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Enhancing Strength of 3D Printed Objects through Composite Mesh Reinforcement

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***Abstract*— Three-dimensional (3D) printing has revolutionized manufacturing by enabling the production of complex geometries with ease. However, one of the primary challenges associated with conventional 3D printing techniques is achieving optimal mechanical strength and durability in printed objects. In this study, a novel approach to enhance the strength of 3D printed objects by incorporating a composite mesh material between layers during the printing process is tested. We have considered 2 types of mesh material for compositing, fibreglass mesh and fine steel wire mesh. Multiple variations of the number of mesh layers and the infill percentage were also tested. The discussion has also been extended into possible issues which arise due to the introduction of a composite material. To evaluate the efficacy of this approach, a series of experiments were conducted using Universal Testing Machine (UTM) to subject the printed objects to a tensile test. Preliminary results show that including the composite mesh improves the mechanical performance of 3D-printed products significantly in certain cases. When compared to control group objects, the tensile strength increased by up to 26% when using fibreglass mesh and the strength increased by 40% when using Steel mesh. It was also observed that the infill pattern had a considerable effect on the strength enhancement. Using a 3D fill pill pattern gave the highest tensile strength followed by triangular and hexagonal patter. In conclusion, this research presents a pioneering approach to improve the strength and performance of 3D printed objects through the integration of composite mesh reinforcement.**

Keywords*— *3D printing, Composite, Strength, Tensile, Universal Testing Machine

I. INTRODUCTION

3D printing, also known as additive manufacturing, is a groundbreaking technique that allows three-dimensional things to be created from digital models. Unlike traditional manufacturing processes, which entail withdrawing material from a solid block or using moulding and casting techniques, 3D printing constructs items layer by layer, straight from a computer-aided design (CAD) file. The digital model is then split into small layers by slicer software, which provides the 3D printer instructions. The 3D printing method involves the layering of material to progressively produce the desired product. There are several 3D printing technologies, each with its own set of principles and materials. FDM (Fused Deposition Modelling), SLA (Stereolithography), SLS (Selective Laser Sintering), and DLP (Digital Light Processing) are some of the most regularly used 3D printing technologies. 3D printing has uses in a variety of industries, including manufacturing, aerospace, healthcare, automotive, fashion, and education. Its benefits stem from its capacity to build complicated and customised designs quickly, eliminate material waste, and enable on-demand production. 3D printing has revolutionised product prototypes, small-scale production, medical implants, architectural models, and even creative works. While 3D printing has transformed industrial processes, it is not without its limitations. Poor surface polish, dimensional errors, warping, weak interlayer bonding, support structures, and quality control are all typical issues with 3D-printed products. Efforts are always being made to overcome these difficulties through breakthroughs in printing technologies, material development, software upgrades, and post-processing approaches. As the area of 3D printing evolves, these challenges are being addressed, making it a more dependable and diverse production process.

The strength of 3D printed materials has been the subject of much research and development. While 3D-printed items can be quite strong in some directions, their total strength might vary depending on the printing process, material qualities, and design concerns. The anisotropic nature of the printing process is one of the primary elements impacting the strength of 3D-printed items. The variation in material characteristics and strength in different directions is referred to as anisotropy. 3D printed items suffer from low strength along the vertical (Z-axis) direction due to stress concentration created by printing individual layers due to the layer-by-layer construction process. However, the horizontal (X and Y-axis) orientations may have a higher strength. To achieve optimal performance and structural integrity in real-world applications, this directional strength variation must be addressed when designing and engineering 3D-printed components.

One of the existing solutions to increasing the strength of the prints is to use filaments with infused carbon fibre filament. One of the major issues with this approach is the cost involved. When 3D printing with carbon fiber filament, achieving proper alignment of the tiny carbon fibres within the printed part can be a complex and challenging endeavour. The orientation and arrangement of these fibres play a crucial role in determining the material's overall strength, stiffness, and other mechanical properties. However, several factors contribute to the difficulty in ensuring optimal fibre alignment during the printing process. The inherent nature of the 3D printing process itself can disrupt the desired alignment of carbon fibers. As the filament is extruded and deposited layer by layer, the fibres may be forced into different orientations, leading to a lack of consistency in alignment throughout the part. This can result in variations in mechanical properties across different sections of the printed object.

This paper presents a more affordable yet efficient method of increasing the strength of 3D-printed parts. The use of mesh materials is highlighted along with the necessary techniques required to edit the Gcodes generated by the traditional slicer software.

II. LITERATURE REVIEW

Composite 3D printing has emerged as a promising technology for creating high-strength materials with intricate geometries. This research paper aims to comprehensively review existing literature on the application of composite 3D printing in strength analysis and propose novel methods for its utilisation. Several studies have investigated the mechanical properties of composite materials produced using 3D printing technology. F Ghebretinsae et al.[1] did the fabrication of composite samples using carbon fiber filament and a thermoset plastic matrix. The mean ultimate tensile strength and tensile modulus were reported to be 560 MPa and 25 GPa, respectively. Using three-point bending tests, the ultimate flexural strength and flexural modulus were estimated to be 271 MPa and 16 GPa, respectively. These tests were conducted and analysed through stress analysis modelling of the layered composite with finite element models. Marco Pizzorni et al.[2] examined the impact of different joint-design factors on the adhesive bonding of mixed short- and continuous-carbon-fiber reinforced Nylon-6 parts, which were 3D printed using Fused Filament Fabrication technology. They explored the influence of adhesive-bonding parameters such as adherend overlap length, geometry, adhesive type, and substrate configuration on the mechanical behaviour of single-lap joints and the modality of crack propagation across the bonded laminates. The experimental findings revealed that higher load levels could be achieved by increasing the joint stiffness by using longer overlap lengths. The joining of continuous-fiber-only adherents was considered a high-performing approach. L.G. Blok et al.[3] talked about the use of composite 3D printing feedstocks in Fused Filament Fabrication (FFF) to increase the mechanical properties of parts by embedding carbon fibres into a thermoplastic matrix. The study covered the key processing parameters for FFF and the state-of-the-art in composite 3D printing, distinguishing between short fiber and continuous fiber feedstocks. The hypothesis was that increasing the fiber length in short fiber filament could lead to increased mechanical properties, potentially approaching those of continuous fiber composites while keeping the high degree of design freedom of the FFF process. Zhijian Li et al.[4] investigated the use of continuous and simultaneous micro-cable reinforcement methods for 3D-printed concrete structures to meet mechanical-property requirements. The specimens were subjected to compressive, shear, and tensile loadings, revealing that micro-cables provide additional strength, ductility, and toughness under compressive loading. The confinement effect of micro-cables and print paths should be considered. Shear strength depends on weak planes' directions between two filaments, while a tensile response is governed by micro-cable reinforcements and configurations depending on print paths. Nanya Li et al.[5] The rapid prototyping approach of three-dimensional (3D) printing was used to manufacture a continuous carbon fiber-reinforced polylactic acid composite. The study analysed the improvement of this new method by comparing printed samples with or without preprocessed carbon fiber bundles. In the experimental findings of the study, it was observed that the modified carbon fiber reinforced composites exhibited a 13.8% increase in tensile strength and a significant 164% increase in flexural strength when compared to the original carbon fiber reinforced samples. Qing Chen et al.[6] investigated the effect of CNT reinforcement on the mechanical properties of 3D-printed PEI composites using the FDM method. The researchers fabricated CNT/PEI composite filaments using the molten co-extrusion technique and then printed composite samples using FDM. They found that the incorporation of CNTs significantly improved the bond strength and reduced the porosity of 3D-printed CNT/PEI composites, resulting in improved mechanical properties. The addition of CNTs, combined with annealing, further enhanced the mechanical performance and reduced the warping of 3D-printed PEI samples.

T Isobe et al.[7] explored using different types of carbon fiber reinforced composite materials, including short fiber and continuous fiber, to enhance the strength of 3D printed objects. The researchers prepared nanocomposites made from polylactic acid as the matrix and multi-wall carbon nanotube as the filler, short carbon fiber reinforced composite, and continuous carbon fiber reinforced composite. They found that the continuous fiber reinforced material exhibited the highest tensile strength and elastic modulus, which were about 7 times and 5 times, respectively, compared to the other two materials. The use of continuous fiber greatly improved the strength of the printed objects. However, the researchers observed poor adhesion between the laminated layers and the relationship between the fiber and the matrix. This suggests that improving these factors is necessary to increase strength further. The study also found that short fiber could be used to improve strength to some degree while maintaining ease of printing. Pedram Parandoush et al.[8] reported a novel approach for 3D printing of continuous carbon fiber reinforced thermoplastic composites (CFRTPs) using prepreg composite sheets. The researchers used a CO2 laser beam and a consolidation roller system to successively cut and bond the prepreg sheets layer upon layer based on the sliced CAD geometry. The technique allowed for controlling the alignment of carbon fiber in printed layers, resulting in CFRTPs with unidirectional, cross-ply, and [0/-45/0/45°]s fiber reinforcement. The CFRTPs produced using this technique had the highest reported tensile strength (668.3 MPa) and flexural strength (591.16 MPa) to date for all 3D printed CFRTPs. The interfacial bonding strength and volume ratio of continuous carbon fiber were also excellent, making this technique broadly beneficial for industries requiring high-performance and lightweight structural materials with complex geometries. Overall, the studies reviewed in this paper demonstrate the potential of composite 3D printing for creating high-strength materials with unique geometries.

III. PROPOSED METHODODLOGY

In general, 3D printers can only print using a single material as the PLA filament is fed using a heated nozzle causing the material to melt and then fuse to the existing print. There are variations of 3D printers which can have multiple nozzles to print with multiple materials. More modern variations use A single nozzle but automatic filament replacement technology to use multiple filaments from a stack of 3D printer filaments. There are certain types of filament like carbon fiber filament which is the closest thing which exists to composite 3D printing. Carbon fibre filament offers a unique mix of strength, stiffness, and lightweight properties, making it particularly well-suited for applications requiring high-performance components. Carbon fibre reinforcing improves the mechanical characteristics of the material, enabling the construction of durable and robust products with high dimensional stability. However, issues like nozzle wear, print settings optimisation, and probable layer delamination might occur, necessitating cautious handling and skill during the printing process. The focus of this research is on using different mesh materials for reinforcing the print. This involves editing the Gcode to accommodate the thickness of the mesh material. Mesh material is the obvious choice for reinforcement as we need adjacent printed layers to adhere to each other through the gaps in the mesh.

Two mesh-type materials were used as the composition material for the 3D prints. When 3D printing there are a lot of variations and settings which can be tweaked to get widely varying results of the end product. Each setting in the slicer software can have an adverse effect on the final product. It is vital to select only a few important parameters to study. In this paper, we focus majorly on the infill pattern and the infill density as these are the parameters affecting the overall density of the print material and will directly affect the strength of the printed object. Figure 1 shows the 3 variations of the infill pattern hexagonal, triangular and 3D used for the testing. Each variation of the infill pattern was printed in 3 different infill densities, 15,30 and 45 per cent. Images are generated from the slicer used for 3D printing.

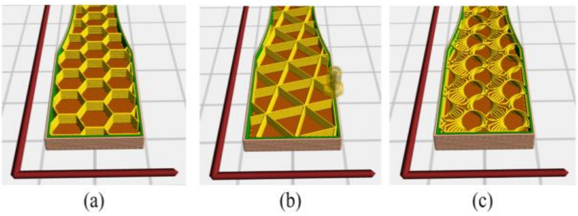
(a) (b) (c)

Fig. 1. Three variations of the infill pattern used for testing. (a) Hexagonal infill pattern (b) Triangular infill pattern (c) 3D infill pattern

A. *Discussion on the Design of Experiments*

The test specimen was designed using the ASME D638 standard which specifies the standard test methods for tensile properties of plastic. Figure 2 shows the design of the specimen as per the ASME standards. Dimension for the Type I specimen was used for the design from the table provided in the standard documentation.

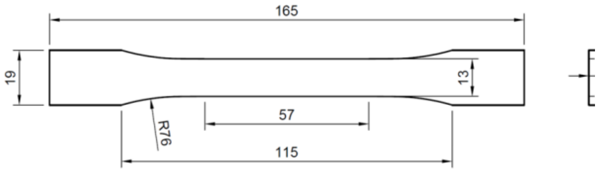

Fig 2. Design of the specimen used for testing

Adding composite mesh material between the prints will increase the layer height by a considerable amount. The thickness of the Fibreglass mesh material is 0.18mm whereas the thickness of the steel wire mesh material is 0.20mm. Individual layer height could be set in the 3D slicer software. The layer height for the fibreglass mesh material was set as the default 0.17mm and the layer height for the steel wire mesh material was set as 0.20mm which corresponds to the thickness of the steel wire mesh. The Gcode generated by the slicer was edited manually to remove the corresponding layers where the mesh has to be placed. For prints with 2 mesh layers, the Gcode is edited accordingly. Figure 3 shows the missing layers in the single and double-layer mesh design which was achieved after editing the Gcode. Fibreglass mesh print had a total of 27 layers of which for the single-layer design the mesh material was placed on the 13th layer whereas for the double-layer mesh design the mesh was placed on the 9th and 18th layers respectively. The steel wire mesh design had a total of 25 layers since we change the layer height to 0.20mm. The single-layer mesh was placed at the 13th layer whereas the double-layer mesh was placed at the 9th and the 17th layer.

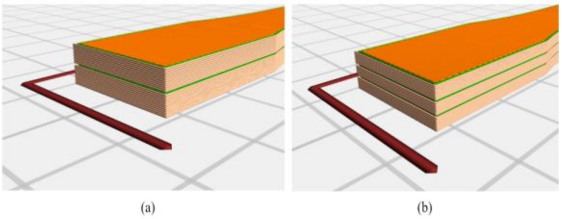
(a) (b)

Fig 3. (a) Single layer removed in the Gcode. (b) Double layer removed in Gcode

Figure 3 (a) shows the visualization of the edited Gcode. Changes have been made in the Gcode for removing single and double layers from the model. A few iterations to the layer height and the number of layers skipped were carried out to zero in on the optimal space between the layers to place the mesh material. This is important as the space between the layers affects the adhesion of the print to the mesh material as less adhesion of the material can cause the upper and the lower portion of the prints to be separated and this can affect the test results drastically.

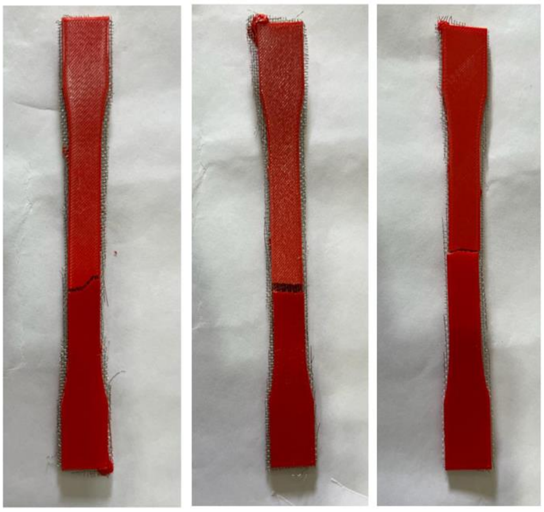

Fig 4. Images of tested sample in UTM

IV. RESULTS

TABLE I. TENSILE STRENGTH OF VARIOUS MODELS TESTED

Sr. No.	Infill	Infill pattern	Control (MPa)	Single Layer Fibre Glass Mesh(MPa)	Double Layer Fibre Glass Mesh(MPa)	Single Layer Steel Wire Mesh(MPa)	Dou St M
1	15%	Hexagon	12.8	11.8	14.7	11.7	
2	30%	Hexagon	13.6	13.8	18.4	12.2	
3	45%	Hexagon	11.0	13.7	14.3	16.1	
4	15%	Triangle	12.4	12.3	12.5	12.1	
5	30%	Triangle	13.6	14.9	15.4	15.7	
6	45%	Triangle	12.4	16.1	14.2	15.6	
7	15%	3D infill	13.9	10.2	11.3	10.7	
8	30%	3D infill	14.8	12.7	13.8	13.0	
9	45%	3D infill	13.3	13.5	14.5	14.7	

Table 1 shows the data collected after testing the 3D-printed models in a UTM. The data shown in the table is in MPa(Mega Pascals). Control models were 3D printed without any additional composite layers or mesh layers. Controls help us understand the improvement in the strength of the print after adding the composite material. Figure 5,6 and 7 shows the tensile strength of the materials plotted against the varying fill percentage.

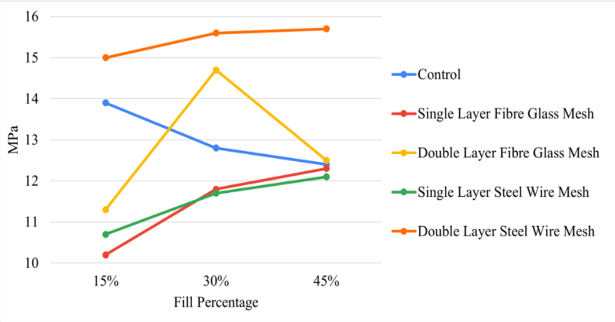

Fig 5. Tensile strength of hexagonal infill pattern with varying infill density

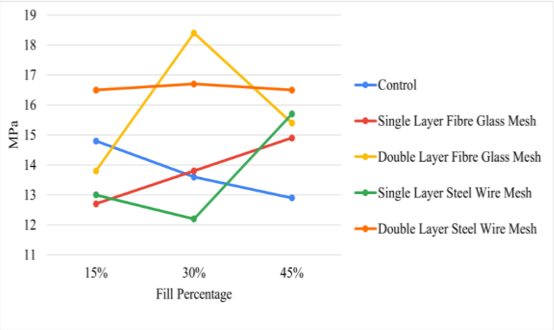

Fig 6. Tensile strength of triangular infill pattern with varying infill density

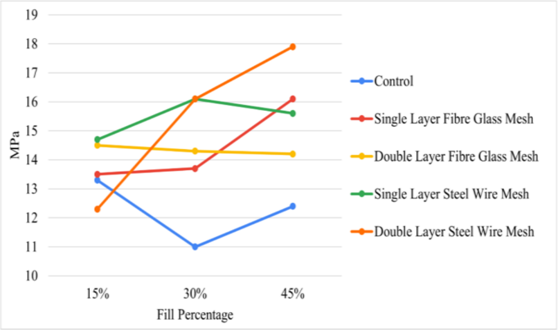

Fig 7. Tensile strength of 3D infill pattern with varying infill density

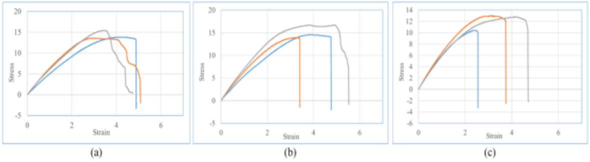

Fig 8. Stress vs Strain curve of Hexagonal infill pattern for varying infill percentage

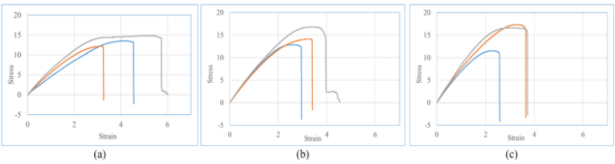

Fig 9. Stress vs Strain curve of Triangular infill pattern for varying infill percentage

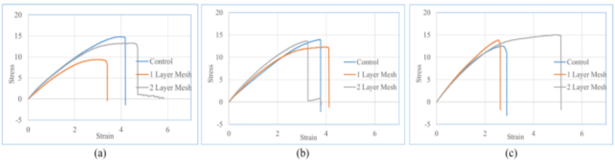

Fig 10. Stress vs Strain curve of 3D infill pattern for varying infill percentage

Figure 8,9 and 10 shows the Stress vs Strain curve of the hexagonal, triangular and 3D infill pattern for varying infill percentages. Image label (a) represents 15% infill, image label (b) represents 30% infill, and image label (c) represents 45% infill. The blue line represents control group prints, the orange line represents single-layer mesh and the grey line represents double-layer Mesh. All the stress-strain plots are for fibreglass mesh material.

V. CONCLUSION

The plots provided in the results section can be used to identify the advantages and disadvantages of using composite printing. The plots also help us understand various parameters of 3D printing which affect the end product strength. Looking at the ultimate tensile strength of varying infill patterns shows that 3D infill patterns increase the strength in the case of composite 3D printing. There is no significant advantage when using a hexagonal infill pattern as the strength of the object is lower than the control object for varying infill percentages. For triangular and 3D infill patterns it can be seen that the strength of the 3D printed increase with increasing level of infill percentage.

When analyzing the cracks on the tested objects it can be seen that objects with proper adhesion between the 3D-printed surface and the mesh have higher strength. If the adhesion between the mesh and the 3D printed surface is less it can cause the upper and the lower 3D printed sections to crack individually and at slightly different locations causing the strength to be even lower than the control objects with no mesh material.

These findings show the possibility of using composite mesh reinforcement to improve the structural integrity and overall performance of 3D-printed products. The proposed technique can help us improve on the inherent limits of traditional 3D printing. Overall, this study improves the area of 3D printing by proposing a unique strategy to increase the strength of printed items, opening the way for the production of strong and dependable 3D printed components with superior mechanical characteristics and broad applicability in a variety of sectors.

VI. FUTURE SCOPE

3D printing is a sophisticated technology with several characteristics that may be adjusted to generate different end-product finishes. This characteristic also has an impact on the product's mechanical qualities. The research only examines the model for differences in mesh layer count and infill %. The adhesion of the composite material to the layers is an essential consideration when employing mesh material for composite 3D printing. We can attempt a different infill pattern to improve adherence. Another option is to duplicate the layer above the mesh material. The temperature of the print head (nozzle) can also be increased to improve layer adhesion. Sufficient caution was taken to ensure proper adhesion between the mesh and the 3D-printed layers. Since there are some inherent variations in the print output even when using the same setting some of the test models printed were not proper and had a portion of the mesh separated from the print. This could have induced variations in the test results causing outliers in the collected data. Further testing and data collection could be done to remove outliers by enhancing the print quality and validating the results.

Further study might concentrate on optimising the composite mesh arrangement, experimenting with other fibre materials and matrix compositions, and assessing the scalability and cost-effectiveness of this technology in real-world production settings. Furthermore, research on the long-term durability and fatigue resistance of reinforced 3D printed products would contribute to a thorough understanding of their performance under a variety of operating settings.

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