Controlling localised properties in fused deposition modelling parts: A feasibility study

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Abstract. Recent advancement in additive manufacturing (AM) enables us to make functional prototypes with the highest accuracy. Among various AM techniques, fused deposition modeling (FDM) is most popular due to its ability to make a complex shape in minimum time and least cost. However, the strength of the parts fabricated with FDM is always of primary concern so present approach provides a way to control localized mechanical property in FDM parts. Model of a 3D object is bifurcated into various subparts by incorporating stress data. All subparts are fabricated by using appropriate process parameters suited to their stress value. As the process parameters have a prominent effect on the strength of the part, hence the part fabricated contains better strength compared to conventional FDM approach.

1. Introduction
Additive manufacturing (AM) provides a platform to make parts with the best quality at a reasonable price within the shortest time, which is essential to survive in the present competitive manufacturing world. In order to reduce the product development cycle time, now a day’s standpoint of industries has changed from conventional manufacturing technique to additive manufacturing. Initially, additive manufacturing was used to make prototypes of the parts to test its functionality, but now a day’s it is used to manufacture actual machines components, as well as the medical equipment, ‘s so that the fabricated parts must possess enough strength to sustain during its functionality. Additive Manufacturing is a manufacturing technique in which any complex parts can be fabricated from 3D computer aided designs (CAD) model in layer-by-layer fashion with a suitable material (polymer, metal, etc.) [1]. Various processes in AM have been evolved that uses a variety of material, ranging from plastics to metals [2,3]. Most popular AM techniques are stereolithography (SLA), selective laser sintering (SLS), fused deposition manufacturing (FDM), selective laser melting (SLM). Schematic diagram of FDM is shown in figure 1. FDM uses a thermoplastic material that passes through heated liquefier, where the state of filament changes from solid to semi-molten, afterward it is deposited through a nozzle having relative motion with the base where it solidifies under a controlled environment. Most commonly used filaments materials in FDM are acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA). FDM is most popular AM process which gives free control of process parameters. FDM allows controlling internal structure of 3D printed object. While the main advantage of FDM process is that it can make parts with locally controlled properties like strength, density, and porosity.
2. Literature review
Despite having several advantages, FDM technology has some limitation too, one of which is the poor strength of the part fabricated. Mechanical properties of the parts fabricated through FDM process are affected by design and processing conditions. Many attempts have been taken in order to improve the strength of the part such as proper material selection or process parameter optimization [4]. Rodriguez et al. [5] researched the effect of infill angle on the fracture behavior of the fabricated parts. It was found that if the infill angle is changed, fracture behavior also changes from ductile to brittle due to improper bonding between the filaments. Ahn et al. [6] have studied the effect of different process parameters like deposition temperature, air gap, bead width and raster angle on the tensile and compressive strengths of directionally fabricated specimens. It was found that parameters such as raster orientation and air gap affect tensile strength by a substantial amount. Zhong et al. [7] studied that tensile strength of ABS filament can be increased by a considerable amount if glass fiber is reinforced into ABS matrix. It was found that at the expense of handleability and flexibility strength of the abs filament can be increased by using glass fiber. Roger et al. [8] have studied about heterogeneous internal filling or multi-materials in FDM process in order to obtain targeted mechanical properties. Also, optimization of infill density distribution can be done in order to improve stiffness in stress concertation zones in the fabricated parts. Ning et al. [9] presented carbon fiber in a matrix of thermoplastic CFRP composites have a significant effect on the mechanical property of the FDM printed parts, but the limitation with this process is that FDM technology is not compatible with all kind of materials. Sood et al. [10] investigated the effect of process parameters such as layer thickness, raster angle and air gap on the tensile behavior of the fabricated specimen. If number of layers is more, it will result in high-temperature gradient towards the bottom of part thus increase the diffusion between adjacent raster and strength will improve. Due to the rapid growth of layered manufacturing now a day’s design and manufacturing of heterogeneous parts are very popular. Present work gives us a way to control localized property in part and same methodology has been used to fabricate part by using FDM.

3. Methodology
Proposed methodology provides us a way for fabricating prototypes having localized mechanical property in different regions by considering stress pattern obtained from ANSYS Programming Design Logic (APDL) of ANSYS software. Procedure for multiple STL printing is shown in the figure. 2.
Firstly, the solid model of an object is generated using any of the modelling software, further finite element analysis of the model is done using APDL module of ANSYS. Stress pattern obtained using
ANSYS (APDL) is shown in figure 3. A MATLAB program is developed to generate point cloud by incorporating obtained stress data from ANSYS(APDL). Point cloud for the critical region can be separated from that of the non-critical region just by giving suitable stress value. Further, a MATLAB program is developed which will generate STL file from the generated point cloud. Hence a single STL is bifurcated into two STL’s by incorporating stress data. Merging of two STL’s is done by using an open source software Replicator-G and printing are performed. The proposed approach can reduce the weight of the parts by assigning faster prototyping condition in the non-critical region also this approach can be used for fabrication of functionally graded material.

**Figure 2. Proposed Methodology**

**Figure 3. Stress pattern obtained from ANSYS**

4. Experimental Details
Among various process parameters four parameters namely infill density, deposition temperature, travel feed and feed rate are the most significant factors impacting the strength of the printed parts. The
importance of these parameters has been seen in the various literature [5–10]. As the primary aim of the work is to investigate mechanical properties of printed parts, test specimens are designed and fabricated by following ASTM D638 standards, which specifies the geometry and dimension of the specimen for tensile tests. Schematic diagram of the designed tensile specimen with along with the dimensions is shown in the figure. 4

5. Tensile Testing
Following ASTM D638 standard (for ABS plastic), tensile testing of each printed specimen (shown in the figure. 4) is performed on a universal testing machine (Tinius Olsen H250K (USA)). Tensile specimen with different regions is shown in figure 5. Also, printing parameters for different regions in a specimen are given in Table 1. Outer region (i.e. non critical region) is printed with 70% infill density, 230°C temperature, 50 mm/min travel feed and 70 mm/min feed rate whereas inner region (i.e. non critical region) is printed with 100% infill density, 250°C temperature, 40 mm/min travel feed and 60 mm/min feed rate.

| Process parameters | Region 1 | Region 2 |
|--------------------|----------|----------|
| Infill density     | 70%      | 100%     |
| Deposition temperature | 230     | 250      |
| Travel feed        | 50       | 40       |
| Feed rate          | 70       | 60       |

6. Results and discussion
Figure. 6 shows the stress-strain curve of fabricated specimens. The plot includes elastic deformation followed by failure point. Depending on the printing strategies, tensile strength, as well as failure point of the specimens, were varying. Three types of printing strategies were employed for fabrication of specimen as shown in figure 7. Specimen for the first experiment was fabricated with 70% infill density
without any overlap. Likewise, other specimens were fabricated with varying infill density in the critical and non-critical region along with some overlap. Printing parameter for critical and non-critical region is given in Table 1. It can be noticed that the maximum tensile strength was achieved for a specimen with maximum overlap and as the overlap amount is decreased tensile strength is also decreased. This is due to the reason that for the specimen having maximum overlap, planes between the two regions are in perfect contact and the adhesion between the layers are stronger resulting in increased tensile strength. Interestingly, the tensile strength of less overlap parts increased by a significant amount compared to parts having no overlap (i.e. uniform infill). An interesting phenomenon that has been observed in experiments is necking at lower strains. This is because when thermoplastic polymers are subjected to deformation by stretching long chain molecule align themselves in the direction of elongation and the specimen becomes stronger and stiffer, and this process leads to early unstable necking [11]. Figure 8 shows the failed tensile test specimens. It can be observed that all specimens were failed almost in the same fashion as the standard specimen, this shows the feasibility of the proposed methodology.

**Figure 6.** Representative stress-strain data of tensile specimens printed with different strategies

![Stress-strain data](image)

**Figure 7.** Specimens with different strategies (A) 70% uniform infill (B) Less overlap (C) Maximum overlap

![Specimens](image)
Figure 8. Failed tensile test specimens (A) 70% uniform infill (B) Less overlap (C) Maximum overlap

7. Conclusion
The main aim of the present research was to evaluate the feasibility of fabricating parts having localized property control. Specimens with localized property control have been successfully fabricated on commercial FDM machine by assigning suitable process parameters in different regions. Deposition temperature, infill density, feed rate, travel feed were selected as the most prominent factor affecting the strength of the FDM parts. Several results were drawn from the analysis. Maximum tensile strength values were reported for samples having maximum overlap and as the overlap amount was decreased tensile strength was decreased also printed specimens were failed almost in the same fashion as the standard specimen, this shows the feasibility of the process.

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