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Fused Deposition Modelling based Printing of Full Complement Bearings

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Abstract

Additive manufacturing, the process of building components layer by layer offers great flexibility and freedom in design and manufacture. Over the advancements in past a few years, application of this technology has changed from mere prototyping to production of functional components. Though most of the functional components made are parts for the assembly. In this study an attempt has been made to produce a movable component- ball bearing in a single go which otherwise require assembly. A low cost desktop fused deposition modeling (FDM) printer has been utilized to print in multiple materials. The bearing was printed using PLA, ABS and Nylon 66. Surface characterization such as area surface roughness and Shore D hardness of the printed materials have been measured and compared. It was found that FDM has the potential to fabricate complicated movable parts in single step.

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Keywords: Additive manufacturing; FDM; 3D printing; Bearings.

1. Introduction

Additive manufacturing (AM) is the process of making components by joining materials layer by layer from three-dimensional (3D) data [1]. AM is also called by other names such as rapid prototyping and 3D printing. The standard AM process follows computer-aided design (CAD) modelling, conversion of the CAD into Stereolithography (STL) file format, machine setup, build, remove and post process [2]. Once the model is 'sliced' to many layers with a slicer, the G-code is obtained, which are the commands to build the part [3]. According to American Society for Testing and Materials F42 (ASTM F42) committee, the AM processes are classified into seven categories [4]:

1. Vat photo-polymerization-SLA
2. Material jetting- MJM (Multi jet modelling)
3. Binder jetting- 3DP (3D printing)
4. Material extrusion-FDM (Fused deposition modelling)

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5. Powder bed fusion-SLS (Selective laser sintering), SLM (Selective laser melting)
6. Sheet lamination-LOM (Layer object manufacturing)
7. Directed energy deposition-LMD/LENS (laser metal deposition/laser-engineered net shaping)

1.1 Material extrusion – Fused Deposition Modelling

Fused Deposition Modelling (FDM) is the most popular method for 3D printing. It was developed by the US company Stratasys [2].

In FDM, the material is fed in the form of a filament. Acrylonitrile butadiene styrene (ABS), Poly Lactic Acid (PLA), polyethylene terephthalate glycol (PETG), and Nylon 66 are a few commonly available filaments. The result of a FDM print is not comparable to the quality level obtained with other industrial techniques such as selective laser sintering (SLS) and stereolithography (SLA). But the material and operational cost is low to medium compared to others [3].

The components used in moving mechanisms which are produced by traditional manufacturing need to be assembled before the operation. This is time consuming and requires high tooling and labour cost. 3D printing is a free form manufacturing technique. This technique helps us to produce complex-designed components which are otherwise not possible using conventional techniques. This potential of 3D printing has been explored in making of assemblies of moving parts as in a single go.

Ball bearings are one such products whose manufacturing consists of many operations to produce the rings, rolling elements and cages. It includes hammering of forgings, turning, heat treatment, cutting, forming, grinding and washing of parts [5]. All the components are made separately and then assembled to produce the final product. It is also important to have proper dimensional tolerances, so that bearings works efficiently and functionally-satisfactory.

Calì et. al. [6] has discussed about the possibilities of printing non-assembly, articulated models. This was achieved using SLS by removing the un-sintered powder to “free” the moving parts. They concluded that with appropriate tolerances, parts with functional hinges, chain-link style textiles, and other types of moving components can be fabricated in a single-step printing without the need for post-print assembly. Surface finish is an important quality parameter for making the parts to come as functionally satisfactory. Alsoufi et al. [7] have studied the roughness of FDM printed parts , its relation to nozzle diameter and layer height. They found that the value of surface roughness decreases with reduction in nozzle size and layer height.

In any assembly of moving mechanism that involves the interaction between components. Defining the right tolerances according to the model, the material and the manufacturing process is a key factor for making the part as per the functional requirement. Of all the 3D printing techniques, FDM has the least resolution. The maximum resolution of a desktop FDM printer is 100 microns. Also the staircase effect (due to approximation of curves in layers) is dominant. Another issue is the removal of support structures. When printed with a single extruder, the support structures leave very rough surface once removed.

In present work the main objective is to build a movable assembly (roller bearing) using FDM technology in different materials (ABS, PLA, Nylon 66) and characterizing the surface features (roughness, hardness). In this this study, we have chosen PLA and ABS because they as the most common filaments available. Nylon66 has a good balance between durability and strength. PLA being a material that can be printed hassle free, it was the first material choice to start with. ABS is one of most industrially used polymer and commonly available filament. Surface roughness and the hardness was measured to characterize the fabricated non assembly to check the level of functionality that could be attained.

2. Methodology

2.1 Experimental setup

For this experiment, Tronxy^{TM} desktop FDM [Fig.1] 3D Printer was used. It is a low cost DIY (Do It Yourself) 3D printer which was assembled in 3D printing laboratory at IIT Madras. It has a build volume of 220 mm × 220 mm × 240 mm and is equipped with heat bed build platform made of aluminium. This can heat up to a temperature of 110°C. This helps in improving print quality by preventing warping. The minimum layer thickness for the printer is 100 μm (0.1 mm). All prints were made using 0.2mm diameter nozzle. In general, the bed was levelled manually before starting each print.

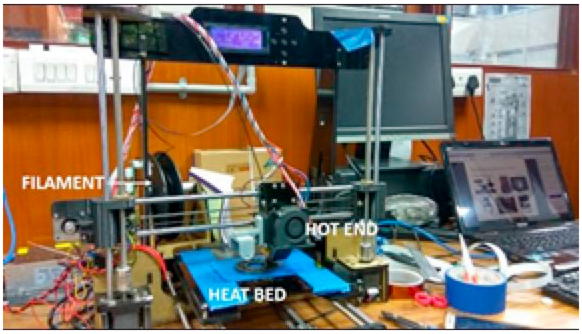

Fig. 1 3D printer setup used in this work

2.1 Design

A ball bearing consists of 4 components: an inner ring, outer ring, balls and the cage. The rings are provided with races, which are slightly larger than the balls and provided with a minimum radial clearance to avoid misalignments during assembly. The cage maintains the balls radial spacing and allows the bearing to operate at a higher speed [8].

In the initial stage a deep groove ball bearing was designed and printed with layer height of 0.1 mm. Since the cages were very close to balls, it was found that this design was too complex for our FDM printer. Therefore, the design was modified by removing cages and adding more balls in the extra space. These are full complement bearings whose load carrying capacity is better than the same sized deep groove ball bearings [9]. But the contact of the ball with adjacent one creates more friction resulting in lesser operating speed.

A full complement ball bearing components was designed [Fig. 2] and assembled in Solidworks 15. In an assembly it is important to provide allowance between the moving components to ensure the smooth movements. Too much clearance will lead to play and less clearance will lead to fusing of components by hindering the movement. For this, a clearance calibration sample was designed and printed as shown in [Fig. 3] which replicates the spacing between two double curved surface. The double-curved surfaces are created by moving the profile (parallel curves) along a curved guideline [10]. This clearance has been varied over a range 0.20mm to 0.50mm in the steps of 0.05mm. This was printed in the FDM printer using the three different materials, ie PLA, ABS and Nylon 66.

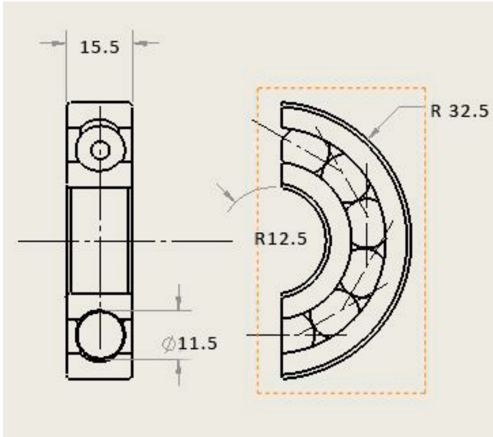

Fig. 2 2D drawing of the assembly (Dimensions in mm)

In this design of bearing the bottom side of the balls requires support structures while printing. There have been studies carried out to reduce the support structure through topology optimization[11] and making the design self-supportive[12]. We cannot avoid support structures for ball as the design change of ball will hinder the functionality of bearing. So the challenge was to print with support structures which leaves least burr on the balls. The overhang angle, the angle of overhang portion less than which support structures are required has been set to 45°. This value was chosen based on the study by Leary et. al.[11] where the build angle greater than 40° has been experimentally assessed as self-supporting. For the identifying a proper support pattern, a ball was printed on different support patterns. This includes lines, grid

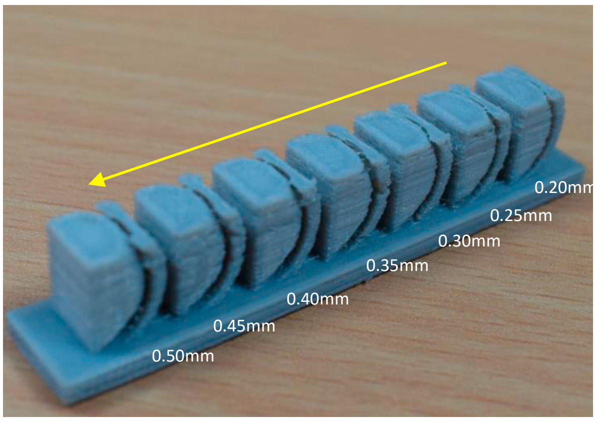

Fig. 3 Calibration model for clearance feature. Arrow shows the direction in which clearance increases

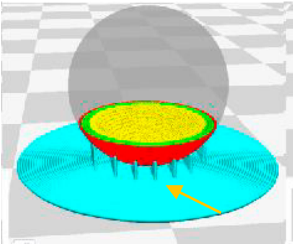

Fig. 4 Line Support Structure

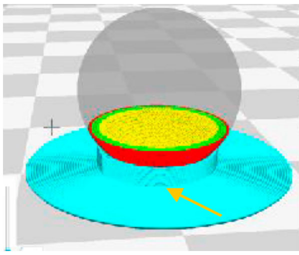

Fig. 5 Grid Support Structure

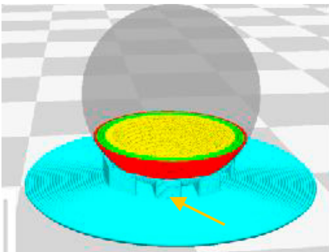

Fig. 6 Zig Zag Support Structure

and Zig-Zag support patterns. These are the default available support structure options in Cura, an open source slicing software. Figs. [4-6] shows the sliced and sectioned data of single ball from Cura with different support structures.

2.2 Materials

Three polymer-based materials were chosen to print the bearing based on their ease of availability, low cost and properties. Samples were prepared with the filaments of following materials:

PLA- Polylactic Acid: PLA is a low cost thermoplastic and biodegradable polymer with a low melting point. This is usually very easy to print and has good stiffness ratio. Nozzle temperatures was kept at 210ºC and bed was heated to 50 ºC. Since PLA is less prone to warping, no particular adhesives were used on the bed.

ABS- Acrylonitrile Butadiene Styrene: ABS is one of the most used thermoplastic polymer in the FDM technology. Nozzle temperature was kept at 240 ºC. This polymer is also common in injection moulding. Since ABS prints are prone to warping[13], heated bed (80ºC) was used for proper adhesion. Also to improve the adhesion poly-vinyl acetate (PVA) glue was applied to the bed before heating.

Nylon 66: Nylon 66 offers good strength and toughness to FDM printed parts. Nylon 66 is hygroscopic and hence it is difficult to print in a humid environment. This will affect the print quality. This material tends to warp in the base and hence it is preferred to have a heated bed (70-80 ºC) and adhesion agents such as PVA glue or ABS slurry. Nozzle temperature are in the range of 240 -260 ºC. In this trial we used nozzle temperature at 260 ºC and a bed temperature at 80ºC. Also to improve the adhesion, the PVA glue was applied to the bed before heating.

2.3 Process Parameters

Samples were printed using a Tronxy 3D printer, which is a low cost desktop FDM printer. The following slicing parameters have been used:

Table 1 Slicing Parameters

Slicer	CuraEngine
Layer height	0.1 mm
Print speed	50 mm/s
Infill Density	80%
Overhang angle	45º

ABS and Nylon were printed on the bed which was heated to 80 ºC. PLA was printed without a heated bed (room temperature of 28 º C).

2.4 Testing

The clearance calibration samples were visually examined for fusion between the surfaces. Surface of the balls with different support structures were also

Fig. 7 Confocal microscope used for measuring the Sa values

examined for the burr left by support structures. In order to compare the bearing specimens, the hardness and surface roughness were measured. Surface roughness measurement was carried out on the samples using Olympus LEXT OLS 4000 confocal laser microscope [Fig 7]. It uses a 405 nm laser, photomultiplier detector for measuring the value of average surface roughness (S_a). A total of 6 readings were taken for each material with an evaluation area of 2561 µm × 2575 µm.

Hardness was measured using a BSE make Shore D hardness tester [14]. It has a range of 0 - 100 Shore D with a least count of 1 shore D. Shore D scale was preferred since hard plastics were used in this study. Measurement was taken along the side walls as well as the top surface to check the uniformity in hardness. Due to the construction of hardness tester indenter and its short length, it was unable to measure the hardness in the races. So, it was assumed that the hardness values of side walls and races are equal. For each sample, six readings were taken and the average value was calculated (Table 3).

3. Results and Discussion

The 3D printed clearance calibration samples were visually examined. It was observed that, the 0.2 mm gap was completely fused which doesn't provide any room for movement. As the clearance increased the quality of clearance improved and 0.4mm showed good clearance. Hence 0.4mm was chosen as the clearance between ball and races in bearing design. This method helped in reducing prototyping time because multiple iterations of full bearings prints would have taken significantly more time.

Support structures were removed from the three samples printed with lines, grid and Zig-Zag support patterns. Surface of the ball after removing the support is shown in [Fig.8] It is seen that the support structure by the same material leaves significant amount of burr. Here the circularity of the ball is lost because of the residue left by the support. It was observed that type of support structure doesn't make significant difference in the burrs.

Fig. 8 Balls with different support structure removed -From Left to right : Grid, Lines and Zigzag.

Fig. 9 Bearing printed using PLA with: 11 Balls(Left) and 12 Balls (Right)

In the first stage, a deep groove ball bearing was designed and printed using 0.2mm (sliced using Slic3r) and 0.1mm (sliced using CuraEngine) layer thicknesses, respectively. PLA was used in this test for printing the bearing. After the print, post processing was done to remove the support structures. Support structures was needed for supporting the balls. Rough surface and fusing of balls and cages was significant in 0.2 mm version while the surface quality improved and only a fine fusing between the balls and cages were observed in the print with 0.1mm layer thickness. This restricted the free rotation of balls inside cage. As the layer thickness reduced, there was significant increase in print time. The 0.2mm layer thickness

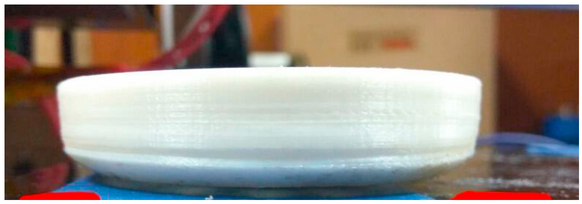

Fig. 10 Nylon 66 sample warped in the base

Fig. 11 Bearing printed using Nylon 6 6

Fig. 12 Bearing printed using ABS

version was printed in 6 hours and 10 minutes while the 0.1 mm version took 9 hours and 50 minutes.

In second stage the design was modified to remove the cage and increase the number of balls. This full complement bearing was printed as per the parameters mentioned in Table 1 using PLA. Design consisted of 11 balls which resulted in lot of gap between the balls as seen in [Fig. 9]. But this ensured free rotation of balls and races, but with significant amount of play. So the design was modified to include 12 balls and printed again. The radial and axial play was reduced and while the balls and races were free to rotate. This 12 balls design was then printed using PLA [Fig. 9], Nylon 66 and ABS. Nylon 66 had issues with print bed adhesion, despite using heated bed and kepton tapes. As a result, in both cases, Nylon 66 had warped base as seen in [Fig. 10].

The situation improved a lot when PVA glue was applied to the bed before printing. Nylon 66 being hygroscopic therefore it has the tendency to absorb moisture from atmosphere which degrades the filament[15]. A closed space with controlled atmosphere can be a solution. All these factors make the FDM of complement bearing using Nylon difficult. The bearing printed using Nylon 6 6 [Fig.11] has not shown any fused balls and was free to rotate. But the rotation was not as free as PLA due to the warped base. ABS printed sample [Fig.12] also had similar issues of bed adhesion in the first trial which was solved later with the application of PVA glue to the bed.

3.1 Surface roughness

Table 2 shows the S_a readings from the confocal microscope. The specimen prepared with ABS, the area roughness value varied from 30.10 µm to a maximum of 36.79 µm. For Nylon 66 it varied from 26.29 µm to 28.42 µm and for PLA it varied from 27.04 µm to 47.59 µm, respectively. The variation of the surface roughness can be due to surface defects in FDM printing. This include stair case effect, support structure burrs and voids [16]. Out of the three materials, the specimen made with PLA showed the highest roughness of 39.254 µm. Nylon 6 6 had the least roughness value of 27.270 µm.

Table 2 Area Surface Roughness

	1	2	3	4	5	6	Average
ABS Sa (µm)	31.29	30.10	31.94	32.15	36.79	34.47	32.79
Nylon 6-6 $S_{a\,(\mu m)}$	28.42	26.29	27.67	26.85	27.92	26.45	27.27
PLA $S_{a\,(\mu m)}$	42.50	27.04	38.69	41.60	38.07	47.59	39.25

Figs. 13-15 contain the images from confocal microscope at a magnification of 5X. It is clearly and visibly seen the striations are stricter for PLA in comparison to ABS and Nylon 66.

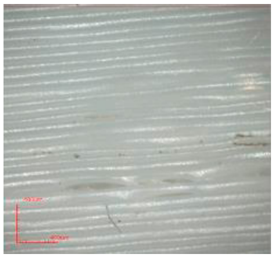

Fig. 13 Magnified view: ABS

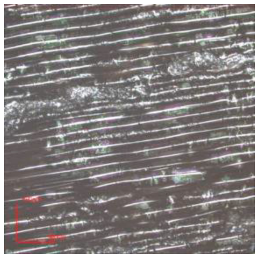

Fig. 14 Magnified view: PLA

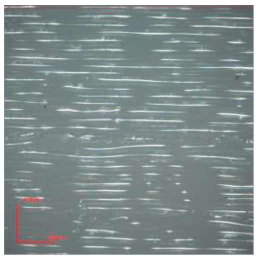

Fig. 15 Magnified view: Nylon 6 6

3.2 Hardness

Shore D hardness was measured on the side walls and the top surface. The values have been tabulated in the Table 3. For ABS, the values varied from shore D

74 to 80. In case of Nylon, it varied from 54 to 65 and for PLA, it varied from 74 to 84 on the same scale. For all the materials, the variation in hardness value between top and side surface was minimum. This shows the uniformity in the hardness along all the directions. The observed average value of shore D hardness for ABS is 76.67. This is in the range of standard ABS material. For Nylon 66 and PLA, the average values are: 60.75 and 78.91, respectively. Among all the three materials, the PLA has shown the hardest surface and Nylon the least. PLA and ABS hardness values are in the range of standard values. But Nylon 66 samples has shown very less hardness compared to standard values. This could be the readily available materials used. There requires a further investigation of the stock filament characteristics.

Table 3 Shore D Hardness

Material	Surface	1	2	3	4	5	6	Average
ABS	Side	75	77	76	74	78	79	76.5
	Top	75	74	75	80	79	78	76.83
Nylon 6-6	Side	55	65	54	63	56	65	59.66
	Top	66	63	62	60	62	58	61.83
PLA	Side	74	77	80	84	76	79	78.33
	Top	80	79	76	80	83	79	79.5

4. Conclusions

The feasibility of using 3d printing for fabricating a movable assembly as a single step by FDM was studied and successfully made. The design of a deep groove ball bearing was quite complicated to be printed. We found that, there was significant fusing of balls with the cages which resulted in non-moving prototype. The design was modified to a full complement bearing which achieved the printing of moving prototype of bearing. This ensured that complex assemblies can be printed in a single step process of 3D printing. Use of FDM technology ensured the cost effectiveness in this process. This will save on time, labour an overhead cost in the production process.

Initial study on clearances using a calibration specimen helped in choosing proper clearance in bearing design. Three different types of support structures - lines, grid and Zig-Zag were studied for their impact on surface roughness. It was found that whichever support type is used, it leaves significant amount of burr on the surface in a single extruder printer. Similar study needs to done in a multi-extruder system in which support structures are printed using water soluble material such as High Impact Polystyrene. Among the materials compared, the least roughness value was for Nylon 66. But its hardness was lesser than that of ABS and PLA. Also the high printing temperature and base warping made such as Nylon 6 6 was difficult to print. In case of ABS, it has a good balance between the roughness value and hardness, while PLA was hard with more roughness. The hardness values of the PLA and ABS falls in the range of standard values. But the hardness value of Nylon 66 specimen was less than the standard values, which requires further investigation.

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