Design of Low Cost Open Source Functionally Graded Fused Deposition based Rapid Prototyping (FG-FD-RP) System

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Abstract
The paper presents the design of a low cost 3d printer head for functionally graded- open source- desktop type rapid prototyping system. Proposed design involves the modification of basic Reprap open source system into functional grading rapid prototyping system, which demands necessary modification in Marlin firmware and G code to enable printing of two polymers simultaneously in a fixed proportion after mixing. Final design presented in this paper is based on the experimental analysis carried out on the available Reprap prusa i3 system in the laboratory as well as the associated simulations in ANSYS Workbench. Possible design solutions to major technical problems such as material leakage through the extruder, heterogenety in mixing and heating failure are addressed. All the iterations in the design of heating block have been mentioned and a feasible configuration of novel heating block has been proposed for functionally graded printing. The future work involves testing of the novel printer head to check the potential of the system in printing functionally graded components using bio degradable polymers with small difference in the density.

Keywords: Additive Manufacturing, Functional grading, Fused Deposition Modeling, Tissue Engineering, ANSYS

1. INTRODUCTION

Fused Deposition Modeling (FDM) is one of the prominent methods in Rapid Prototyping (RP) which uses thermoplastic filament, driven by controlled movement of stepper motor which is eventually heated to its melting point temperature and extruded layer by layer creating a three dimensional object. Functionally Graded Rapid Prototyping (FGRP) is a novel design approach by which one can have spatial property variation in a 3D printed component in at least one direction. Novel biomimetic systems, tissue engineering, bio-inspired materials etc., demand functional grading in the material [1]. Interface tissues such as ligament-to-bone, cartilage-to-bone, tendon-to-bone etc., show spatial variation in properties [2]. Functionally graded scaffolds provide biological and mechanical functions potentially similar to those of native tissues [3]. FDM rapid prototyping systems are really convenient to print functionally graded tissue scaffolds in bio-printing because it doesn't use any toxic solvents and can handle material very easily [4]. Such FGRP systems should be capable of mixing base and reinforcing materials simultaneously and printing it at critical regions especially in components failing due to high stress concentration [5]. Taubert P. [6] has shown feasibility of application of such FG-FDM technology on Reprap machines. His work involves design of dynamic mixing nozzle for bowden type extruder systems for such application. However, in depth testing samples of functionally graded components are not reported. Corbett J. [7] has shown design of active mixing nozzle for multi colour printing on bowden type extruders. Commercially available colour mixing nozzles are capable of mixing basic colours to print with any colour such as diamond hot end designed by Reprap for bowden type extruders [8]. Little to no work has been found on functionally graded printing on such FDM systems [9]. No previous work has been found on implementation of low cost FGRP system on one of the most widely used 3d printers which uses direct drive extruder, originally designed by Joseph Prusa - "Reprap prusa i3" [10]. Garland A. et. al. [9] presented challenges and their solutions for additive manufacturing of functionally graded components on Big Builder dual feed FDM 3d printer system which is already capable of printing by mixing of multi-colours, using a combined melting chamber. Design and manufacturing of functionally graded cantilever beam from PLA and nylon filaments having gradient in Z direction has been presented in their study. However, an uneven mixing of multi-materials can be identified as a typical technical challenge discussed in this work. Further, some researchers have also reported studies related to functional grading by controlling deposition density and deposition orientation in FDM [11]. Current direct drive extruders used with Reprap printers are capable of processing and extruding single filament of uniform colour. The design of novel FGRP system revolves around experimental iterative design and simulation results of heating block and necessary modification in the overall assembly to enable functional grading in components. The iterations in the design of heating block are based on experimental results after testing it on Reprap prusa i3 system. The final design has been provided based on simulation results and challenges faced in previous designs. To enable multi drive extrusion of two materials in mixing chamber, latest marlin firmware (Marlin 1.1.4) has been implemented on the system [12]. Modified CNC motion commands have also been implemented in the newly proposed system, by incorporating the mixing ratios in G-commands.

2. REPRAP PRUSA I3: CURRENT CONFIGURATION AND PROPOSED MODIFICATIONS

Reprap 3D printing systems are open source systems developed by University of Bath. Reprap RP systems consist of extruder block, Cooling fins, Heating element or heating block and nozzle for extrusion. The heating block is connected with cooling fins via heat breakers. Cooling fins are attached with extruder block via adaptors. Except nozzle all the components are manufactured from aluminum. Reprap RP systems use Marlin Firmware which basically controls all the functions of 3d printer by microcontroller and also consists of all the safety instructions for successful running of a 3d printer. Current system uses open source Sli3r software for producing Gcode which takes .STL file as an input. To enable

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functional grading in basic Reprap prusa i3 system, it is necessary that the system's controller is capable of processing extrusion of two filaments from brass nozzle using one integrated melting and mixing chamber. The G-code also should contain information regarding extrusion amount of both the filament and accordingly the stepper motor should drive the filament ahead in the assembly to get controlled mixing of two materials [9]. Open source software Sli3r is not capable of including such information. Tabert P. [6] has developed G-code based programs to generate three dimensional objects, considering the user inputs related to length, width and height of printing. A simple G1 command (G code file) without specifying mixing ratio is “G1 X 50 Y 50 E 2 F5000”, where G1 suggests a co-ordinate where the extruder head will travel, corresponding to an extrusion of 2 mm. The whole movement will be performed at a feed rate of 5000 mm^3/min. Now, to effectuate functional grading in the component, G code should contain information regarding mixing of two filaments at a specified location. For instance, if it is needed to deposit two filaments in proportion of 25:75 at (50,50) location, a modified G1 command is used : “G1 X 50 Y 50 E 2 F5000 A0.25 B0.75”, where the total extrusion of 2 mm will be contributed 25% by the first extruder and the remaining 75% by the second one. This proportion can be varied as per the requirement of end user at any location. The main advantage of functionally graded components is a smooth transition between material type, so there can be no delamination at the interface [9]. Incorporation of mixing information in G1 command solve problem of delamination reported by Garland A. et al.[9]. Figure 1 shows conceptual representation of functional grading achieved by modified G code. The black dot represents initial position of nozzle head. With the command of G1 X 50 Y 50 E 2 F5000 A0.25 B0.75, the extruder head will travel to (50,50) depositing two materials in ratio of 25:75. Subsequent layers will be deposited in specified mixing ratio as indicated by G code file. After laying first layer the process goes on repeating building a three dimensional component having functional gradient in X direction. Many researchers have carried out extensive research on virtual modeling of functionally graded components. There are two types of composition representation methods found in literature 1) Voxel based representation 2) Function based models [9]. Finding a suitable model for composition representation is area of continuing research.

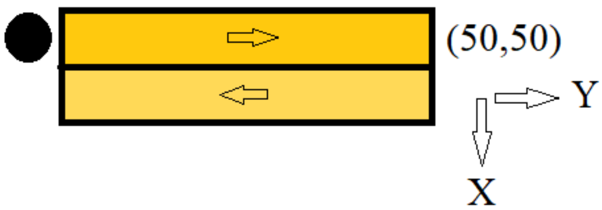

Fig. 1. Conceptual Represntation of Printing Process Illustrating Fucntional Gradient in X direction

3. ITERATIVE DESIGN PROCEDURE

Mechanical elements in the proposed extruder head assembly consists of extruder unit and its motors, heating block and integrated heat sinks, as shown in Figure 2. The nozzles were placed at the bottom side of heating block, aligning such a way to extrude the filaments smoothly.

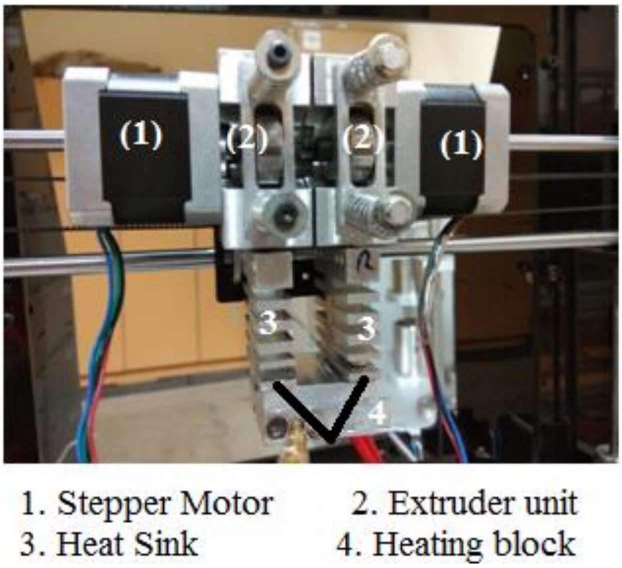

Fig. 2. Heating Block V1

The main focus in the functionally graded printing was to modify the design of integrated heating block, added with the capability of melting the filaments and mixing them in various proportions. The initial design was using a rectangular heating block having inclined holes (V-shaped), top of which are aligned with the outlets of two extruder units and bottom of the same converging to a common nozzle opening, as shown in figure 2. There were two options to choose the material of the block from aluminum or brass. Due to higher heat conductivity values shown by aluminum than brass, and due to lower overall weight constraint of the assembly, aluminum was chosen. Testing result showed failure of heating to the ABS melting point temperature (heating failure) which was the reason the block couldn't be used to test mixing of ABS and PLA. As the block was attached to the fins as shown in figure 2, it expedited the heat transfer through the fins. Enhanced heat transfer through the overall upper section of the assembly resulted in clogging of PLA in the fin section and thereby failed the functionally graded mixing. The second revision (V2) was attempted with the same rectangular heating block with V-shaped holes, directly connected to the extruder units (as in Figure 3) with a common heat sink on the back side of extruders. However the technical issue associated with the same was the leakage through the interface of extruder and heat block as indicated in Figure 4.

4. MODIFIED HEATING BLOCK: DESIGN AND TESTING

Final design of extruder was proposed to overcome the identified troubles such as heating failure of ABS material, temperature control in extruder head as well as leakage of materials. The heating failure problem was addressed by introducing heat breakers (2) in the extruder assembly.

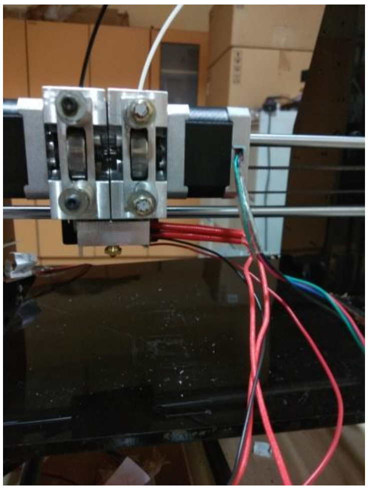

Fig. 3. Heating block V2

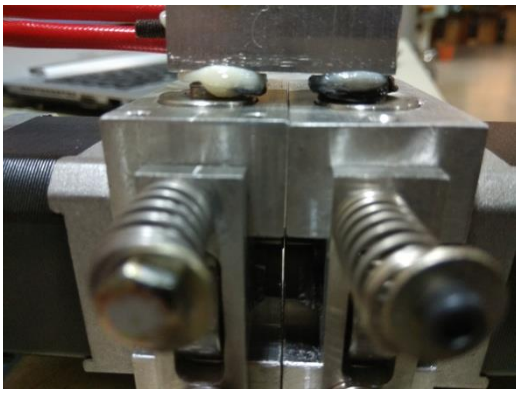

Fig. 4. Leakage of PLA & ABS

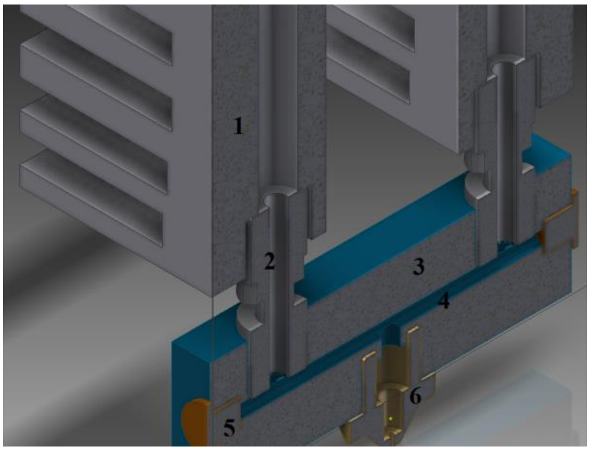

Fig. 5. Sectional View of Novel Heating Block

The heater block (4) was made more compact to accomplish more homogenous mixing, with two vertical holes aligned with heat sink (1) via heat breakers (2) and interconnected to a common nozzle (6) through a horizontal (4) passage (H-shaped hole), as in Figure 5. The primary function of heat breakers is to prevent the heat flow from heating block to the upper part of assembly. The heat breakers also minimized the contact interface area of the heating block with remaining surfaces of extruder unit. Further, larger length of heat breakers contributed to increment in resistance for the conduction mode of heat transfer according to Fourier law of heat conduction. Leakage problem was solved in this design by fixing heat breakers with the heating block rigidly leaving no space in between. The horizontal mixing channel was also found convenient for cleaning by the removal of plugging fasteners (5) from both the sides.

5. RESULTS AND DISCUSSIONS

5.1 Assessment of Mixing Quality

The new designed heating block was directly attached to extruder blocks as shown in figure 6. Mixing quality of the proposed extruder was examined by different combinations of filaments, first one with ABS (orange) and ABS (white), as well as ABS and PLA. The mixing quality showed some encouraging results while using the ABS orange-white combination. However, some non-homogeneity was evident during the mixing of ABS and PLA in the same extruder. This may be attributed to the change in density of the two filament materials, as they not exist in completely dissolved liquid state while mixing. The reported heterogeneity was also shown by Garland A. et al [9] in their experiments of mixing PLA and Nylon. Since the density difference of ABS and PLA is higher than that of PLA-Nylon combination, the observed heterogeneity can be justified by the above hypothesis.

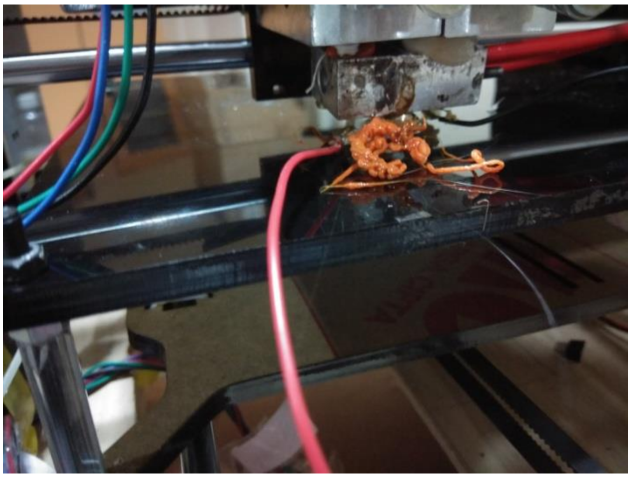

Fig. 6. Mixing Results of ABS(Orange) & ABS(White)

5.2 Analysis of Extruder Assembly and Performance

As a primary consideration, leakage of heated polymer filament through the joints in the extruder assembly was verified. As an immediate solution, it was premeditated to tighten the fasteners as good as possible to avoid the leakage issues. But in association with this, there was a very interesting analysis result observed during the present study. Simulation studies were conducted on the heating block-extruder assembly, using ANSYS-transient thermal module by applying internal heat generation, at various tightening conditions of fasteners. Heat input was provided by referring to the specification of heating element. The simulation was carried out for 10 seconds and typical values of temperature achieved by heating block with and without fasteners are shown in Table 1. It is clear from these results that the rapid maximization of temperature in the heating block can be achieved by an assembly without fasteners or by loosening the fasteners. While tightening the fasteners, it may contribute to the increment in contact surface area and thereby promotes an enhanced heat transfer to the upper assembly. Even though it can be considered as a common, well-understood and simple phenomenon, it plays a significant role in filament extrusion. Even at a slight enhancement in heat transfer, there is high chance that the filament gets solidified inside the assembly, creating a serious clogging issue. However, it cannot be resolved by maximizing the temperature using *too much loosened fasteners* or *no fasteners* as indicated in the simulation result. As without fasteners the heating block couldn't be attached with the extruder outlet, an alternative solution of using heat breakers is proposed for the modified assembly as shown in Figure 5. The hypothesis is to slow down the conduction by the usage of custom designed heat breakers.

Table 1 Temperature Comparison

Temperature	Heating block with fasteners
Maximum	227.45
Minimum	22

Temperature	Heating block without fasteners
Maximum	272.16
Minimum	22

Extensive analysis of modified extruder design has been repeated in ANSYS, by applying internal heat generation, convective conditions and convective coefficient of stagnant air. Temperature results of heating block can be observed in the Table 2. The results for other components can also be seen in Figure 7. It was observed that maximum temperature in cooling fins was 52.2°C, which can be maintained easily at room temperature with help of forced convection with fan which will further prevent clogging issue of PLA in the heated assembly.

Table 2 Novel Heating block Temperature Values

Temperature	Heating block
Maximum	260.49
Minimum	22

Stress analysis was also performed to investigate thermal stress values for critical sections such as heat breakers which is in direct contact with the heating block and constrained from both the sides as shown in Figure 8. It was observed that the stress values reached beyond yield strength of aluminum for heat breaker in the thin section which can lead to failure of heat breaker. So it is very critical to optimize the size and shape of heat breakers.

6. CONCLUSION

After iterative revisions in the heating block design, a modified extruder configuration for functionally graded 3d printing is proposed in this paper. In the new design, the volume of fused filament extrusion was optimized to prevent failure of heating; leakage as well as issues associated with heat transfer. Simulation results were also substantiating the aforementioned design advantages. Two different colored materials of same density showed encouraging results in mixing, while PLA and ABS were showing heterogeneity in mixing due to their significant difference in density. It can be concluded that two different materials with slight changes in density can achieve homogenous mixing in the new extruder [9], which demands further experimental testing by taking different set of materials. Through the results of the present work, it can be concluded that the modifications related to software compatibility for processing functional gradient printing can be achieved cost effectively and conveniently.

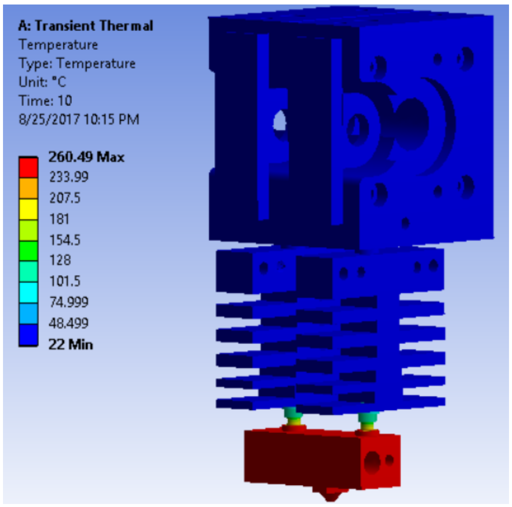

Fig. 7. Temperature in Assembly with Final Design

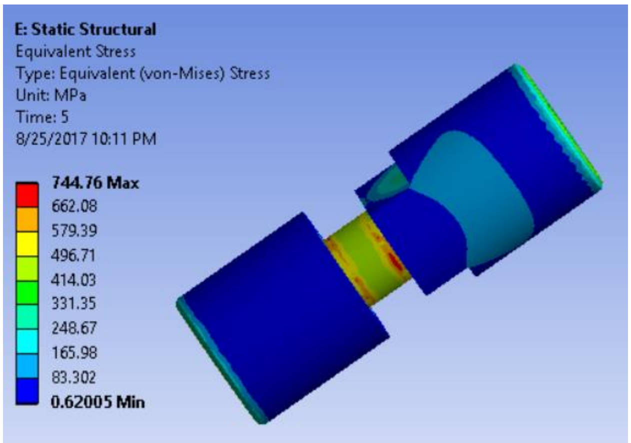

Fig. 8. Thermal Stress in Heat Breaker

However, further modifications can be attempted on the extruder-heating block assembly for leak proof- clog free- homogeneous mixing of polymer filaments with varying density values. A typical proposal is to go for a dynamic stirrer to be incorporated in the mixing chamber. With the existing hardware, it is feasible to generate functional graded three dimensional components, subjected to the improved design considerations in extruder unit. Further works in future can be focused on the implementation of such systems to test different variants of materials, especially bio-degradable ones to use it for functionally graded fused deposition 3D printing of tissue scaffolds.

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