use of one of the rapid prototyping process i.e. fused deposition modeling as a manufacturing method instead of Injection Molding whenever small volume production is required for achieving reduction in cost and time.

1.4 Significance

- No intermediate process required (like SLA patterns in case of silicone rubber molding or RP patterns for producing metal tools) and tools can be made directly from CAD data.
- Time saving as intermediate step of pattern making is not required.
- Tools produced from FDM are stronger, economical, and easy to manufacture and have longer life than current silicone rubber molding.
- Complicated parts which are not possible to be made using Silicone rubber molding are possible using FDM.

2. FDM 3D Printer

The fused deposition modeling printer used is the Prusa i3, from Prusa Research. This printer prints itself most of its plastic components. All parts of this 3D printer are Open Source and are part of the RepRap project. The nozzle is able to move in the Y direction while the platform has two degrees of freedom moving in the X, Z directions. The printer can be considered as three main components: the filament or spool, the extruder and the platform. The filament is the material that is used to create the object, the extruder heats and extrudes the material and the platform is where the material is deposited. By a combination between the extruder and Platform movements the machine is able to create any 3d shape.

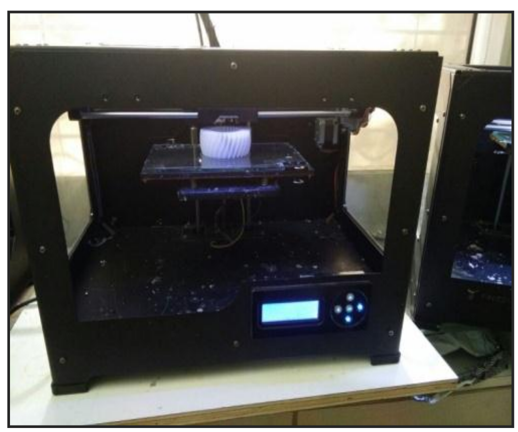

Fig -1: FDM 3D Printer

2.1 Printer specification

Table 1: Printer Specification

Printing Material	ABS or PLA
Material Color	Red, White
Nozzle Type	Duel Nozzle
Bed Size	225 X 150 X 150
Resolution	70 – 400 Microns
Extrusion Temperature	ABS : 240-270^{o}c , PLA : 200^{o}c
Platform Temperature	60-100^{o}c

2.2 Software used

In this project we will be using Cura software which is a 3D printer slicing application. Cura has been released under the open source License. Cura is the preferred slicer software for Ultimaker 3d printers, but can be used with other printers as well.

2.3 3D Printing Design Guidelines

To obtain a successful and the best possible quality, functionality of a print some design guides must be considered for Fused Deposition Modeling.

- The minimum wall thickness of a model has to be of 1mm to be able to provide a strong solid surface.
- The orientation of the model has to be decided depending on which surface requires a better quality finish. Since FDM prints layer by layer the "staircase effect" can be observed resembling a topographic map, a visual representation of this effect can be observed in Figure.

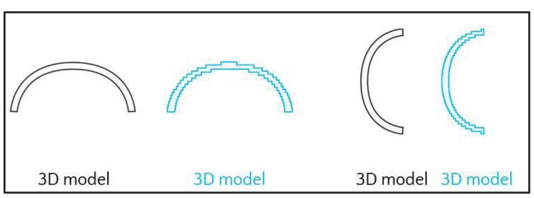

Fig -2: Staircase effect in 3d printed models

- The orientation of the model also depends on the forces that the component will face. Ideally the forces and the orientation of the layers have to be perpendicular. This is because if they are parallel the force may cause a layer to delaminate which is weakest orientation of the component.

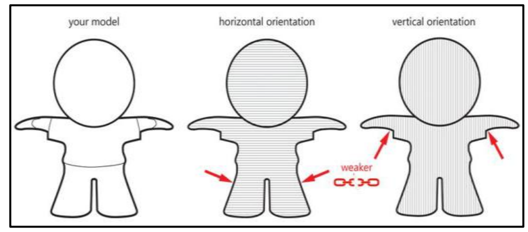

Fig -3: Strength of component depending on printing orientation.

- The printed component will have a tolerance that depends on the model size, 0.1% of the nominal size and a minimum of +/-0.2mm.
- FDM builds the material in the air so if there is an angle that is inferior to 45° support material has to be printed to prevent them from falling due to gravity. This support can be printed external and internal depending on the design requirement. Figure: explains when the support material is needed depending on the angle following the 45° rule. Depending on the safety and stability needed for the model the 45° value can be changed to higher or lower, but 45° is recommended.

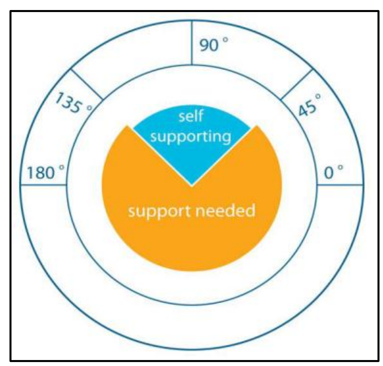

Fig -4: Requirement of support according to 45° rule

- Due to friction if there are components that are meant to be assembled there should be at least 0.3mm difference between parts.
- If the model requires some text in the surface engraved is preferred from embossed. For engraved use a minimum line thickness of 1mm and a depth of 0.3mm. For embossed minimum line thickness of 2.5mm and a depth of 0.5mm.

3. METHODOLOGY

FDM parts are used to produce direct tooling by using burnout process; however no significant efforts to use these FDM parts as a direct tool in form of mold for producing wax patterns have been made. The FDM molds have a higher life as compared to the rubber molds produced by existing process silicone rubber molding. However the surface roughness associated with the FDM parts make it less suitable for using it as a direct tool. Also the wax gets trapped in the layer to layer gap and hence the removal of the wax pattern without damaging the pattern is not possible. Here the authors have made an effort to produce FDM molds so that it can be used as direct tooling in place of metal molds which are made by conventional manufacturing.

3.1 Numbers of criteria's to be selected for the validation of the process

- Cost associated for fabrication of FDM tool and post processing.
- Time required for tooling design and manufacturing the tool.
- Life of the tool and reusability options.

3.2 Direct Manufacturing method

For applications where only a small number of units are required injection molding may not be a viable option. Due to the fact that initial cost of tooling design for injection molding is very high thus the method is only cost effective when very large numbers of parts are required to be manufactured. In order to check feasibility of using 3d printing as a method for directly manufacturing for small volume production we will design a spur gear and manufacture it using 3d printing and compare the cost with injection molding to find out a breakeven point below which we can consider that directly manufacturing is more cost effective.

3.3 Spur Gear Design Calculations

In order to design the spur gear some calculations are required such as the diametric pitch, base radius, base pitch, addendum, deddendum. These gear properties determine the design.

To obtain the gear properties for standard gear the following equations have been used:

$$m = dp/N$$
$$dp = m * N$$
$$Pd = \pi * dp/N = \pi * m$$
$$Pb = 2 * \pi * Rb/N$$
$$Cr = dp\ spur/2 + dp\ pinion/2$$
$$(Rbspur + Rbpinion)/\cos(\phi) = Cr$$
$$a = 1 * m$$
$$aR = Pd + a$$
$$b = 1.25/Pd$$
$$dR = Pd - b$$

Where:
m = module
dp = diametral pitch
N = number of teeth
Pd = circular pitch
Pb = base pitch
Rb = base circle
a = Addendum
aR = Addendum radius
b = dedendum
dR = Dedendum radius
Cr = centre distance between gears
ϕ = Pressure angle

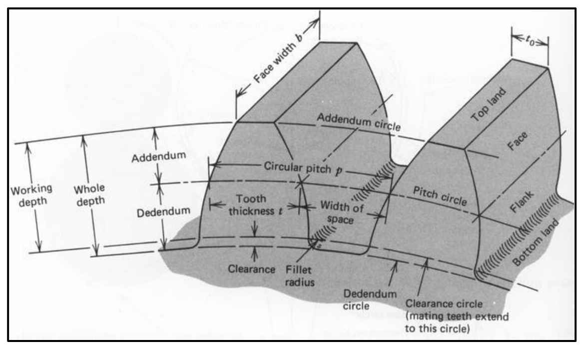

Fig -5: Gears nomenclature

3.4 Gear Calculator

Table 2: Values of different gear parameter

Description	Abbreviation	Spur	Units
Pitch diameter	Dp	33.1	Mm
Circular Pitch	Pd	10.4	Mm
Base Radius	Rb	17.75	Mm
Base Pitch	Pb	9.3	Mm
Addendum	A	1.25	Mm
Addendum Radius	aR	17.8	Mm
Dedendum	b	1.85	Mm
Dedendum Radius	dR	16.55	Mm
Outer Diameter	OD	35.6	Mm

The values from above Table will be used in the design of the CAD model for the gear that would be used for 3d printing.

3.5 Mold Design process for Rapid Tooling

In order to evaluate the feasibility of using 3d printing for tooling we will now create a mold design for the existing spur gear. This mold will be manufactured using 3d printing and the output part will be used for creating wax pattern that can be used for producing metal gears using investment casting.

Mold is designed in two pieces split along the center line of the part. A mold can be designed by doing a Boolean subtract operation of a stock with the actual model. The original model is offset outward by 2mm before Boolean to compensate for the shrinkage allowance i.e. to compensate for shrinkage that will happen in the wax pattern. The resulting cad model is split along the centerline and locator pins are added for easy alignment of the two pieces of mold.

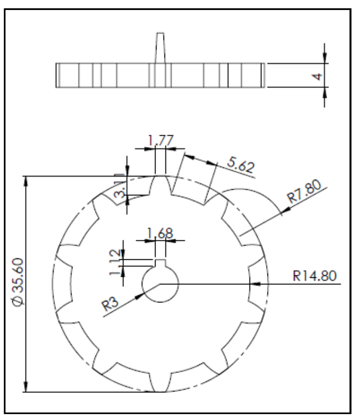

Fig -6: 2d drawing of the Spur Gear

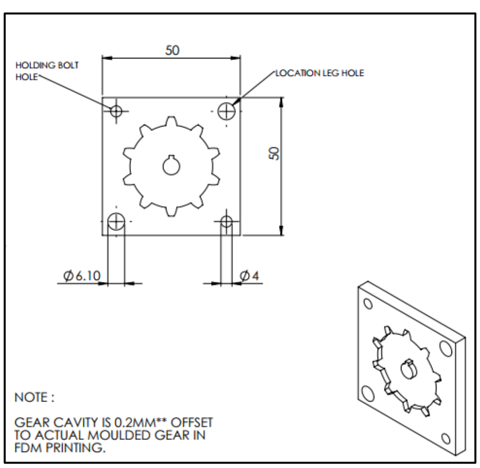

Fig -7: 2d drawing of the mold Part1

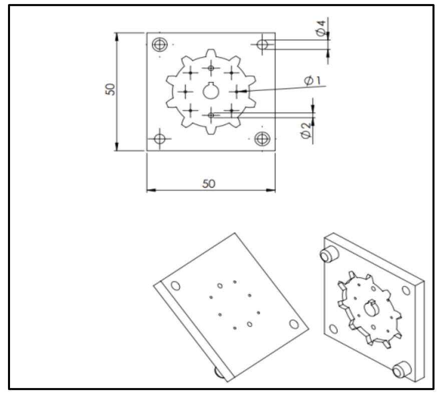

Fig -8: 2d drawing of the mold Part2

The mold is design in 3d modeling software solid work. The 3D model of mold is as shown in figure below.

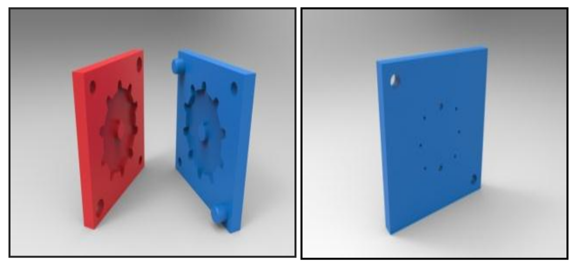

Fig -9: 3D Models of the mold

This designed mold will be used for 3d printing. Both the spur gear and the gear tooling are manufactured using FDM 3d Printing and appropriate post-processing treatment is done for improving the surface finish. The post-processing treatment includes a chemical bath which smoothens the surface roughness due to the layered effect of the step effect usually associated with additive manufacturing. This helps for easy removal of wax pattern in case of mold and a better surface finish increases the aesthetics in case of a final part.

Fig -10: Printed Spur Gear Using FDM 3D Printer

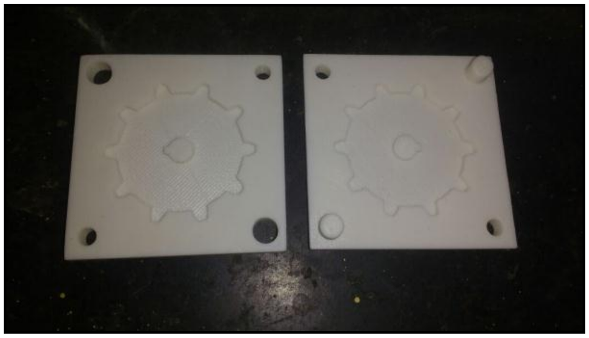

Fig -11: Printed Mold Using FDM 3D Printer

4. Results

To see the effectiveness of using a fused deposition modeling method over a convectional injection molding method to manufacture a Spur gear, the time and cost had to be analyzed. The lead time required for manufacturing of conventional tooling can range between 2-3 weeks whereas using rapid tooling the time reduces to hours. The gear took little more than 30 minutes for printing while the gear mold took close to 90 minutes. Both of these beat the conventional processes in terms of lead time required.

Table 3: FDM 3D Printing cost summary for gear and mold

	Production cost	Material cost	Total cost
Gear	**3.1**	**0.2**	**3.3**
Gear Mold	**7.7**	**0.7**	**8.4**

Material cost/ kg = $0.03/gram& Production cost/ hour = $5.00/hour

Table 4: Injection Molding Cost summary for spur gear

Volume	10	100	1000	10000
Material	**0.3**	**3**	**30**	**149**
Production	**134**	**154**	**351**	**1225**
Tooling	**2358**	**2358**	**2358**	**2861**
Total	**2492**	**2515**	**2738**	**4235**
Cost/part	**249.216**	**25.146**	**2.738**	**0.424**

As shown in above tables we can see that the manufacturing cost/part of investment casting goes on decreasing as the number of volume of parts goes on increasing. Since the cost/part 3d printing is constant we can conclude from the above table that FDM 3D printing is feasible as a direct manufacturing process where the total volume of parts is less than 750 beyond which injection molding proves to be cost efficient.

5. CONCLUSION

The results of this study showed substantial advantages when employing fused deposition modeling as a method for manufacturing functional tooling for manufacturing spur gears. The advantages derived include significant amounts of cost and time savings. There is much difference seen in lead time and costing between the convectional tooling process and rapid tooling process. Where In convectional process for gear and mold manufacturing lead time ranges between 2-3 weeks, in rapid tooling its takes 30 to 90 minute. The manufacturing cost/part is also less in FDM 3D printing than injection molding for low volume of production.

It is also noticeable that the cost of 3D printed FDM tooling is at least 3 order of magnitude lesser than conventional metal tooling however it is justified due to the fact that the life of conventional metal tooling is also orders of magnitude more than 3D printed tooling especially in case of complex parts. However still 3D printed tooling can be a viable option for low volume manufacturing.

Additionally replacing conventional tooling with 3d Printed tooling can be justified in cases where frequent design modification is expected. Due to the decreasing cost of 3D printing, Rapid tooling has become economically viable and it also decreases the lead time and provides a much needed freedom for design changes.

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