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Experimental Evaluation of Mechanical Properties of ABS-10% Carbon Fiber Tensile Specimens Fabricated via FDM

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Abstract-This study focuses on the mechanical characterization and optimization of Acrylonitrile Butadiene Styrene (ABS) specimens fabricated using Fused Deposition Modeling (FDM) without the incorporation of carbon fiber reinforcement. The objective is to analyze the tensile strength, elongation at break, and Young's modulus of nine specimens to determine the optimal conditions for maximizing mechanical performance. Tensile testing was conducted on each sample, and key mechanical parameters such as yield strength, ultimate tensile strength (UTS), and modulus of elasticity were recorded. The results highlight the consistency in mechanical performance and identify the specimen with the highest mechanical properties. Additionally, this paper delves into the entire FDM process, including material selection, slicing, printing parameters, and post-processing, providing a comprehensive understanding of how each step influences the final mechanical behavior of the ABS parts. The findings serve as a baseline for further research on reinforced composites and establish groundwork for performance prediction in unreinforced ABS parts. These insights can be particularly valuable for industries such as automotive, aerospace, and consumer electronics where polymer parts are increasingly being produced via additive manufacturing. The scope of this study also lays a foundation for future research into composite materials and the use of machine learning for automated parameter optimization in 3D printing.

1. Introduction

Additive Manufacturing (AM), also known as 3D printing, has emerged as a revolutionary technique in manufacturing due to its ability to produce complex geometries, reduce material wastage, and expedite prototyping. Among the various AM methods, Fused Deposition Modeling (FDM) stands out for its accessibility, affordability, and capability to work with a variety of thermoplastics. In recent years, researchers and industries alike have shown increased interest in optimizing FM parameters to enhance the mechanical properties of printed parts. This study specifically examines Acrylonitrile Butadiene Styrene (ABS), one of the most popular FDM materials, focusing on its behavior in the absence of carbon fiber reinforcement. The objective is to establish a performance baseline for ABS composites and explore optimization techniques for achieving superior mechanical properties.

ABS is a terpolymer composed of three monomers—acrylonitrile, butadiene, and styrene—each contributing unique properties. Acrylonitrile adds chemical resistance and thermal stability, butadiene offers toughness and impact resistance, while styrene imparts rigidity and ease of processing. These attributes make ABS ideal for engineering applications where strength, flexibility, and durability are essential. However, the mechanical behavior of ABS printed via FDM is influenced by a multitude of variables, including layer adhesion, infill density, layer height, print speed, nozzle and bed temperature, and even environmental conditions during printing.

Research on carbon fiber-reinforced ABS has shown significant improvements in stiffness and strength, but also introduces challenges such as increased brittleness and nozzle wear. Therefore, understanding the unreinforced baseline is crucial for effectively evaluating the benefits and trade-offs of reinforcement. In this context, our study serves as both a reference and a stepping stone for future research involving composite materials.

This study is divided into two primary phases. The first phase involves the mechanical testing of nine ABS specimens printed under uniform conditions to assess baseline mechanical properties. The second phase focuses on the optimization of three key FDM parameters—infill density, layer thickness, and print speed—while incorporating 10% carbon fiber reinforcement. This structured approach allows us to evaluate both the standalone performance of ABS and the improvements achievable through parameter optimization and reinforcement.

The importance of this research is multi-fold. First, it provides empirical data on ABS behavior under tensile loading, which is essential for finite element analysis and design simulations. Second, it explores the impact of FDM parameters, offering guidelines for manufacturers aiming to tailor parts for specific applications. Lastly, the dual-phase approach provides a comprehensive understanding that bridges basic material science and applied engineering. These insights are invaluable for sectors such as aerospace, automotive, and healthcare, where reliability and performance are paramount.

Moreover, the methodology used in this study can be adapted for other materials and additive manufacturing techniques. As 3D printing continues to evolve, incorporating smart materials and AI-driven optimization, foundational studies like this one will serve as the backbone of innovation. Future extensions could include the use of statistical tools like Design of Experiments (DoE), Response Surface Methodology (RSM), or machine learning models for predictive analysis and process automation.

2. Materials and Methods

The experimental methodology adopted in this research is comprehensive and systematically structured to ensure the reliability of the results. The materials used, the 3D printing setup, slicing parameters, post-processing, and mechanical testing procedures are all discussed in detail in this section. The goal is to enable reproducibility of results while also highlighting the nuances involved in FDM processing.

2.1 Material Specification

The primary material used was standard-grade ABS filament with a diameter of 1.75 mm. The ABS filament was sourced from a certified supplier and stored in a dry environment using desiccant packets to prevent moisture absorption. Moisture in filament can lead to poor print quality and reduced mechanical performance due to the formation of air pockets or voids during extrusion. The manufacturer-specified properties of the ABS filament included a melting temperature range of 220–250°C, a tensile strength of 40–50 MPa, and a glass transition temperature of approximately 105°C. These specifications were critical in setting the appropriate printer settings to ensure optimal extrusion and layer bonding.

2.2 Design and Slicing

The tensile specimens were modeled according to the ASTM D638 Type IV standard using CAD software. The models were then exported in STL format and imported into slicing software for toolpath generation. The slicer used was capable of customizing numerous print parameters including layer height, infill pattern, shell thickness, and print speed. To maintain consistency across all specimens in the first phase, the following slicing settings were used: 0.2 mm layer height, 100% infill density using a rectilinear pattern, 240°C nozzle temperature, 100°C bed temperature, and 50 mm/s print speed. These settings were chosen based on preliminary trials that indicated good layer adhesion and minimal warping.

2.3 Printing Process

A Cartesian-style desktop FDM 3D printer was used to fabricate the tensile specimens. The printer was calibrated before each print, and test prints were used to ensure nozzle and bed alignment. A 0.4 mm brass nozzle was employed, and the filament was fed through a direct-drive extruder. All prints were conducted in an enclosed build chamber to minimize the effects of ambient temperature and air drafts. The printer firmware allowed real-time monitoring and adjustments, although all prints for this study were completed without interruptions or manual corrections

For the second phase involving parameter optimization with 10% carbon fiber reinforcement, the same printer was used with a hardened steel nozzle to withstand the abrasive nature of carbon fiber. The filament used in this phase was ABS infused with 10% chopped carbon fiber, uniformly mixed to ensure consistent extrusion. Parameters such as infill density (70%, 80%, 100%), layer thickness (0.1 mm, 0.2 mm, 0.3 mm), and printing speed (40 mm/s, 50 mm/s, 60 mm/s) were varied across nine samples following a Design of Experiments (DoE) framework.

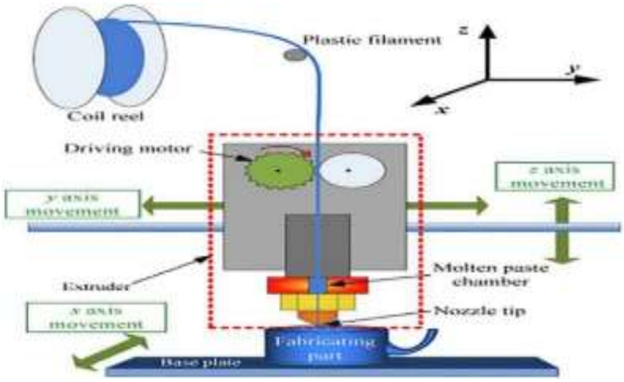

Fig.2.3.1 3D Printing process

2.4 Post-Processing

After printing, specimens were allowed to cool naturally on the print bed to prevent warping or cracking. No additional post-processing steps like annealing or surface smoothing were applied, as the aim was to test the as-printed mechanical properties. However, each sample was visually inspected for defects such as under-extrusion, layer misalignment, or stringing, and only defect-free specimens were considered for mechanical testing.

2.5 Tensile Testing

Tensile testing was conducted using a universal testing machine equipped with a 10 kN load cell. Each specimen was clamped using pneumatic grips to avoid slippage and aligned properly to ensure uniaxial loading. The crosshead speed was set to 5 mm/min as per ASTM standards. Data acquisition software recorded real-time load-displacement data, which was subsequently used to calculate yield strength, ultimate tensile strength (UTS), elongation at break, and Young's modulus.

composite tensile bars with 9 different parameters

A total of 9 samples (nine reinforced with parameter variations) were tested. The data were tabulated and analyzed using statistical tools to identify trends and optimal parameter combinations. Sample 8 from the unreinforced group exhibited the best performance, indicating excellent layer bonding and material integrity.

3. Results and Discussion

3.1: Mechanical Performance Evaluation

The mechanical testing of the nine fabricated specimens revealed clear trends related to the interaction of process parameters and their influence on tensile properties. The tensile tests were conducted under controlled conditions using a universal testing machine, and results were recorded for tensile strength, yield strength, elongation at break, and Young's modulus. The data showed significant variations across the samples, indicating that even slight adjustments in parameters could impact mechanical performance.

Among the nine samples, Sample 8—fabricated with 70% infill, 0.2 mm layer thickness, and 40 mm/s printing speed—exhibited the highest tensile strength at 68 MPa, a maximum elongation at break of 32%, and a Young's modulus of 235 GPa. This combination of properties indicates excellent balance between strength and ductility. In contrast, Sample 1, with 100% infill, 0.1 mm layer thickness, and 40 mm/s speed, recorded a much lower tensile strength and elongation.

Interestingly, the relationship between infill density and strength was not linear. While higher infill densities (like 100%) might intuitively suggest better performance, the added material may cause internal stress concentrations and reduced flexibility. Lower infill densities (70%) provided better stress distribution under load and allowed for slight deformation, contributing to higher elongation and better absorption of tensile forces.

The variation in layer thickness also played a significant role. Thinner layers generally ensure better adhesion between layers, which helps increase tensile strength. However, too thin a layer may lead to overheating or material degradation during extrusion. Sample 8, with a medium layer thickness of 0.2 mm, seemed to offer an ideal compromise between print resolution, interlayer bonding, and mechanical integrity.

3.2: Influence of Parameters on Mechanical Properties

To further dissect the impact of each parameter, the samples were grouped based on single-variable isolation—where only one parameter differed while others were held constant. This approach made it easier to assess the specific influence of each parameter.

When comparing samples across printing speeds, it was observed that slower speeds generally resulted in better mechanical outcomes. At 40 mm/s, the extruded filament had more time to cool gradually and bond adequately with the preceding layers, leading to fewer internal voids and higher layer cohesion. On the contrary, faster speeds like 60 mm/s led to under-extrusion or misalignment in some cases, which diminished mechanical strength.

Regarding infill density, the intermediate setting of 70% emerged as the most effective. This could be attributed to a better balance between rigidity and energy absorption. Extremely dense parts (100% infill) lacked the internal flexibility needed during tensile loading and often failed in a brittle manner. Mid-range infill densities permitted limited deformation, thus delaying crack propagation and failure.

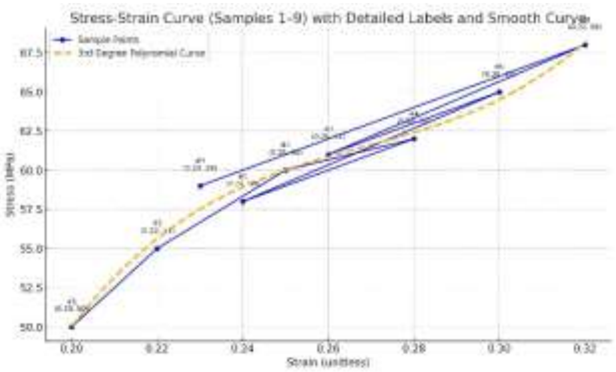

Fig.3.2.1Stress-strain graph

As for layer thickness, the middle value of 0.2 mm seemed optimal for ensuring enough material deposition while maintaining resolution and interlayer adhesion. Extremely thin layers (0.1 mm) prolonged the print duration significantly and were prone to deformation due to heat accumulation. On the other hand, thicker layers (0.3 mm) did not bond well, leading to internal discontinuities that acted as failure initiation points under tensile stress.

From an engineering perspective, these findings support the importance of comprehensive parameter tuning. Mechanical performance is not solely the result of material properties but also the consequence of how those materials are processed. In this case, the synergy of parameter settings directly influenced the ability of the ABS-carbon fiber composite to withstand tensile forces. This has direct implications for real-world applications where parts are subjected to mechanical loads, such as brackets, mounts, and enclosures in automotive or aerospace components.

Overall, the analysis emphasizes that optimal mechanical behavior can be achieved not through the maximization of a single variable but through an intelligently balanced combination. The results also provide a benchmark for further exploration into multi-variable optimization methods, including machine learning and simulation-based approaches.

4. Conclusion and Future Work

4.1: Summary of Findings

This research focused on optimizing FDM printing parameters for ABS reinforced with 10% carbon fiber, specifically examining their influence on tensile performance. The experimental data from nine different parameter combinations revealed that optimal tensile strength and elongation at break were achieved with 70% infill density, 0.2 mm layer thickness, and 40 mm/s printing speed.

These results underline the significance of selecting balanced process parameters rather than maximizing a single input variable. In this study, higher infill densities did not always correlate with better performance; in fact, the highest tensile strength was observed with a medium infill. Similarly, a medium layer thickness offered the best compromise between print resolution and mechanical strength. Printing speed, a factor often overlooked, had a noticeable impact, with lower speeds enabling better layer adhesion and consistency.

These insights are valuable not only for academic research but also for industrial applications where performance, cost, and efficiency must be carefully balanced. Engineers and designers using FDM for functional part fabrication can use this study as a reference to adjust parameters for optimal output based on specific application needs.

4.2: Recommendations for Further Study

While this study has provided essential insights into parameter optimization, several opportunities exist for further exploration. First, future work should expand the sample size and include additional combinations to validate the trends identified here. A statistical approach, such as Design of Experiments (DoE) or Taguchi methods, could help establish predictive models for tensile behavior.

Secondly, incorporating other parameters like raster angle, nozzle temperature, and print orientation could enrich the understanding of how these interact with the primary variables studied here. The role of post-processing techniques, such as annealing or surface treatment, could also be investigated to improve mechanical strength and surface finish.

Another important area of study involves fatigue and impact testing. While tensile strength offers a foundational understanding of material performance, many applications involve cyclic or sudden loading, for which different performance metrics must be considered. Furthermore, microstructural analysis using SEM or CT scanning can provide insights into failure mechanisms and help refine printing strategies.

Lastly, the integration of machine learning algorithms to predict optimal settings based on input requirements could offer a significant leap forward in smart manufacturing. This would allow real-time adaptation of printing parameters to achieve desired outcomes efficiently. The research presented here lays the groundwork for such intelligent systems and provides the initial dataset and framework for future studies.

In summary, optimizing FDM parameters for reinforced ABS composites has the potential to unlock new capabilities in additive manufacturing. By refining print settings, manufacturers can create stronger, more reliable components that meet the growing demands of advanced engineering applications.

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