The Impact of Slicing Softwares on the Mechanical Properties of 3D Printed Parts

Solomon B Selvaraj, Narasimhan K, Daniel Abishai L, Krishna Kaanth M, Ashish Daniel

Abstract: "Slicing tool" or "Slicing Software" computes the intersection curves of models and slicing planes. They improve the quality of the model being printed when given in the form of STL file. Upon analyzing a specimen that has been printed using two different slicing tools, there was a drastic variation on account of the mechanical properties of the specimen. The ultimate tensile strength and the surface roughness of the material vary from one tool to another. This paper reports an investigation and analysis of the variation in the ultimate tensile strength and the surface roughness of the specimen, given that the 3D printer and the model being printed is the same, with a variation of usage of slicing software. This analysis includes ReplicatorG, Flashprint as the two different slicing tools that are used for slicing of the model. The variation in the ultimate tensile strength and the surface roughness are measured and represented statistically through graphs. An appropriate decisive conclusion was drawn on the basis of the observations and analysis of the experiment on relevance to the behavior and mechanical properties of the specimen.

***Keywords*: FFF, Slicing software, STL file, UTS, Surface roughness, Wanhao Duplicator 4S-printer**

I. INTRODUCTION

3D printing or three-dimensional printing is a generally used term for Additive Manufacturing (AM), in different fields of engineering and industry to produce prototype models. ISO/ASTM52900-15 defines that AM process has seven different categories: Binder Jetting, Directed Energy Deposition, Material Extrusion, Material Jetting, Powder Bed Fusion, Sheet Lamination and Vat Photo Polymerization [1]. Physical objects can be rapidly constructed layer-by-layer upon addition of a certain material directly from digital data in a computer-aided design (CAD) system [2-3].

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***** Correspondence Author
Solomon B Selvaraj*, School of Mechanical Engineering, Vellore Institute of Technology, Vellore, Tamil Nadu, India, ssolomanbobby@vit.ac.in
Narasimhan K, School of Mechanical Engineering, Vellore Institute of Technology, Vellore, Tamil Nadu, India.
Daniel Abishai L, School of Mechanical Engineering, Vellore Institute of Technology, Vellore, Tamil Nadu, India.
Krishna Kaanth M, School of Mechanical **Engineering**, Vellore Institute of Technology, Vellore, Tamil Nadu, India.
Ashish Daniel, Director, GEMS Polytechnic College, Aurangabad, Bihar, India

The conventional manufacturing and machining of the products can hold various limitations where considerable amount of raw material is wasted and the machining tool (cutting/grinding tool) must be replaced after few numbers of cycles due to heavy abrasion. 3D printing here can help to avoid such mishaps [4-5]. A properly developed and better visualization can be easily observed through rapid prototyping from a designed digital data and the uncertainties during a massive scale production can be altered significantly. Thus, 3D printing reduces the time required to process and develop a prototype model during the stage of designing and can help significantly for the quicker evaluation of the model [6]. 3D printing has undergone various developments and its application has extended boundaries. The rapid prototyping technologies have application ranging from medical aspects in cardiovascular diseases, art and handicraft, to industrial engineering applications [7-11]. 3D printing and rapid prototyping can possibly be the future of manufacturing products with limited uncertainties and obstacles. The materials that are used in printing (FDM) like ABS and PLA has been well researched and its mechanical properties have been completely analyzed and complement 3D printing manufacturing in multiple ways [12]. The PLA material is biodegradable, aliphatic polyester has similar mechanical characteristics of polyethylene terephthalate and has a lower maximum continuous use temperature. The PLA material can be recycled and reused by melting and processing the material by hydrolyzing to lactic acid. Thus, 3D printing (FDM) is an eco-friendly option for manufacturing [13]. Several studies also show that conventionally that the tensile strength of the material being printed depends on the mass of the specimen and its respective density [14]. However certain 3D printing methods have few drawbacks that have to be overcome with the advancements in chemical technologies. The most common is the SLM 3D metal printing that has a limitation of not producing multiple layers of multiple materials [15]. The American Society for Testing and Materials (ASTM) has defined Additive Manufacturing as "a process of joining materials layer-by-layer to make objects from 3D model digital data, as opposed to subtractive manufacturing methodologies" [16]. However, 3D printing or Rapid prototyping has a fundamental step that is basically included in the designing and development stage of the model that is crucial for the printing quality of the material and also to obtain the product without undergoing any defects. This fundamental step that is required for 3D printing is called "Slicing". Slicing requires computing the intersection curves of models and slicing planes. This operation is time-consuming, and is a key factor that affects printing quality.

Most slicing algorithms work on standard tessellation language (STL) models [17-18], as STL is a standard file format for 3D printing. “Tessellation” is an approximation of the surfaces of the object in which an STL file is converted into many small planar triangular facets [19].
However, the data in the STL file format is a discretized form of the 3D models, which contain discretization errors. Thus, many studies consider a slicing algorithm on the original data of the 3D models. Valid slicing software will produce different parameters related to the printing speed, description of coordinates, nozzle and bed temperature, accuracy of the product, and other accuracy variables based on the appropriate geometry of a given STL file [20]. The quality of the printed product differs according to the 3D printer and the slicing tool that has been used [21]. Slicing process can be classified into various sub-tasks that include:

1. Uniform Slicing (constant layer thickness)
2. Adaptive Slicing (variable layer thickness)
3. Mesh slicing (plane-triangle intersection computation).
4. Determination of polygon pattern (clockwise/anti-clockwise).

Slicing tool also converts the model into a series of thin layers and produces a G-code file that consists of information and data that has to be given as an input to the 3D printer. The 3D printing client software then loads the G-code files and uses them to navigate and instruct the 3D printer during the 3D printing process [1]. However, higher standards and quality of the 3D printed material can be achieved through the optimization of certain parameters that includes the wall permeability of a printed object that depends on the geometry of the material that has to be printed. The wall permeability of the printed material gradually decreases tracing the following order: cylinder > cube > pyramid > sphere > cone. Filament feed rate, wall geometry, wall permeability and G-code defined wall structure are the primary parameters for a quality printed product. An appropriate optimization of the above mentioned parameters can lead to a product with a better quality and improved sealing qualities [22].

II. EXPERIMENT

Table- I: Factor and Parametric Value

Factor	Abbreviation	Parameters	-1	0	1
F1	LH	Layer Height	0.1	0.2	0.3
F2	FD	Fill Density	20	50	80
F3	PS	Print Speed	20	40	60

The experiment is classified on three different factors F1, F2 and F3. The abbreviations LH, FD and PS are used for easier representation of the parameters involved in the experimentation. F1, F2 and F3 factors have been designated with appropriate value of representation with regard to each factor in the parameters as shown in Table-I.

Table- II: Box-Behnken design of experiment

Run	Layer Height (F1) (mm)	Infill Density (F2) (%)	Print Speed (F3) (mm/sec)
1	0.1	20	40
2	0.3	20	40
3	0.1	80	40
4	0.3	80	40
5	0.1	50	20
6	0.3	50	20
7	0.1	50	60
8	0.3	50	60
9	0.2	20	20
10	0.2	80	20
11	0.2	20	60
12	0.2	80	60
13	0.2	50	40
14	0.2	50	40
15	0.2	50	40

Table-II provide the details about the parametric value given to the specific slicing software/slicing tool as per the Box-Behnken design of experiment.
The specimens used for the experimentation were printed by same generic brand of PLA with WANHAO Duplicator 4S Desktop 3D printer as shown in Figure 1. Each Specimen used in the experimentation was classified according to the slicing software/slicing tool used. ReplicatorG and Flashprint are the two different slicing tool used in the experiment for the analysis and the specimens were printed individually having the same parameters. The experiment was based on the analysis of mechanical properties of the specimen that includes the ultimate tensile strength and its surface roughness. The variations of parameters for the experimentation were the printing speed, layer height and the infill ratio of the specimen that was printed using the specific slicing tool.

Fig. 1. WANHAO Duplicator 4S Desktop 3D printer

A. ULTIMATE TENSILE STRENGTH

The ultimate tensile strength of the specimens was observed on the Servo Dynamic Hydraulic Universal Testing Machine as per ASTM standards as shown in Figure 2. The experiment was done for each slicing tool used for printing the specimen with the variation of the layer height, infill ratio and printing speed until its fracture point. Three separate specimens of 0.1 mm, 0.2 mm and 0.3 mm respectively, that were printed with the help of ‘ReplicatorG’ were tested for their ultimate tensile strength with increasing infill density of a constant printing speed. The specimens were held on two load cells and the optimal load was applied on the strain gauge load cell as shown in Figure 3.

The tests were conducted in batches, and the outcome was observed by three separate statistical data. The statistical trend was obtained from the data acquisition monitor on the basis of the experiment for each batch of analysis of the specimen of the particular slicing software/slicing tool.

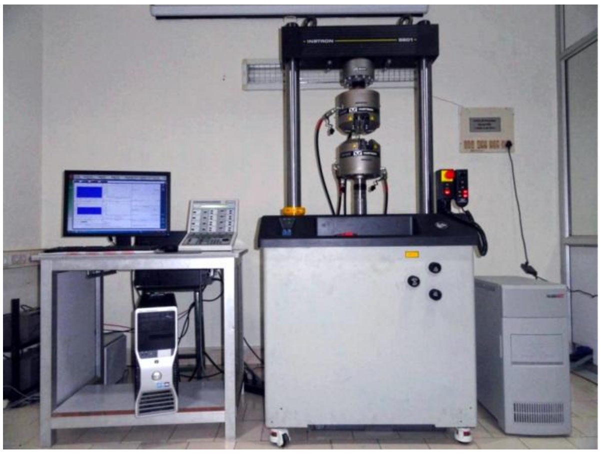

Fig. 2. Servo Dynamic Hydraulic Universal Testing Machine

Similar experimentation were conducted for the specimens that were printed using 'Flashprint' to obtain its Ultimate Tensile Strength having the same parameter of investigation until the specimen reached its fracture point. A total of six statistical trends were obtained from the UTS test of the specimen of both the slicing software/slicing tool.

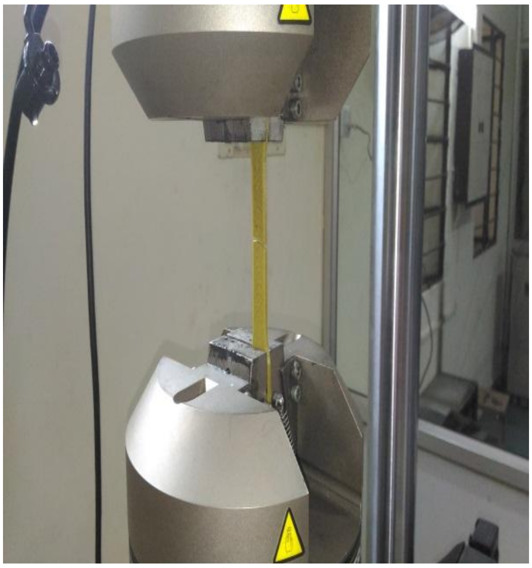

Fig. 3. UTS test on Servo Dynamic Hydraulic Universal Testing Machine

B. SURFACE ROUGHNESS

The surface roughness of the specimens were observed using the MITUTOYO Portable Surface Roughness Measurement as per ASTM standards as shown in Figure 4. The Ra values were obtained from the probe of the instrument for the given specimen. The surface roughnesses of the specimens were also taken in batches, including the variations of infill density, layer height and with constant printing speed.

Fig 4. MITUTOYO Portable Surface Roughness Measurement

Each batch involved three specimens of layer heights 0.1 mm, 0.2 mm and 0.3 mm, with increasing infill density and constant printing speed for the specimens that were printed using 'Replicator G'. Similarly, the surface roughness of the specimens printed using 'Flashprint' were also analyzed using the same parameters. The statistical data was obtained from each batch measuring the surface roughness of the specimens.

III. RESULT AND DISCUSSION

The Ultimate Tensile Strength and Surface Roughness of the specimens were measured with three constant printing speeds of 20 mm/sec, 40 mm/sec, and 60 mm/sec as mentioned before.

Table- III: Ultimate Tensile Strength, MPa

Run	ReplicatorG		Flashprint	
	Experiment value	Model value	Experiment value	Model value
1	13.3	13.00	12.7	11.04
2	20.7	19.89	18.3	18.04
3	25.8	24.57	22.0	22.41
4	29.6	27.86	23.0	24.80
5	22.9	20.44	16.7	17.18
6	27.3	25.43	22.3	21.33
7	18.2	19.14	15.6	15.61
8	22.9	24.33	22.3	21.85
9	19.2	21.24	16.9	18.13
10	33.4	30.76	29.7	29.23
11	18.9	19.80	19.6	20.14
12	33.7	29.80	28.2	27.17
13	21.4	20.80	22.2	22.24
14	21.4	20.80	22.2	22.24
15	21.4	20.80	22.2	22.24

Table- IV: Surface Roughness, Ra

Run	ReplicatorG		Flashprint	
	Experiment value	Model value	Experiment value	Model value
1	3.052	2.61	1.874	1.70
2	2.811	1.47	16.127	12.59
3	0.983	2.36	1.894	5.43
4	2.945	3.43	2.918	3.09
5	2.055	1.97	2.72	1.38
6	1.858	2.67	2.081	4.11
7	2.671	1.90	1.602	-0.42
8	1.018	1.14	4.08	5.42
9	1.357	1.91	1.973	3.48
10	5.419	4.19	3.354	1.14
11	1.268	2.54	1.572	3.78
12	2.47	1.97	1.862	0.36
13	1.237	1.25	5.844	5.85
14	1.237	1.25	5.844	5.85
15	1.237	1.25	5.844	5.85

Table III and Table IV represents the experiment value and model values of the Ultimate tensile strength and the Surface Roughness of the specimens printed using 'ReplicatorG' and 'Flashprint'.

ANOVA was performed to find the influencing parameters at 95% confidence level, second order quadratic equation was farmed and values were substituted to obtain model values. Calculated the model values using regression equation and drawn the graph to see the trend by varying one parameter and keeping other parameters as fixed.

A. Comparison of Ultimate Tensile Strength, batch 1

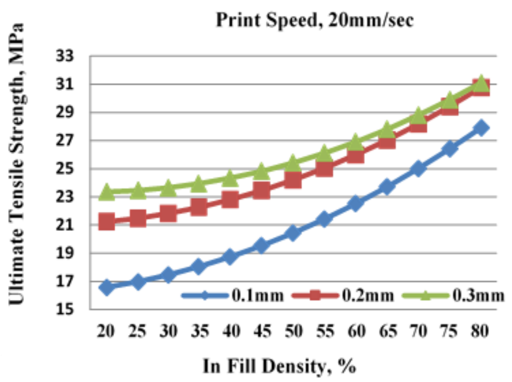

Fig. 5. ReplicatorG, Print Speed 20mm/sec (UTS)

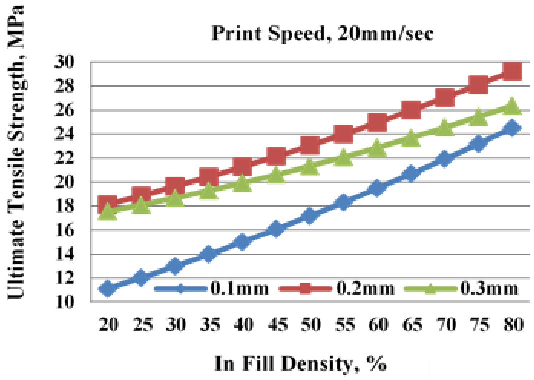

Fig. 6. Flashprint, Print Speed 20mm/sec (UTS)

Figure 5 and Figure 6 represent the specimens printed in batch 1 process with constant printing speed of 20mm/sec. Figure 5 is the UTS MPa vs Infill Density % statistics for the specimens that were printed using ReplicatorG whereas Figure 6 represent the specimens printed using Flashprint. Here, as per the observation, we find a defined trend in Figure 5, where the ultimate tensile strength increases with increase in the percentage of infill density of the specimen. We can observe that the specimen with 0.1 mm layer height has lower UTS point at lower infill density when compared to the specimen with layer heights 0.2 mm and 0.3 mm. The same pattern can be observed at the end point and the ultimate tensile strength point of the specimen of layer heights 0.2 mm and 0.3 mm were almost similar when the infill density was maximum. However, the same cannot be said for the specimen printed using 'Flashprint' (as observed in Figure 6) as the ultimate tensile strength of the specimens happen to vary drastically when compared to that of the specimens printed with ReplicatorG. In Figure 6, we were able to observe an abnormal trend that contradicts with the graphical aspects of Figure 5. According to the data from Figure 6, we were able to conclude that the ultimate tensile strength point for the specimen with layer height 0.2 mm was higher than that of the specimen with layer height 0.3 mm. The trend can be seen being maintained throughout the graph, and no deviation can be observed from it as seen in the previous case. However, the basic criteria were maintained as the ultimate tensile strength was observed to be increasing with increasing infill density.

B. Comparison of Ultimate Tensile Strength, batch 2

Similar process of experimentation was conducted to obtain the batch 2 samples of 3D printed specimen at a constant printing speed of 40mm/sec. The statistical data representing UTS MPa vs Infill Density % were taken from the specimens that were printed using 'ReplicatorG' and 'Flashprint' respectively as observed from Figure 7 and 8. As observed in Figure 5 of batch 1 samples, we were able to identify that a similar trend was carried on with the specimens that were printed using 'ReplicatorG' even when the print speed was changed to 40mm/sec (Figure 7). We were able to find that the specimens printed using 'ReplicatorG' happened to have a wider consistency with the graphical trend that was previously observed. However, there was a minor change in the Ultimate Tensile Strength observed in the specimen as per

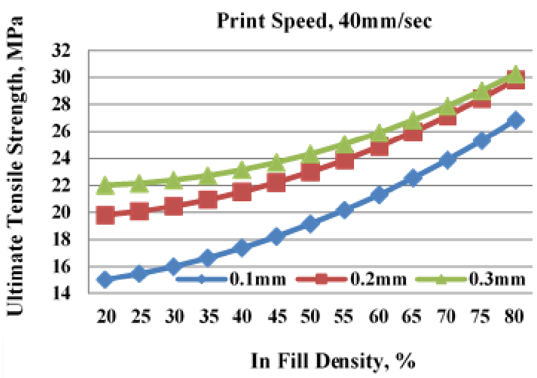

Fig. 7. ReplicatorG, Print Speed 40mm/sec (UTS)

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the trend observed in Figure 7. Similarly, from Figure 8 the graphical trend was maintained as observed from the previous experimentation. The second batch of experiments also began to contradict each other and the results were similar to the ones that were obtained from the batch 1 experiment. The analyses of the two batches were consistent with respect to their slicing software.

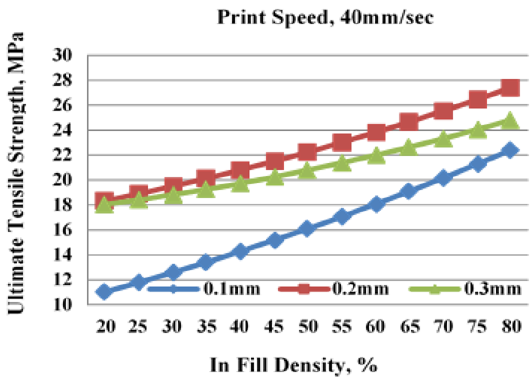

Fig. 8. Flashprint, Print Speed 40mm/sec (UTS)

The second batch of experiments also began to contradict each other and the results were similar to the ones that were obtained from the batch 1 experiment. The analyses of the two batches were consistent with respect to their slicing software.

C. Comparison of Ultimate Tensile Strength, batch 3

We continued the process of analysis to the third stage, where we experimented on specimens that were printed with the constant printing speed of 60mm/sec. As per the experiments that were previously conducted, similar statistical data were obtained to understand the graphical trend of the 3D printed specimen for both the slicing softwares (ReplicatorG and Flashprint).

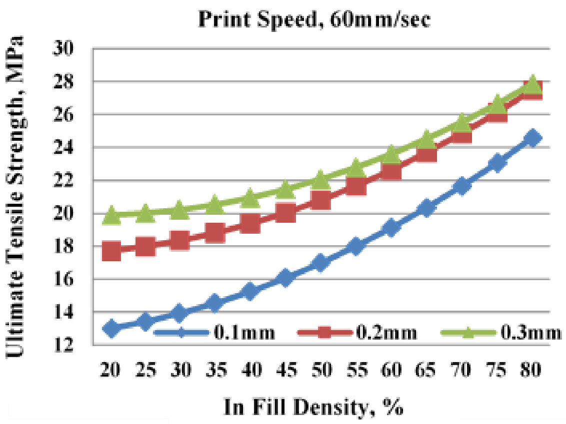

Fig. 9. ReplicatorG, Print Speed 60mm/sec (UTS)

As per the observation of the statistical data from Figure 5, 7 and 9 we were able to say that the graphical trend from the previous two experiments has been maintained with huge similarity and minor differences in values. These specimens that were printed using 'Ultimaker Cura' were able to maintain the consistency of pattern even when printing speed changes from 20mm/sec to 60mm/sec.

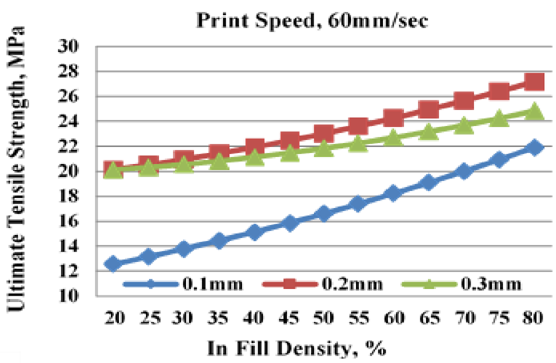

Fig. 10. Flashprint, Print Speed 60mm/sec (UTS)

The regular trend was observed as the specimen with the least layer height showed the least Ultimate Tensile Strength for the least infill density, and it increases with increase in infill density. The same trend was found on specimen with 0.2 and 0.3 mm layer height, and the point of intersection (almost equal Ultimate Tensile Strength) was seen at the higher end of the graph when infill density was high. Vice versa, the trend can also be observed in Figure 6, 8 and 10 of the specimens that were printed using 'Flashprint'. However, it was different from what was observed from the specimens that were printed using 'ReplicatorG'. Specimens printed using the 'Flashprint' slicing tool had a different pattern of UTS MPa vs Infill Density %. The ultimate tensile strength of the specimens with layer height 0.2 mm was observed to be almost equal or higher to that of the specimens having layer height of 0.3 mm and as the infill density increases, we were able to identify that the specimen with 0.3 mm had lower ultimate tensile strength when compared to the specimen having 0.2 mm as the layer height.

D. Comparison of Surface Roughness, batch 1

The specimens were also observed for the analysis of their surface roughness for their respective slicing software. The surface roughnesses of the specimen were observed in terms of Ra values under the probe and the statistical data of Surface Roughness VS Infill Density was obtained for all the six different experimentations.

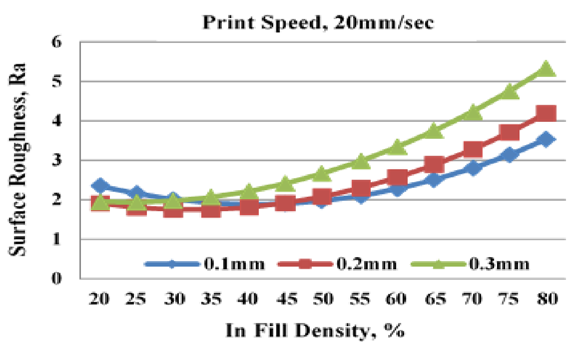

Fig. 11. ReplicatorG, Print Speed 20mm/sec (SR)

The first batches of experiments were conducted to obtain the surface roughnesses of the specimens with a constant printing speed of 20 mm/sec for their respective slicing softwares. From Figure 11 we could see that the specimens of layer height 0.2 and 0.3 mm had almost the similar surface roughness, however the specimen with layer height 0.1 mm had a higher surface roughness than the other two.

As the curve progresses as we increased the infill density of the specimen that has been tested, we found the trend reversing as observed from the specimen having lesser infill density. At the highest point of infill density, it was found that 0.3mm layer height had the highest surface roughness, followed by specimen with layer height 0.2 mm and 0.1 mm.

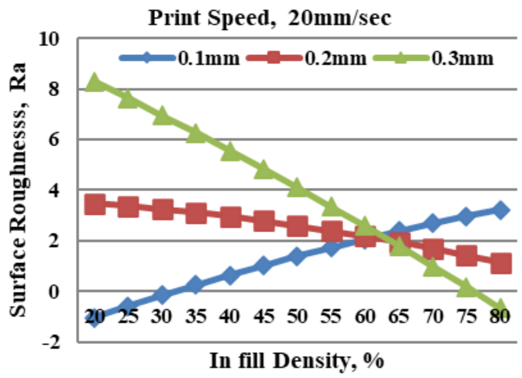

Fig. 12. Flashprint, Print Speed 20mm/sec (SR)

However, for specimens that were printed using 'Flashprint' showed a varying trend that was very inconsistent and different. As shown in Figure 12, the surface roughnesses of the specimens at a lower infill density match with that of the aspects of its counterpart, but had a greater difference in the values. As the specimens printed using 'ReplicatorG' had almost equal surface roughnesses for lower infill density as shown, the specimens printed using 'Flashprint' were observed to have different surface roughnesses for different layer heights of the specimen. Interestingly, at the certain range of infill density from 60-65 %, the curves traced by the three different specimens of different layer heights begin to intersect, showing that the surface roughnesses to be approximately equal. The divergence in the trend was observed to be constant and as the infill density increases in percentage, the variation was seen reversing itself.

E. Comparison of Surface Roughness, batch 2

As the print speed increased from 20mm/sec to 40mm/sec, the specimens showed a considerable variation at a lower infill density.

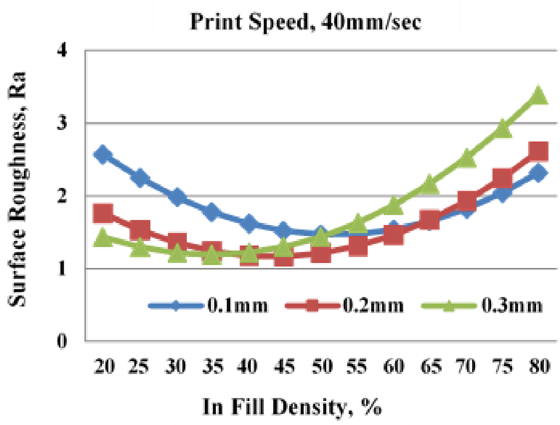

Fig. 13. ReplicatorG, Print Speed 40mm/sec (SR)

This variation was observed as; specimen having 0.3mm layer height had the least surface roughness, followed by specimen with 0.2 mm layer height infill density (Figure 13). This variation was observed as; specimen having 0.3mm layer height had the least surface roughness, followed by specimen with 0.2 mm layer height and specimen with 0.3 mm layer height. The specimens were also observed to seen matching surface roughnesses at different intervals of infill density. The trend was noticed to end as per the analysis of experiments that were conducted in batch 1 (Figure 11). The observation also noticed the shift in the increasing pattern of the curve as the infill density of the specimen was increased to a certain range.

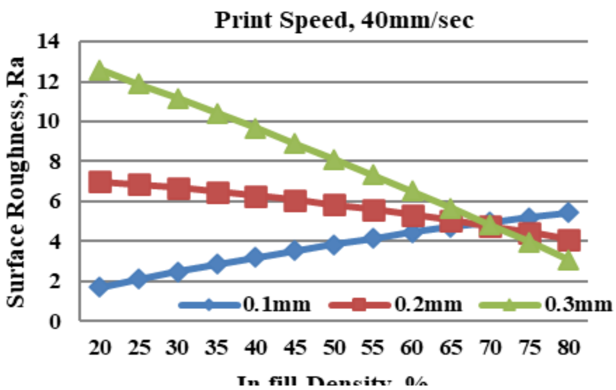

Fig. 14. Flashprint, Print Speed 40mm/sec (SR)

Similarly, there was a change in the surface roughnesses of the specimens of all the layer heights and a minor shift in the divergence of the curves after the point of intersection was also observed (Figure 14).

F. Comparison of Surface Roughness, batch 3

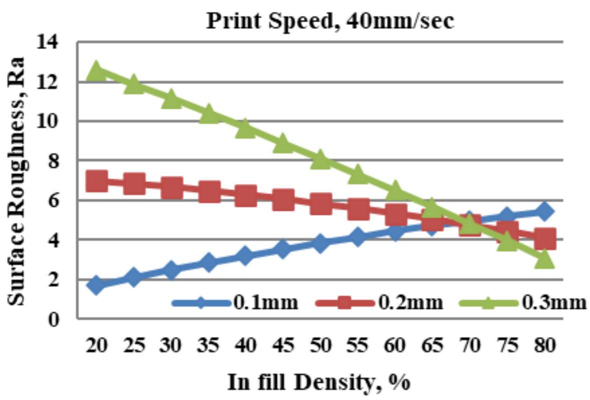

Fig. 15. ReplicatorG, Print Speed 60mm/sec (SR)

From Figure 15, we observed the shift to be even larger when compared to specimen of batch 2 (Figure 13). The shift of trend was noticed to not occur together and the end points of the curves had a distinct value. The increase in infill density also showed us results where the specimens with 0.1mm layer height begin to surpass the curves traced by the specimen with 0.2 mm layer height. This trend was primarily observed only in the third batch of specimens when the print speed is increased to 60 mm/sec.

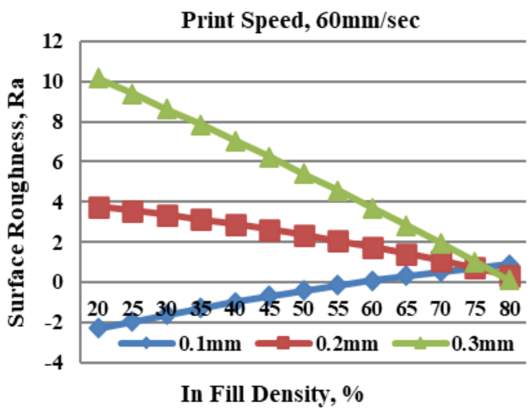

Fig. 16. Flashprint, Print Speed 60mm/sec (SR)

Whereas, specimens printed using 'Flashprint' had returned back to the original state as referred in first batch of the experiment (From Figure 12). The curve of the specimen of 0.1 mm layer height was noticed to reach the negative axes the second time after the analysis of the first batch of samples. However, this trend was not observed in the second batch of samples, where the specimens were printed at the speed of 40 mm/sec.

IV. CONCLUSION

1. The ultimate tensile strength of the specimens increases with the increase in infill density.
2. The specimens of layer height of 0.3 mm printed using 'ReplicatorG' showed the highest Ultimate tensile strength followed by specimens of layer height 0.2 mm and 0.1 mm.
3. The specimens of layer height of 0.2 mm printed using 'Flashprint' showed the highest Ultimate tensile strength followed by specimens of layer height 0.3 mm and 0.1 mm.
4. A defined trend for the surface roughness of the specimen cannot be concluded from the experiment as both the samples of specimen contradict with their results.
5. A shift in the increasing pattern of curves of the different layer heights can be observed for both the samples of the experiment.
6. The specimens of layer height of 0.1 mm printed using 'ReplicatorG' showed the highest Surface Roughness followed by specimens of layer height 0.2 mm and 0.3 mm for a lower critical infill density and the specimens of layer height of 0.3 mm showed the highest Surface Roughness followed by specimens of layer height 0.2 mm and 0.1 mm for a higher infill density in the same experiment.
7. The specimens of layer height of 0.3 mm printed using 'Flashprint' showed the highest Surface Roughness followed by specimens of layer height 0.2 mm and 0.1 mm for a lower critical infill density and the specimens of layer height of 0.1 mm showed the highest Surface Roughness followed by specimens of layer height 0.2 mm and 0.3 mm for a higher infill density in the same experiment.
8. The above observations and analysis from the experiment can finally conclude that specimens printed using 'ReplicatorG' were more consistent and showed precise graphical pattern when compared to the specimens printed using 'Flashprint'.

V. ACKNOWLEDGMENT

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AUTHORS PROFILE

Dr. S. Solomon Bobby Selvaraj received a PhD from Auckland University of Technology, Auckland, New Zealand**.** Working as Associate Professor at Department of Manufacturing Engineering, School of Mechanical Engineering, VIT Vellore, Tamil Nadu, India. He has developed a 3D printing lab which is largest among the academic institutions in India at VIT. Research activities are varying from Industrial application to medical application. Life member in Additive Manufacturing Society of India.(AMSI) Received a national award for the successful implementation of the largest 3D printing lab and contribution to Additive Manufacturing from AMSI.

Narasimhan K, System Administrator, School of Mechanical Engineering, VIT Vellore, Vellore, Tamil Nadu, India. Very good in design and modeling the parts using design soft wares. Having hands on experience in handling machines especially 3D printers. Conducting experiment systematically is the major strength of him.

Daniel Abishai. L pursuing B.Tech , 2nd year, Mechanical Engineering. Presently the Tech and Projects head of SPE-VIT, a student chapter (Society of Petroleum Engineers) that focuses on inspiring young engineers to develop technical skills on the platform of research, event organizing, and engineering on different fields. Interested in Achieving new dimensions in every field that has been entrusted with. Enthusiastic in learning new things and never hesitates in taking up new tasks and achieve different levels by totally indulging in it. Brings forth appropriate conclusion on the basis of commendable analysis and research.

Krishna Kaanth M, doing 2nd year B.Tech Mechanical Engineering at Vellore Institute of Technology, Vellore. Always reading books to getting updated with new technology and to learn about new businesses. Planning to have a startup based on a very new idea or a technology to become an aspiring entrepreneur with the love for technology and want to be an inspiration for the world. His strengths are to get work done to every finest finish and on time. Maintaining the ethics of "never neglect an opportunity for any improvement".

Ashish Daniel received bachelor and master degrees in Bio-Informatics from Karunya Institute of Technology, Coimbatore, Tamil Nadu, India. Working as Director**,** GEMS Polytechnic College, Aurangabad, Bihar, India, He is young and energetic having passion for research and development in the additive manufacturing technology. Under his leadership and vision, he has established a largest 3D printing lab at his polytechnic college which is not only first at Bihar state also in India. He is a very good motivator and understanding the problems at the ground level which helps the students to achieve their goals and go out from polytechnic college with flying colors.