

Effect of Process Parameters on Strength of Fused Deposition Modelling

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Abstract:- Additive Manufacturing (AM) technologies have been emerged as a fabrication method to obtain engineering components within a short span of time. Desktop 3D printing, also referred as additive layer manufacturing technology is one of the powerful method of rapid prototyping (RP) technique that fabricates three dimensional engineering components. In this method, 3D digital CAD data is converted directly to a product. In the present investigation, ABS + hydrous magnesium silicate composite was considered as the starting material. Mechanical properties of ABS + hydrous magnesium silicate composite material were evaluated. ASTM D638 and ASTM D760 standards were followed for carrying out tensile and flexural tests, respectively. Samples with different layer thickness and printing speed were prepared. Based on the experimental results, it is suggested that low printing speed, and low layer thickness has resulted maximum tensile and flexural strength, as compared to all the other process parameters samples.

Keywords- FDM; Additive Manufacturing; Rapid prototype; 3D printing; Tensile Strength; Flexural Strength; Mechanical Properties

I. INTRODUCTION

Additive Manufacturing (AM) is extensively used to fabricate a scale model of a physical part or assembly using three-dimensional computer aided design (CAD) data at a faster rate. The CAD data is fed to the 3D printing machines that allow designers to quickly create tangible prototypes of its designs, rather than just two-dimensional pictures. 3D printing is a form of layered manufacturing / additive manufacturing technology where a three-dimensional object is created by laying down successive layers of material. The material extrusion additive manufacturing (AM) process [1], commonly known as FDM. As a result, much of the research is focused on transforming this technology towards manufacturing production grade and end use products [2]. Rapid Prototyping (RP) technologies offer viable and simpler alternative methods for fabricating 3D models to 3D digital data. Existing commercial AM machines are currently being modified to an extent to improve their accuracy and capabilities. However, high costs, material restrictions, and difficulty in studying process parameters are an issue. But in this context, the present work is focused on the study and optimization of a novel open-source and low-cost 3D printer machine, called 3D protomaker STURDY, and employed to fabricate samples. Several process parameters like layer thickness and printing speed are studied.

FDM is a technique in RP that is based on surface chemistry, thermal energy, and layer manufacturing technology. In this process, filaments of heated thermoplastic are extruded from a tip that moves in the x-y plane. The controlled extrusion head deposits very thin beads of material onto the build platform to form the first layer [3-6]. The platform is maintained at a low temperature, so that the thermoplastic is quickly hardens. After the platform lowers by the specified distance (i.e., layer thickness), the extrusion head deposits a second layer upon the first. The process is continued to form the desired prototype of specified dimensions [7]. Supports are built along the way, fastened to the part either with a second weaker material or with a perforated junction. In this paper, tensile strength properties of ABS + hydrous magnesium silicate composite material made by Desktop 3D printer process with different build parameters such as layer thickness, printing speed, and raster orientation are discussed.

Said et. al. [6] suggested that the raster orientation causes alignment of polymer molecules along with the direction of deposition during fabrication of the tensile, flexural and impact strength depends on orientation of the sample. Since semi-molten filament is extruded from nozzle tip and solidified in a chamber maintained at certain temperature, change of phase is likely to occur. As a result, volumetric shrinkage takes place resulting in weak interlayer bonding and high porosity. This is resulted in reduced load bearing area. Ahnet. al. [8] have reported that process parameters such as air gap and raster orientation significantly affect the tensile strength of FDM fabricated part as compared to other parameters such as raster width, model temperature and colours through experimental design and analysis. In addition, built parts exhibit anisotropic properties depending on build orientation as far as tensile and flexural strength is concerned. Khan et.

al. [9] have also suggested that layer thickness, raster angle and air gap influence the elastic performance of the compliant FDM ABS prototype. Lee et. al. [10] performed experiments on cylindrical parts made from three RP processes such as FDM, 3D printer and nano composite deposition (NCDS) to study the effect of build direction on the compressive strength. Experimental results show that compressive strength is 11.6% higher for axial FDM specimen as compared to transverse FDM specimen. It has been observed that deformation is more in bottom layers than upper layers. High stacking section lengths, are responsible for large deformations. If chamber temperature is increased, deformation gradually decreased and became zero when chamber temperature equals glass transition temperature of material. Therefore, it is proposed that material used for part fabrication must have lower glass transition temperature and linear shrinkage rate.

Wang et. al. [11]. When material is extruded from the nozzle, it cools from glass transition temperature to chamber temperature causing inner stresses to be developed due to uneven deposition speed resulting in inter layer and intra layer deformation that appear in the form of cracking, de-lamination or even part fabrication failure. These phenomena combine to affect the part strength and size. Bellehumeur et al. [12] has experimentally demonstrated that bond quality between adjacent filaments depends on envelope temperature and variations in the convective conditions within the building part while testing tensile and flexural strength specimen. Temperature profiles reveal that temperature at bottom layers rises above the glass transition temperature and rapidly decreases in the direction of movement of extrusion head. The minimum temperature increases with the number of layers. Microstructural studies indicated that diffusion phenomenon is more prominent for adjacent filaments in bottom layers as compared to upper layers. Chou et al. [13] suggested that simulation of FDM process using finite element analysis (FEA) shows that distortion of parts is mainly caused due to accumulation of residual stresses at the bottom surface of the part during fabrication

II. Experimental Details

ASTM D638 (Type 1) and ASTM D790 standards were used for the fabrication of tensile and flexural samples, respectively. The initial goal was to fabricate the sample with varying process parameters like different layer thickness (0.2 mm, 0.25 mm and 0.3 mm) and different printing speeds (30 mm/s, 40 mm/s and 50mm/s). It was observed that variations in fabrication time of preparation of test samples when the different built parameters. For all experiments, 0.6 mm diameter nozzle were used. The nozzle was maintained a temperature of ~190 °C for the extrusion of the ABS + hydrous magnesium silicate composite material and the build platform was maintained at ~70 °C. The samples were prepared based on the various combinations and shown in Table 1, it provides a detail combination of 9 different samples for the process parameters. All test samples were subjected to tensile and flexural tests. For each test, 3 reading were taken and an average reading is reported. Among various desktop 3D printing machines, low cost 3D printing machine was used for preparing samples i.e 3D protomaker STURDY. For the process parameter control while manufacturing a slicing software called slice 3r was used.

Table: 1: Various process conditions for specimen preparation

Sample parameter	Sample 1	Sample 2	Sample 3
Layer thickness, mm	L1 = 0.2	L2= 0.25	L3 = 0.3
Printing Speed, mm/s	S1 =30	S2 = 40	S3=50
Nozzle dia, mm	N1=0.6	N1=0.6	N1=0.6

A universal testing machine having tensile and flexural fixtures with 10 kN load cell capacity was used to perform tensile and flexural tests. For ASTM D638, the test is stopped when the specimen reaches 2.5% elongation or the specimen breaks. For ASTM D790, a 3 point load conditions were followed for the flexural strength. Since the physical properties of many materials (especially thermoplastics) can vary depending on ambient temperatures, it is desired to test samples at temperatures that simulate the intended end user environment [14].

III. Results and discussion

3.1 Tensile Specimen

Tensile strength was determined for 3D printing models prepared from a 0.6 mm diameter nozzle with variation in speed and layer thickness. The related stress strain curves are plotted in figure's 3-5 for all experimental samples. It is noticed that the tensile stress is decreased with increase in layer thickness as well tensile stress decreases with increase in printing speed. However, this effect is less as the layer thickness is increased. Therefore, the layer thickness played a significant

role in tensile properties of ABS + hydrous magnesium silicate composite material printed with 0.6 mm diameter nozzle and 60% infill density.

Figure 3 show the tensile behavior of ABS + hydrous magnesium silicate composite material, fabricated using 0.6 mm nozzle diameter with layer thickness 0.2 mm. It can be seen from these tensile values that the trend of failure is almost same and is also observed that the lowest printing speed sample exhibited highest tensile stress values. It illustrates the curves closest to the average values obtained for the different printing speed. Moreover, 30 mm/s speed printed specimen exhibited maximum tensile strength of 28.5 MPa and strain of 2.3 %. Similarly, the tensile Stress of 27 MPa, 25 MPa and the strain of 2.1% are obtained for printing speed of 40 and 50 mm/s samples. The tensile Stress results further suggest that increasing the printing speed is responsible for lowering the tensile Stress values.

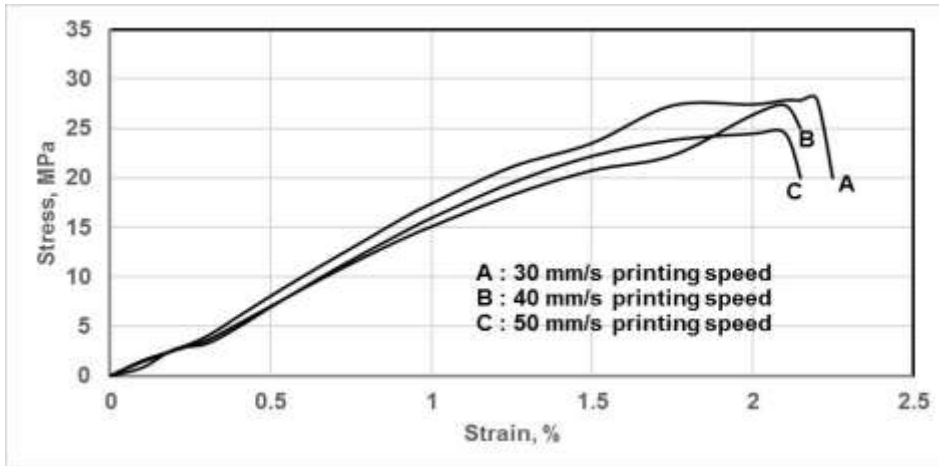


Fig: 3 Tensile behavior of ABS composite with 0.2 mm layer thickness

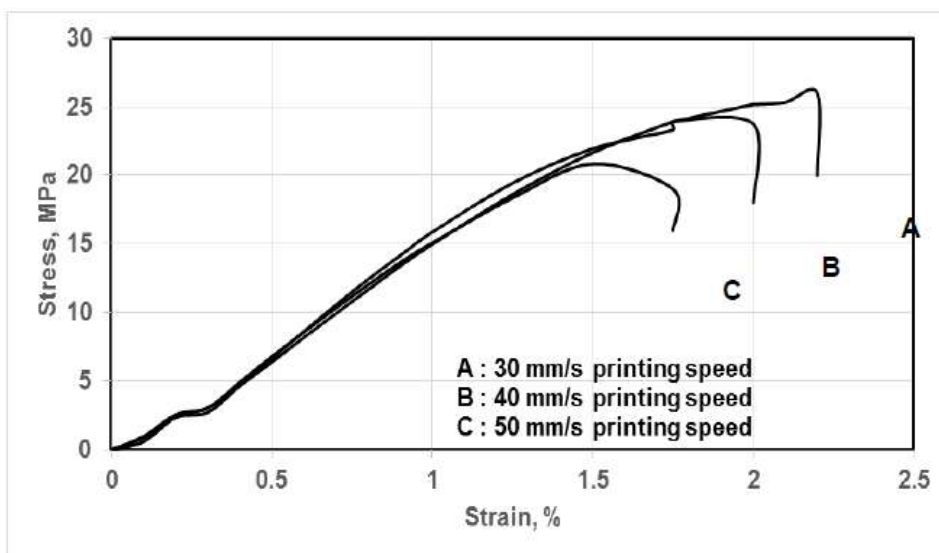


Fig: 4 Tensile behavior of ABS composite with 0.25 mm layer thickness

The tension test results for the 2.5 mm Layer thickness with different printing speeds are plotted in Figure 4. curve A represents the tensile behavior of sample with 30 mm/s printing speed. It depicts tensile Stress of ~26 MPa and strain of ~2.2 %. Similarly, Figure 4 curve B illustrates a maximum tensile Stress of 24 MPa with ~2% strain for a sample made with 40 mm/s printing speed. The third sample shown in Figure 4 curve C shows the tensile Stress as 21 MPa and strain of 1.7 %. The maximum tensile Stress achieved is 30 mm/s print speed. It is interesting to observe from these results that the Stress decreases as the strain levels also decreased. This is typically a reverse trend of tensile behavior that is observed for most of non-metallic materials.

Figure 5 shows the tensile Stress properties of ABS + hydrous magnesium silicate composite material fabricated using 0.6 mm nozzle with 0.3 mm layer thickness and 60 % fill density. Figure 5 curve A depicts 30 mm/s printing speed with horizontal orientation. It exhibited maximum tensile Stress of 25.5 MPa with a strain of 2.4 %. Similarly, Figure 5 curve B shows the tensile properties of the ABS + hydrous magnesium silicate composite material with a printing speed of 40 mm/s. It shows the maximum tensile Stress of 24.5 MPa with strain of 2.1 %. The trend followed for this sample is completely different from other samples with different layer thicknesses. Even though the Stress value is comparatively lower than 30 mm/s sample, initial trend showed high tensile Stress levels as compared to 30 mm/s printing speed sample. Figure 5 curve C illustrate the tensile behavior of the sample printed with a printing speed of 50 mm/s. It exhibited maximum tensile Stress of 18 MPa with a strain of 1.75 %. These values are comparatively lower than other two printing speeds.

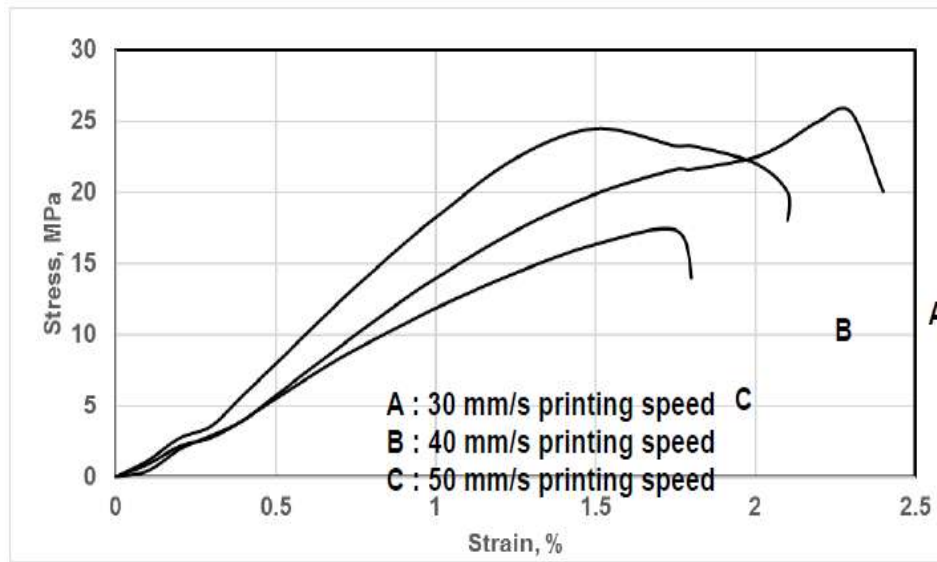


Fig: 5 tensile behavior of ABS composite with 0.30 mm layer thickness

From the above results (Figure 3-5), it is clearly shown that the ABS + hydrous magnesium silicate composite material fabricated using 0.6 mm nozzle with 0.2 mm layer thickness and 30 mm/s printing speed exhibited a maximum tensile Stress of 28.5 MPa and the sample with 0.3 mm layer thickness and having printing speed of 50 mm/s showed a lowest tensile stress of 17 MPa. The tensile Stress of 0.3 mm layer with a printing speed of 50 mm/s very low, probably due to the additive manufacturing/ layered manufacturing samples have weak interlayer bonding or inter layer porosity [6]. The result further conforming that the layer orientation of additive manufacturing/ layered manufacturing samples contributes to the anisotropic properties [8]. Tensile testing causes low Stress interference between 2D laminates or layer to delaminate prior to the fracture of 2D laminates or layers. Delamination is frequently observed in layered materials and the stress variation was due to the delamination [10].

3.2 Flexural strength

Figure 6 show the flexural strength properties of ABS + hydrous magnesium silicate composite material, fabricated using 0.6 mm nozzle diameter with 0.2 mm layer thickness. Figure 6 illustrates the curves of load vs. displacement for the different printing speeds. Figure 6 curve A illustrates for the 30 mm/s speed printed specimen. It exhibited a maximum flexural load of 43 N and displacement of 14 mm. Similarly, Figure 6 curve B shows the maximum flexural load of 37 N and the displacement of 13.5. It is observed that as the printing speed is increased from 30 to 40 mm/s, there is a reduction in both flexural load and displacement values. Figure 6 curve C exhibited a maximum flexural load of 32N and displacement of 14.5 mm. As compared to the both 30 and 40 mm/s printing speed specimens, this specimen exhibited low flexural load with marginal improvement in the displacement value. As a result, the overall performance of these samples suggests that the flexural strength is decreased as the printing speed is increased.

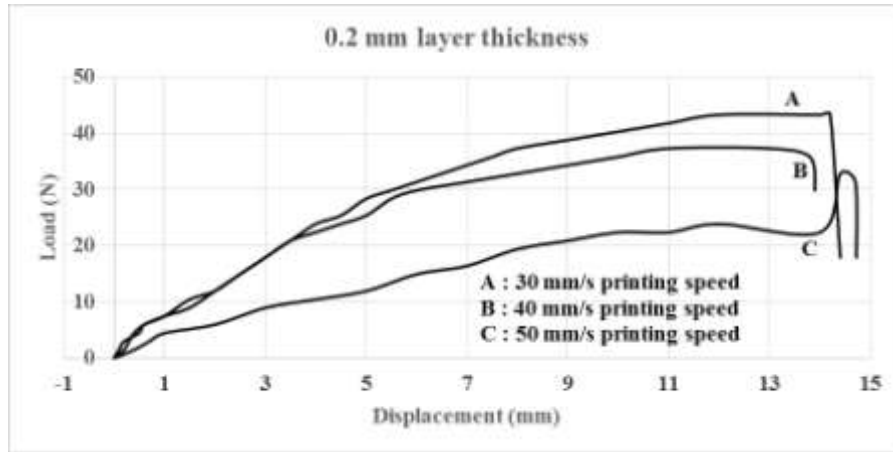


Fig: 6 Flexural behavior of ABS composite 0.2 mm layer thickness

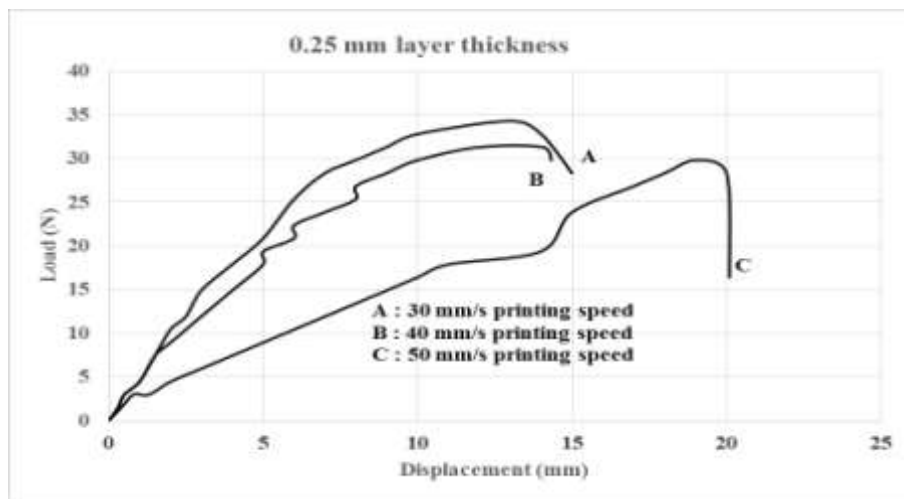


Fig: 7 Flexural behavior of ABS composite 0.25 mm layer thickness

The flexural test results for the 2.5 mm layer thickness specimens with different print speed are plotted in Figure 7. Figure 7 curve a shows the flexural behavior of the specimen with a 30 mm/s printing speed and it showed a maximum flexural load of 34 N and a displacement of 15 mm. Figure 7 curve B depicts the flexural behavior of specimen with 40 mm/s printing speed. This showed a maximum flexural load of 31N and a displacement of 14.5 mm. There is 10% reduction in load values are observed when the sliding speed is increased from 30 mm/s to 40 mm/s. The third sample in Figure 7 curve C shows the flexural load of 30 N and displacement of 20 mm, where the printing speed is maintained at 50 mm/s. this behavior is also similar to the sample with 40 mm/s printing speed, where the increase in printing speed is responsible for lowering the flexural load and displacement values.

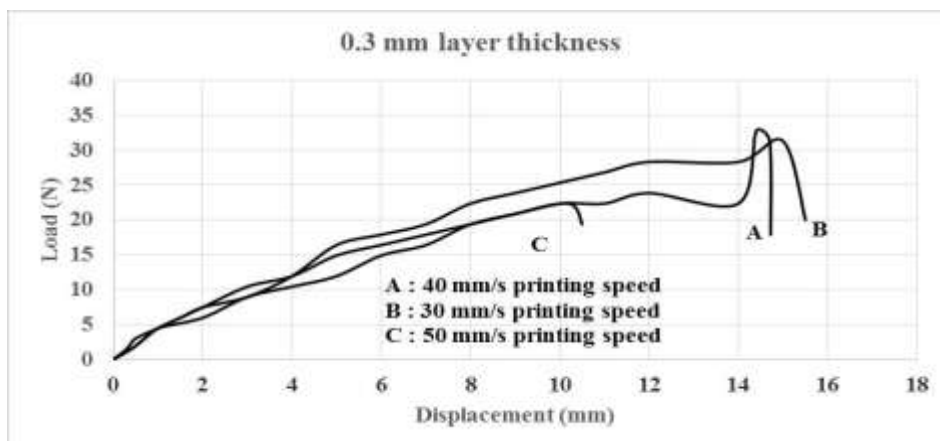


Fig: 8 Flexural behavior of ABS composite 0.3 mm layer thickness

Figure 8 shows the flexural strength properties of ABS + hydrous magnesium silicate composite material fabricated using 0.6 mm nozzle with 0.3 mm layer thickness and 60 % fill density. Figure 8 curve A depicts 30 mm/s printing speed with horizontal orientation. It exhibits a maximum flexural load of 33 N with a displacement of 14.5 mm. Similarly, Figure 8 curve B showed a maximum flexural load of the ABS + hydrous magnesium silicate composite material with a printing speed of 40 mm/s. It exhibited a maximum flexural load of 31 N with displacement of 15 mm. this trend has been observed from all specimen as the printing speed is increased. Figure 8 curve C illustrate the flexural properties of the sample with a printing speed of 50 mm/s. It exhibited maximum flexural load of 22 N and displacement of 10.5 mm.

From the above results (Figure's 6-8), it is clearly understood that the ABS + hydrous magnesium silicate composite material fabricated using 0.6 mm nozzle with 0.2 mm layer thickness and 30 mm/s printing speed exhibited a maximum flexural load of 40 N and the sample with 0.3 mm layer thickness and having printing speed of 50 mm/s showed a lowest flexural load of 22 N. The flexural load of 0.3 mm layer thickness with a printing speed of 50 mm/s exhibited very low flexural loads. This is probably due to the additive manufacturing/ layered manufacturing samples have weak interlayer bonding or inter layer porosity and also suggested by other researchers [6]. The results further confirming that the layer orientation of additive manufacturing/ layered manufacturing samples contributes to the anisotropic properties [8]. Flexural testing which causes to the low strength interference between 2D laminates or layer to delaminate prior to the fracture of 2D laminates or layers. Delamination is frequently observed in layered materials, stress variation due to delamination [10].

From all the results and discussions, it is suggested that tensile and flexural strength part is made with thicker layer then each individual layer shows more resistance against the failure as compared to part of same thickness made with thinner layer. Tensile and flexural strength of the material is decreasing with respect to increasing layer thickness, this is due to the stepped effect, in this layer deposited over another layer is due the sample orientation there may be some portion is vacant this lead to the weak strength of material [15].

IV. CONCLUSIONS

ABS + hydrous magnesium silicate composite material was successfully fabricated by using desktop 3D printer, based on the various build parameters. From the present research work, the following conclusions were drawn:

1. A maximum tensile and flexural strength values are reported for samples which has low layer thickness of 0.2 mm and printing speed of 30 mm/s.
2. The other samples with maximum printing speed of different layer thickness of 0.25 and 0.3 mm has exhibited a marginal reduction in strength values.
3. A low printing speed with low layer thickness gives a better bonding with the previous layer due to that it exhibited a better tensile and flexural strength.

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