

Comparative Effects of Thermal Annealing and UV Treatment on the Tensile Strength of 3D-Printed PLA-Carbon Fibre Composites: A Design-of-Experiments Approach

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ABSTRACT

Fused Deposition Modelling (FDM) offers substantial advantages in terms of manufacturing flexibility, material efficiency, and cost; however, its broader use in load-bearing applications remains constrained by process-induced voids and weak interlayer bonding. Short carbon fibre-reinforced polylactic acid (PLA-CF) can partially address these limitations, although the mechanical performance of printed composites may be further modified through appropriate post-processing. Despite increasing interest in post-processing strategies, direct experimental comparisons between thermal annealing and ultraviolet (UV) treatment under controlled printing conditions remain limited, particularly for short-carbon-fibre-reinforced PLA. This study therefore compared the effects of thermal annealing and UV treatment on the ultimate tensile strength (UTS) of FDM-printed PLA-CF containing 10 wt.% short carbon fibre. Two independent 3² full-factorial experiments were conducted using ASTM D638 Type IV specimens fabricated under identical printing conditions. The effects of the post-processing parameters were evaluated using descriptive statistics, analysis of variance (ANOVA), and regression modelling. Untreated specimens exhibited a mean UTS of 31.55 ± 2.43 MPa. Thermal annealing at 120 °C for 60 min produced the highest UTS of 36.53 MPa, corresponding to a 15.78% improvement over the untreated condition, with annealing temperature exerting a statistically significant effect on UTS ($p < 0.001$). UV treatment achieved a maximum UTS of 35.01 MPa at an exposure time of 40 min and a lamp distance of 8 cm, representing a 10.97% improvement, with both exposure time and lamp distance significantly affecting the tensile response ($p < 0.01$). Annealing produced a numerically higher and less variable UTS than UV treatment at their respective best-performing settings. However, the direct difference of 1.52 MPa was not statistically significant, indicating that independent confirmation with a larger sample size is required. These findings demonstrate that post-processing route and treatment parameters play distinct roles in controlling the tensile performance of FDM-printed PLA-CF and provide a quantitative basis for selecting post-processing conditions for mechanically demanding printed components.

Keywords: Fused deposition modelling; PLA-carbon fibre composite; Annealing; UV treatment; Design of experiments

INTRODUCTION

The relatively low cost and geometric flexibility of material extrusion using Fused Deposition Modeling

(FDM) has made this process popular for functional prototyping and component manufacturing. It allows for complex and customized geometries to be produced directly from CAD data, with minimal material waste and no need for custom tooling. This has contributed to its use in sectors such as aerospace, automotive, and biomedical engineering where components need to be lightweight and intricate (Zotti et al., 2025).

Structural performance, however, remains a persistent concern. The layer-by-layer additive manufacturing process creates mechanical anisotropy naturally, in the form of non-isothermal cooling of deposited filaments, lack of complete fusion between adjacent layers, and the formation of micro voids during solidification (Omer et al., 2025). These properties compromise interlayer adhesion, inhibit stress transfer and lead to early interlaminar failure, leading to reduced tensile properties compared to traditionally fabricated parts. The most common parameters that need optimisation are the printing parameters, which include raster orientation, layer height, infill density, nozzle temperature, etc. (Gao et al., 2022; Hsueh et al., 2021; Rathod et al., 2023), as these have a significant impact on interlayer bonding. However, printing-parameter optimisation alone cannot fully overcome the intrinsic limitations of the deposition process.

The most frequently used thermoplastics in FDM are still based on polylactic acid (PLA) which is widely used due to its biodegradability, low processing shrinkage, renewable origin, and ease of processing (Farah et al., 2016). It has, however, its restricted ductility and thermal stability which limits its use in severe structural applications (Ekşi & Karakaya, 2025). With these limitations, more and more research has focused on short fiber-reinforcing PLA composites.

Carbon-fiber-reinforced PLA (PLA-CF) has emerged as a promising composite for FDM, combining the printability of PLA with the stiffness and load-transfer capability provided by short carbon fibers (Kargar & Ghasemi-Ghalebahman, 2023; Wang et al., 2024). Even modest fiber loadings can improve mechanical performance. For example, the incorporation of 5 wt.% CF has been shown to enhance stiffness and mechanical performance relative to neat PLA (Wang et al., 2024), provided that adequate fiber-matrix interfacial bonding enables effective load transfer (Hozdić & Hasanagić, 2024).

The extent of this improvement depends strongly on fiber loading, length, dispersion, and interfacial bonding quality. Moreover, the presence of stiff fibers can increase melt viscosity and introduce defects such as interfacial voids, weakened interlayer adhesion, and localized stress concentrations. Consequently, PLA-CF tends to exhibit greater brittleness than neat PLA, while its tensile response becomes increasingly sensitive to voids and interlayer defects (Alkabbanie et al., 2024; Shbanah et al., 2023). This sensitivity makes PLA-CF particularly relevant for evaluating whether post-processing can mitigate the mechanical limitations associated with FDM-induced defects.

Post-processing offers an alternative approach for mitigating these defects after fabrication through microstructural modification, residual-stress relief, and improved load transfer across interlayer boundaries (Kantaros et al., 2024). Thermal annealing and UV treatment are practical post-processing approaches because of their relatively low cost and ease of integration into existing manufacturing workflows. However, they operate through fundamentally different mechanisms. Thermal annealing promotes bulk polymer-chain mobility above the glass transition temperature (T_g), facilitating molecular rearrangement and diffusion across interlayer boundaries, whereas UV treatment predominantly induces surface-level photochemical changes with limited bulk restructuring.

The effects of annealing on PLA are well documented and include increased chain mobility, stress relaxation, enhanced crystallinity, and improved interlayer diffusion (Bhandari et al., 2019). In carbon-fiber-reinforced FDM components, annealing temperature has been reported to exert a greater influence on mechanical performance than holding time. Specifically, temperatures between 110 and 170 °C have been reported to increase tensile strength by up to 16.7% and tensile modulus by up to 35%, whereas variations in holding time produced comparatively minor effects (Tujmer & Pilipović, 2025). Annealing near T_g has also been reported to shift the failure mode from brittle inter-bead separation toward a more cohesive fracture associated with enhanced molecular diffusion (Nassar et al., 2026). Excessive annealing temperature or duration, however, can promote excessive chain mobility, leading to dimensional distortion and

embrittlement. Therefore, an appropriate processing window must be established to balance the beneficial and detrimental effects of annealing (Seok et al., 2023; Shbanah et al., 2023).

Controlled UV exposure can improve local mechanical behaviour and surface integrity; however, increasing the delivered energy may reverse these beneficial effects. UV exposure has been reported to reduce Young's modulus by 13–30% through Norrish-type chain scission, with the resulting response strongly dependent on total exposure, light intensity, and source (Akderya, 2023; Chang et al., 2020). Beyond a critical exposure threshold, UV irradiation can accelerate chain scission and embrittlement, resulting in deterioration of mechanical performance. Given its surface-limited and exposure-sensitive nature, UV treatment should therefore be evaluated as an independent processing variable rather than as a secondary form of thermal treatment.

Although thermal and UV treatments have been individually investigated, most studies focus on neat PLA or examine a single post-processing treatment, often alongside printing-parameter optimization (Ekşi & Karakaya, 2025; Gao et al., 2022). Comparatively less attention has been given to short-carbon-fiber-reinforced PLA (PLA-CF), particularly to direct comparisons of thermal and UV post-processing under matched experimental conditions. Recent studies have begun to broaden this scope; for example, annealing temperature has been investigated together with infill parameters using a factorial design (Nassar et al., 2026), while the sequence of combined UV and thermal exposure has been examined in relation to compressive performance (Anachebe et al., 2026). Nevertheless, the relative effectiveness of thermal annealing and UV treatment on the same PLA-CF material system, including their interactions with treatment-specific processing factors, remains insufficiently understood.

In response to these limitations, this study investigates the effects of thermal annealing and UV-curing post-processing on the ultimate tensile strength (UTS) of FDM-printed PLA-carbon fiber composites, PLA-CF (10 wt.% short carbon fiber) using two independent 3² full-factorial designs. Specifically, thermal annealing (evaluated at temperatures of 80°C, 100°C, and 120°C for up to 60 min) and 405 nm UV-curing (evaluated across exposure times up to 40 min and lamp distances of 8 to 12 cm) are systematically analyzed to establish optimal processing windows and quantify strength improvements over untreated baselines. ANOVA were used to quantify those effects and identify optimum conditions for each route. The principal contribution of this study is a controlled factorial comparison of two mechanistically distinct post-processing strategies applied to the same PLA-CF system, providing a systematic basis for selecting an appropriate treatment and informing the design of future combined-treatment studies.

METHODOLOGY

Specimen Preparation and Experimental Design

Specimens were fabricated from a commercially available, 1.75 mm PLA-CF filament containing 10 wt.% short carbon fibre. All specimens were printed on an Elegoo Centauri Carbon desktop FDM printer (0.4 mm nozzle) using a fixed process profile. A standardized process profile (Table 1) was maintained to eliminate fabrication variability across sample sets. Specimens were designed to ASTM D638 Type IV geometry (ASTM International, 2022) using AutoCAD and sliced in Elegoo Cura; build orientation (flat on the build plate) and infill (100%, cross pattern) were held constant for all specimens.

Table 1. Fixed FDM printing parameters used for all PLA-CF ASTM D638 Type IV specimens

Parameter	Value	Parameter	Value
Layer height	0.20 mm	Nozzle temperature	220 °C
Wall thickness	2.0 mm ($\approx$ 5 lines)	Bed temperature	60 °C
Top/bottom thickness	1.2 mm	Print speed	50 mm/s
Infill density / pattern	100% / cross	Cooling fan	100% (after first layers)
Build orientation	Flat on build plate	Build-plate adhesion	Brim; support disabled

Post-Processing: Annealing and UV Treatment DOE

Specimens were evaluated across three primary experimental groups: untreated baseline control, thermally annealed, and UV post-cured. The annealing process was carried out in a laboratory convection oven with two factors: temperature (80, 100, 120 °C) and holding time (30, 45, 60 min). A 3² full factorial Design of Experiments (DOE) was conducted for both post-processing routes to capture main effects and interactive dependencies. Each treatment combination was tested using three independent replicates (n = 3), resulting in 27 specimens for each post-processing DOE. UV treatment was carried out using a UV lamp at fixed exposure times (20, 40, 60 min) and lamp distances (8, 10, 12 cm), again following a 3² full-factorial design with three replicates per combination (n = 27). Specimens were positioned on a flat, non-reflective surface with the gauge section fully exposed at the specified distance for the specified time, then allowed to cool to room temperature and inspected for discolouration, cracking, or distortion before storage. All specimens were stored at room temperature in a dry, dark environment prior to testing and handled only by the grip ends to avoid damage to the gauge section. All specimens were conditioned for at least 24 h prior to tensile testing. The experiment parameters are summarized in Table 2 below.

Table 2. Factors and levels of the two 3² full-factorial post-processing designs

Post-processing	Factor	Levels
Annealing	Temperature (°C)	80, 100, 120
Annealing	Holding time (min)	30, 45, 60
UV treatment	Exposure time (min)	20, 40, 60
UV treatment	Lamp distance (cm)	8, 10, 12

Tensile Testing

Tensile evaluation was performed at ambient conditions (23 ± 2 °C) using a HannYa Electronic Universal Testing Machine (HY-WDW-100D) in accordance with ASTM D638. A constant crosshead speed of 5 mm/min was applied. Load–displacement data were converted to engineering stress–strain curves, and the ultimate tensile strength (UTS) of each specimen was taken as the primary response variable. Ultimate Tensile Strength (σ_{uts}) was calculated using Equation 1:

$$\sigma_{uts} = F_{max} / A_0 \quad (1)$$

here F_{max} is the maximum force at failure ("N") and A_0 is the initial nominal cross-sectional area ($[mm^2]$) of the gauge section. Experimental results were subjected to Analysis of Variance (ANOVA), main effects analysis, interaction modeling, and residual diagnostics using MINITAB.

Design of Experiments and Statistical Analysis

Data were analysed using MINITAB through descriptive statistics, including the mean and standard deviation, as well as main-effects and interaction plots, two-way analysis of variance (ANOVA; $\alpha = 0.05$), regression modelling, and residual diagnostics. Normal probability, versus-fits, and versus-order plots were examined to assess the normality and homogeneity-of-variance assumptions underlying the ANOVA for each DOE. For each DOE, the null hypothesis stated that the respective factors and their interaction had no significant effect on UTS, with statistical significance established at $p < 0.05$. Model adequacy was further evaluated using R^2 , adjusted R^2 , predicted R^2 and residual diagnostics.

RESULTS AND DISCUSSION

Baseline Properties (Untreated PLA-CF)

The untreated as-printed specimens established the baseline mechanical capacity of the PLA-CF composite under the fixed printing parameters summarized in Table 1. The baseline tensile testing yielded an ultimate tensile strength (UTS) of 31.55 ± 2.43 MPa (Table 3). The relatively low baseline strength may be

associated with FDM-induced micro-voids, incomplete inter-bead fusion, residual thermal stresses, and local fibre–matrix interfacial defects reported in similar PLA-CF systems (Alkabbanie et al., 2024; Omer et al., 2025).

Table 3. UTS of untreated (as-printed) PLA-CF specimens

Specimen	UTS (MPa)
Untreated 1	34.15
Untreated 2	31.18
Untreated 3	29.33
Mean $\pm$ SD	31.55 $\pm$ 2.43

Effect of Annealing on Tensile Strength

The mean UTS values obtained for the thermal annealing 3² full-factorial experimental design is presented in Table 4. Tensile strength ranged from a minimum of 31.15 MPa ([80]^o "C" , 45 min) to a maximum of 36.53 MPa ([120]^o "C" , 60 min), representing up to a 15.78% enhancement over the untreated baseline.

Table 4. Mean UTS for the annealing DOE (n = 3 per condition).

Run	Temp. (°C)	Time (min)	Mean UTS (MPa)
1	80	30	33.59
2	80	45	31.15
3	80	60	32.08
4	100	30	31.56
5	100	45	32.33
6	100	60	34.00
7	120	30	34.91
8	120	45	35.42
9	120	60	36.53

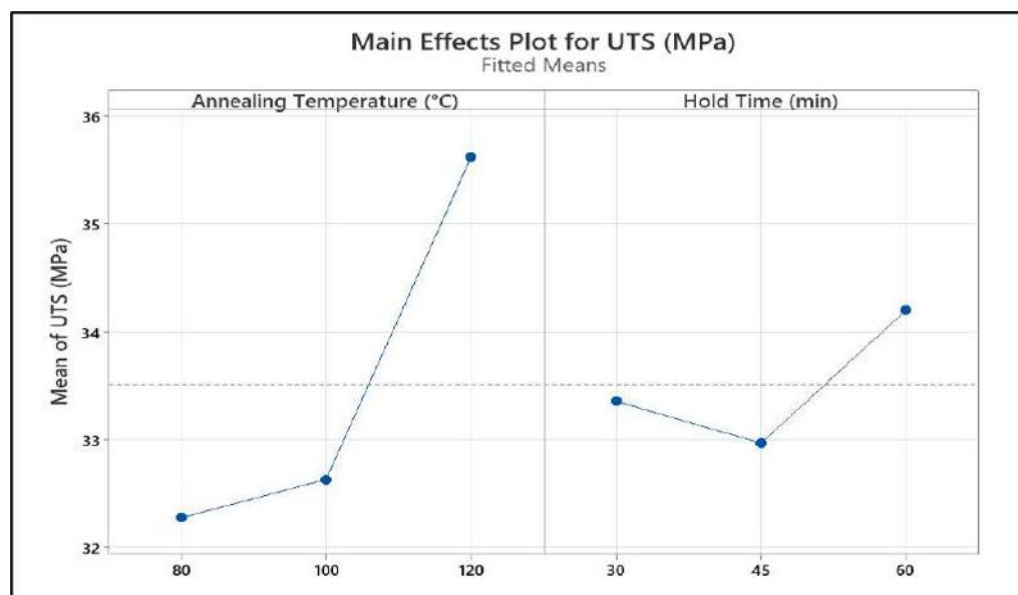


Figure 1. Main-effects plot of annealing temperature and holding time on UTS.

The main-effects plot (Figure 1) demonstrates a strong, monotonic increase in tensile strength as the annealing temperature rises from 80°C (mean 32.27 MPa) to 120°C (mean 35.62 MPa). Conversely, holding time exhibited a minor, non-linear influence across the evaluated duration. Two-way ANOVA confirmed that the model was significant ($p < 0.001$). Annealing temperature was statistically significant ($p < 0.001$), whereas holding time ($p = 0.125$) and the temperature $\times$ holding-time interaction ($p = 0.079$) were not significant.

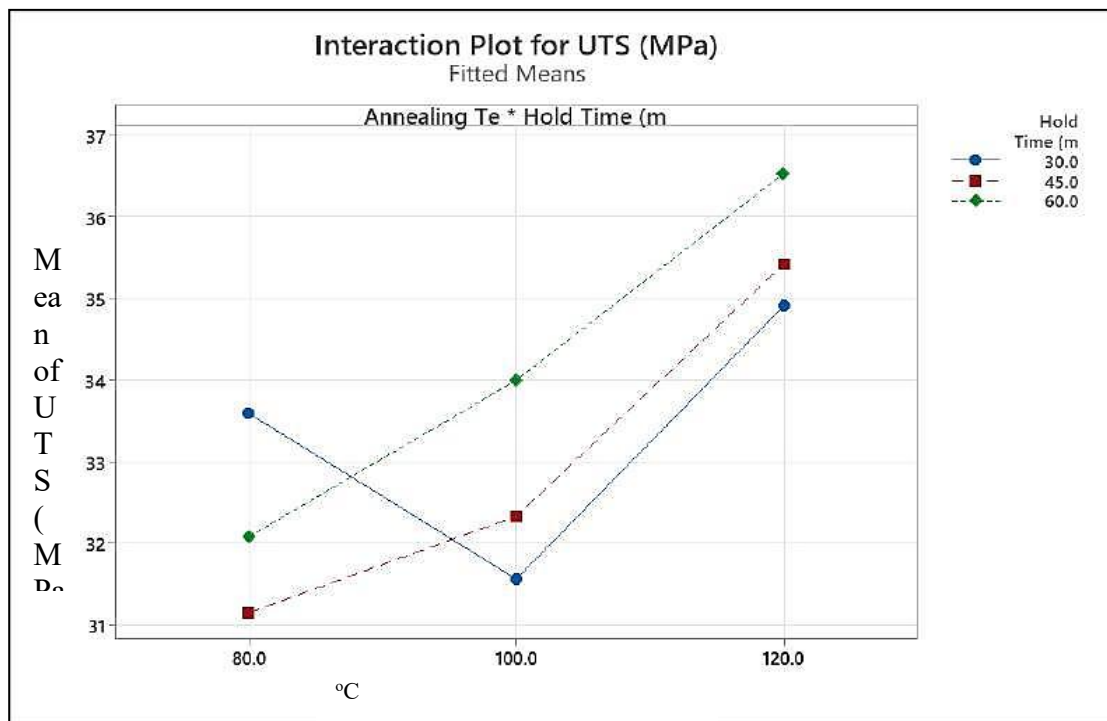


Figure 2. Interaction plot of annealing temperature and holding time on UTS.

The interaction plot (Figure 2) shows a mild, non-parallel trend in which the benefit of extending holding time becomes more apparent at 120°C , where UTS rose progressively from 34.91 MPa (30 min) to 36.53 MPa (60 min). Because the interaction term was not statistically significant, this trend should be treated as descriptive rather than as evidence of a true synergistic effect within the tested range.

As shown in Table 5, The ANOVA results for the annealing experiment show that the overall model is statistically significant ($F=6.78$, $p<0.001$), confirming that the selected variables reliably predict Ultimate Tensile Strength (UTS). Among the individual factors, Temperature (A) is the only statistically significant variable directly driving changes in UTS ($F=23.41$, $p=0.000$). In contrast, Holding time (B) does not have a statistically significant main effect on UTS ($F=2.34$, $p=0.125$), and the combined Interaction ($A \times B$) between temperature and holding time is also not statistically significant at the standard 5% significance level, despite showing a slight marginal trend ($F=2.49$, $p=0.079$).

Table 5. ANOVA summary for the annealing DOE (response: UTS)

Source	DF	F-value	p-value
Model	8	6.78	< 0.001
Temperature (A)	2	23.41	0.000
Holding time (B)	2	2.34	0.125
Interaction $A \times B$	4	2.49	0.079

Annealing temperature emerged as the dominant factor governing tensile performance, whereas holding time had a comparatively minor influence within the investigated range. Increasing temperature generally

enhanced the UTS of PLA-CF specimens, with the highest value obtained at 120 °C for 60 min. The improvement may be associated with thermally induced molecular rearrangement, increased structural consolidation and modification of the interlayer region, as reported for annealed PLA-based FDM materials. However, these mechanisms were not directly measured in the present study.

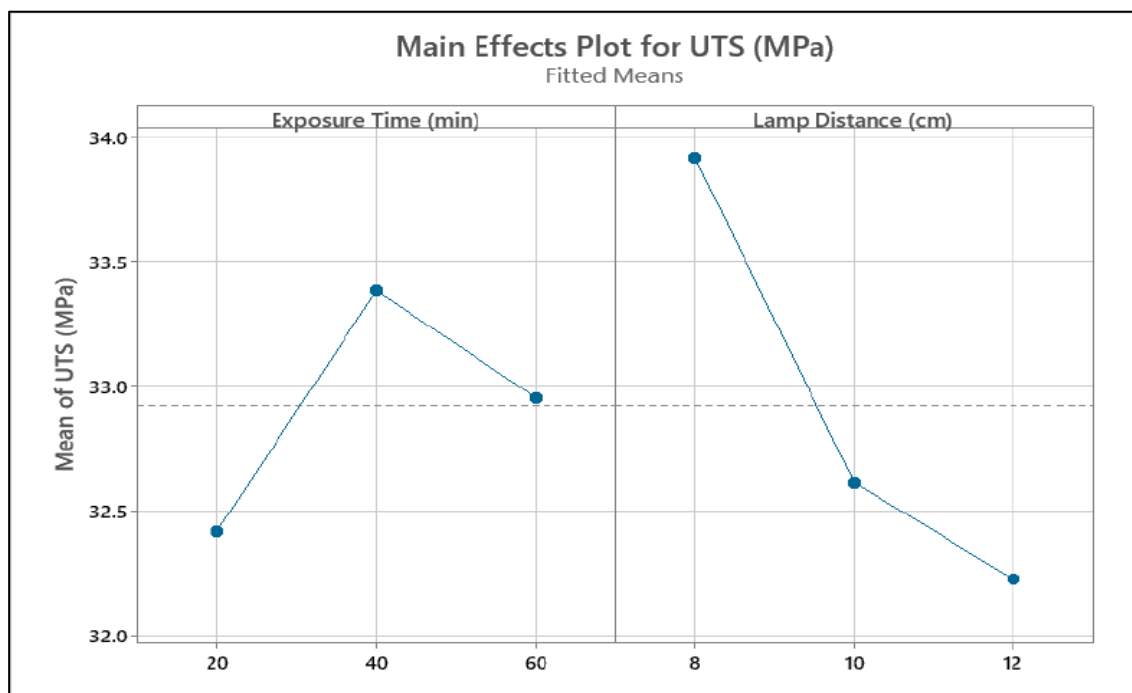
Effect of UV Treatment on Tensile Strength

Table 6 summarizes the experimental responses for the 3² UV treatment DOE. The mean UTS values varied from 30.94 MPa (40 min exposure, 12 cm distance) to a peak value of 35.01 MPa (40 min exposure, 8 cm distance), achieving a maximum improvement of 10.97% relative to untreated specimens.

Table 6. Mean UTS for the UV Treatment DOE (n = 3 per condition)

Run	Exposure Time (min)	Lamp Distance (cm)	Mean UTS (MPa)
1	20	8	32.35
2	20	10	31.63
3	20	12	33.27
4	40	8	35.01
5	40	10	34.04
6	40	12	30.94
7	60	8	34.39
8	60	10	32.18
9	60	12	32.29

Figure 3. Main-effects plot of UV exposure time and lamp distance on UTS.



The main-effects plot (Figure 3) indicates that positioning the lamp closer (8 cm) produced higher average UTS (33.92 MPa) compared to longer distances (12 cm, 32.23 MPa) which is consistent with the expectation of higher irradiance at shorter source-to-specimen distances. Exposure time demonstrated a non-

monotonic trend, peaking at 40 min. However, the interaction plot (Figure 4) revealed severe non-parallel response lines, highlighting that factor effects are non-additive.

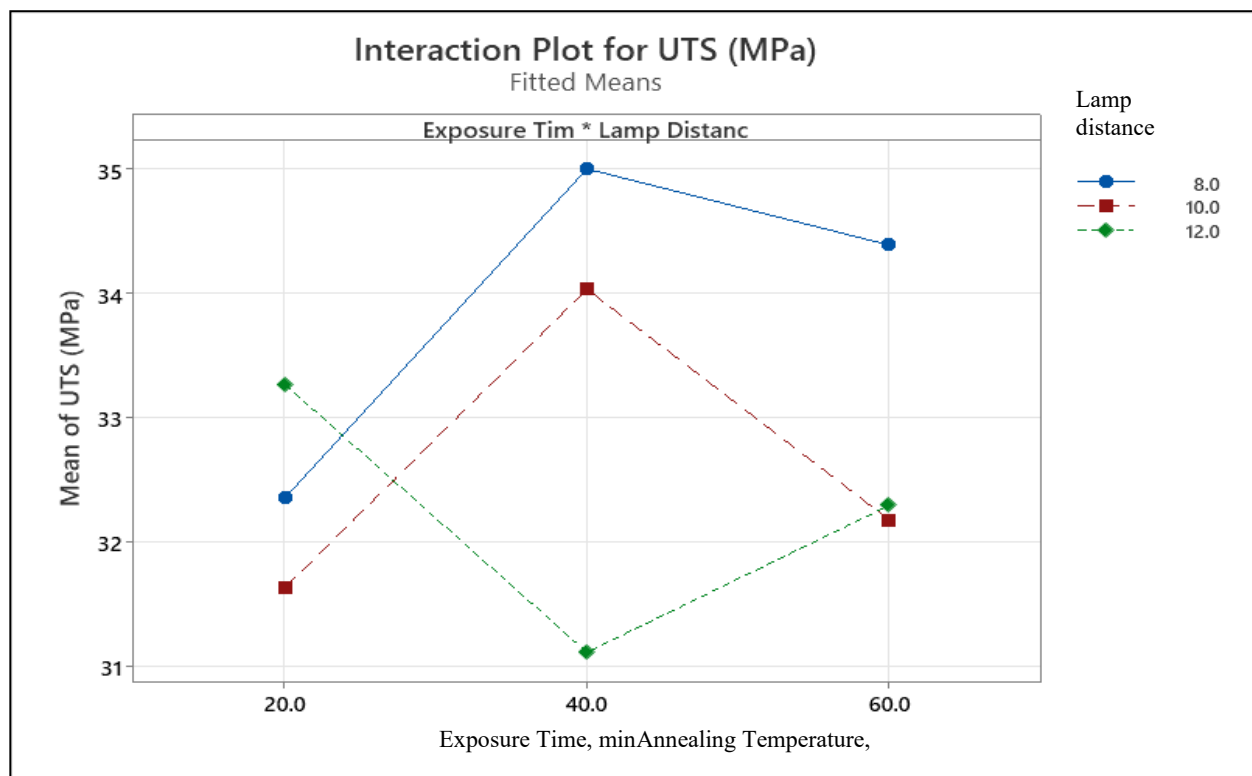


Figure 4. Interaction plot of UV exposure time and lamp distance on UTS.

The ANOVA results (Table 7) confirm a statistically significant model ($F=5.23$, $p=0.002$). Lamp distance was a significant main effect ($p=0.006$), while exposure time alone was non-significant ($p=0.153$). Crucially, the exposure time $\times$ lamp distance interaction was highly significant ($p=0.003$), indicating that UV post-processing performance is governed by interaction dynamics.

Table 7. ANOVA summary for the UV Treatment DOE (response: UTS).

Source	DF	F-value	p-value	Significant ($\alpha = 0.05$)
Model	8	5.23	0.002	Yes
Exposure time (A)	2	—	0.153	No
Lamp distance (B)	2	—	0.006	Yes
A $\times$ B	4	—	0.003	Yes

The significant interaction between exposure time and lamp distance indicates that UV treatment effectiveness is sensitive to the combined effect of exposure duration and source-to-specimen distance received by the specimen, rather than to either factor independently. Moderate exposure conditions produced improvements in tensile strength, whereas excessive or insufficient UV dosage reduced performance.

Comparative Analysis: Thermal Annealing vs. UV Treatment

Figure 5 and Table 8 compare the optimum conditions obtained from the annealing and UV treatment experiments. Both post-processing routes improved the tensile strength of PLA-CF relative to the untreated condition, with annealing producing the greater enhancement.

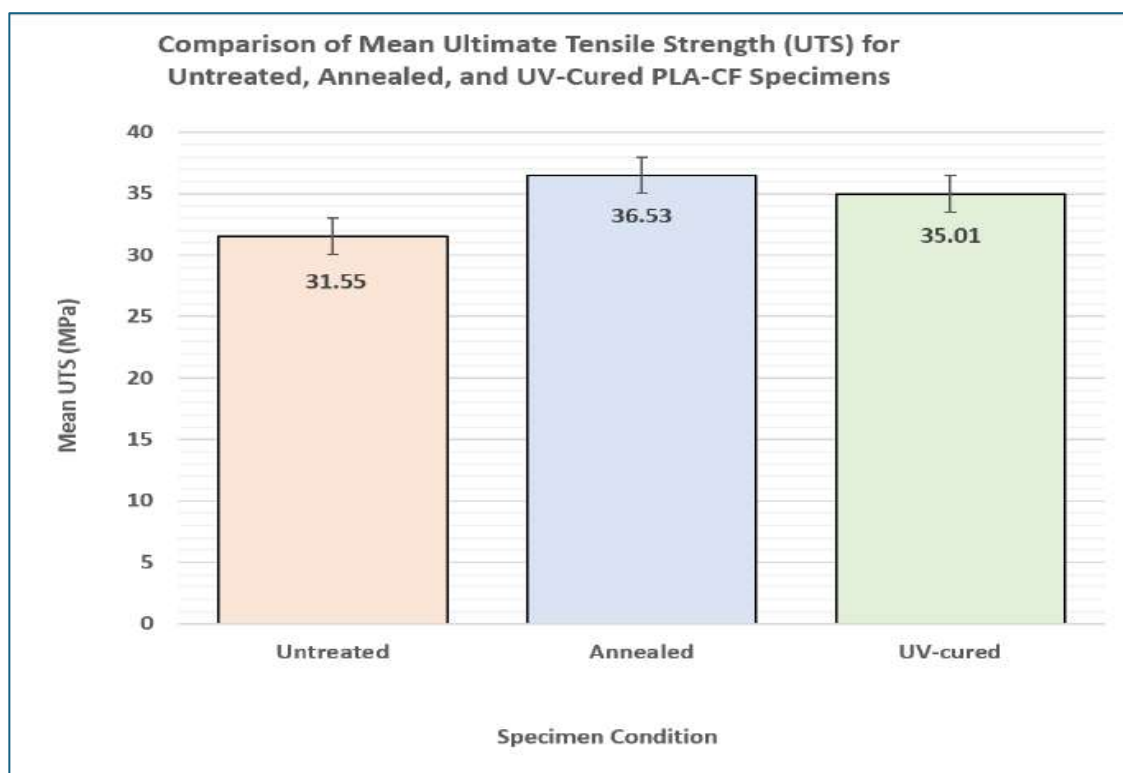


Figure 5. Mean UTS of untreated, best-annealed (120 °C, 60 min), and best-UV-cured (40 min, 8 cm) PLA-CF specimens

Table 8 compares the best-performing condition observed within each post-processing design with the untreated baseline. Annealing at 120 °C for 60 min increased UTS by 15.78%, while UV treatment at 40 min and 8 cm produced an improvement of 10.97%. The mean UTS of the annealed specimens was 1.52 MPa, or 4.35%, higher than that of the UV-treated specimens. Although annealing produced a numerically higher mean UTS and lower variability, the small number of replicates resulted in substantial statistical uncertainty. Therefore, the present results indicate that annealing was numerically more effective and more consistent, but they do not establish its definitive statistical superiority over the best UV-treatment condition. An independent confirmation experiment with a larger sample size is required

Table 8. Best-performing condition from each post-processing route compared with the untreated baseline

Condition	Selected setting	Mean UTS (MPa)	Improvement vs. untreated
Untreated Baseline	As-printed	31.55 ± 2.43	Reference
Best-performing annealed	120 °C, 60 min	36.53 ± 0.68	15.78%
Best-performing UV-treated	40 min, 8 cm distance	35.01 ± 1.50	10.97%

Interpretation of Tensile Strength Responses

Influence of Post-Processing Parameters on Tensile Performance

The results demonstrated that both annealing and UV treatment improved the tensile performance of FDM-printed PLA-CF specimens compared with the untreated condition. However, the magnitude and statistical behaviour of the improvements differed between the two post-processing routes. The untreated specimens exhibited a mean UTS of 31.55 ± 2.43 MPa, while the highest UTS values achieved through annealing and UV treatment were 36.53 MPa and 35.01 MPa, respectively.

For the annealing DOE, tensile strength generally increased with increasing annealing temperature. The mean UTS increased from 32.27 MPa at 80 °C to 35.62 MPa at 120 °C, and ANOVA identified temperature as the only statistically significant factor affecting tensile strength. Similar improvements in tensile properties following annealing have been reported for FDM-printed PLA and fibre-reinforced thermoplastic composites, where temperature was found to be a critical parameter influencing mechanical performance (Bhandari et al., 2019; Shbanah et al., 2023). Within the investigated range, the present findings indicate that annealing temperature had a greater influence on tensile strength than holding time, suggesting that the strengthening effect was primarily associated with the level of thermal treatment applied.

In contrast, the UV treatment results exhibited a less consistent response across the experimental domain. The highest UTS was obtained at an exposure time of 40 min and a lamp distance of 8 cm, whereas the lowest value was recorded at the same exposure time but with a lamp distance of 12 cm. ANOVA further revealed that lamp distance and the interaction between lamp distance and exposure time significantly affected UTS, while exposure time alone was not significant. These findings indicate that the effectiveness of UV treatment depended on the combined selection of process parameters rather than on a single factor acting independently. Similar observations have been reported by (Akderya, 2023) who showed that the mechanical response of UV-treated FDM polymers can vary considerably depending on irradiation conditions.

Although both treatments improved tensile strength, their response patterns were noticeably different. Annealing produced a relatively consistent increase in tensile strength with increasing temperature, whereas UV treatment showed greater sensitivity to parameter combinations. The tensile response to annealing was considerably easier to predict than the response to UV treatment.

Response Behaviour of Annealing and UV Treatment Processes

A comparison of the two DOE studies revealed clear differences in how annealing and UV treatment influenced the tensile behaviour of PLA-CF. Annealing produced the larger observed improvement, with a 15.78% increase at 120 °C for 60 min compared with a 10.97% increase for UV treatment at 40 min and 8 cm. However, the direct replicate-level comparison showed that the 1.52 MPa difference between these best-performing conditions was not statistically significant. The most defensible interpretation is therefore that annealing produced a numerically higher and more predictable tensile response within the investigated ranges, rather than that annealing was conclusively superior to UV treatment.

The statistical analyses further revealed differences in process sensitivity. For the annealing experiments, temperature was the only significant factor affecting tensile strength, while holding time and the temperature-time interaction were not statistically significant. This outcome indicates that tensile performance was governed primarily by temperature within the investigated parameter range. Previous investigations on annealed PLA and fibre-reinforced FDM composites have reported comparable tensile-property improvements, with temperature identified as the dominant parameter affecting mechanical properties (Bhandari et al., 2019; Seok et al., 2023). Furthermore, the relatively parallel trends observed in the interaction plot suggest that the influence of holding time remained reasonably consistent across the different temperature levels.

In contrast, the UV treatment DOE exhibited a significant interaction between exposure time and lamp distance. The interaction plot showed notable variations in tensile response among different parameter combinations, indicating that the effect of one factor depended strongly on the level of the other factor. As a result, similar exposure durations produced different tensile-strength values when different lamp distances were applied. Comparable behaviour has been reported in previous studies investigating UV-treated polymer materials, where mechanical performance was found to be highly dependent on irradiation conditions and treatment parameters (Pandžić et al., 2023).

A notable difference between the two post-processing routes was the consistency of the tensile-strength response. The annealing results showed a clearer strengthening trend throughout the experimental domain, whereas the UV treatment results exhibited greater variation between treatment conditions. This behaviour is

reflected in the significant interaction effect observed for UV treatment and indicates a narrower optimum processing window compared with annealing. Consequently, annealing offered a more predictable route for improving tensile strength within the investigated parameter range.

Based on the observed mean values and DOE response patterns, thermal annealing represents the more promising route for further optimization. It produced the highest observed UTS and a clearer factor–response relationship. Nevertheless, the direct statistical comparison did not establish a significant difference between the best-performing annealing and UV conditions. Therefore, further confirmation using a larger number of independently printed specimens is required before selecting annealing as the definitively superior treatment.

From an industrial perspective, annealing and UV treatment present different processing advantages and limitations. Annealing can modify the full cross-section of a printed component and may therefore provide a more effective route for improving bulk load transfer and interlayer bonding. However, its practical implementation requires control of treatment time, energy consumption, shrinkage, warpage, and dimensional tolerances. In contrast, UV treatment is relatively simple to implement and may permit selective surface treatment. Nevertheless, it is a line-of-sight process and is sensitive to lamp distance, component geometry, shadowing, lamp ageing, and dose uniformity. These processing trade-offs must be considered before either treatment is adopted for geometrically complex or load-bearing PLA-CF components.

DOE-Based Optimization of Post-Processing Parameters

The application of full-factorial DOE provided a systematic approach for evaluating the effects of post-processing parameters on the tensile strength of FDM-printed PLA-CF specimens. Unlike a one-factor-at-a-time experimental approach, DOE enabled the simultaneous assessment of main effects and interaction effects, thereby providing a more comprehensive understanding of the relationships between process parameters and tensile performance. Similar advantages of DOE in identifying influential factors and optimizing process conditions have been reported for additive manufacturing applications and polymer-processing studies (Gao et al., 2022).

For the annealing experiments, the DOE results demonstrated that temperature was the most influential factor affecting tensile strength, whereas holding time did not significantly influence the response within the investigated range. This finding is important from an optimization perspective because it indicates that achieving an appropriate annealing temperature is more critical than extending treatment duration. Consequently, process optimization efforts may focus primarily on temperature selection, potentially reducing unnecessary processing time while maintaining improved mechanical performance. The optimum condition of 120 °C and 60 min produced the highest UTS of 36.53 MPa, representing a 15.78% improvement relative to the untreated specimens.

In contrast, the UV treatment DOE demonstrated a more complex response behaviour due to the significant interaction between exposure time and lamp distance. The interaction effect indicates that the influence of one factor depends on the level of the other factor, making optimization based on individual factors less reliable. This behaviour was evident from the interaction plot, where the response trends varied considerably across different combinations of exposure time and lamp distance. Consequently, the optimum UV treatment condition could only be identified through simultaneous evaluation of both parameters. Under the investigated conditions, the highest UTS of 35.01 MPa was achieved at 40 min exposure and an 8 cm lamp distance, corresponding to a 10.97% improvement over the untreated condition.

The outcomes of the two DOE analyses also highlight differences in process controllability. The annealing process exhibited a factor-dominated response, characterized by a clear increase in tensile strength with increasing temperature. In contrast, UV treatment exhibited an interaction-dominated response, where tensile performance was more sensitive to parameter combinations. From an optimization standpoint, the annealing process therefore presents a broader and more predictable processing window, whereas UV treatment requires more careful parameter selection to achieve consistent improvements in tensile strength.

The DOE methodology proved effective in identifying significant processing factors, establishing optimum treatment conditions, and distinguishing the response characteristics of the two post-processing routes. The findings demonstrate the value of statistical experimental design as a practical tool for optimizing post-processing conditions and improving the mechanical performance of FDM-printed PLA-CF composites.

Macroscopic Failure Characteristics

Macro-scale examination of the fractured specimens revealed that failure consistently occurred within the gauge section for all testing conditions (Figure 6), indicating that the tensile tests were successfully conducted in accordance with ASTM D638 requirements and that the measured tensile strengths were representative of the material response rather than grip-induced failure.

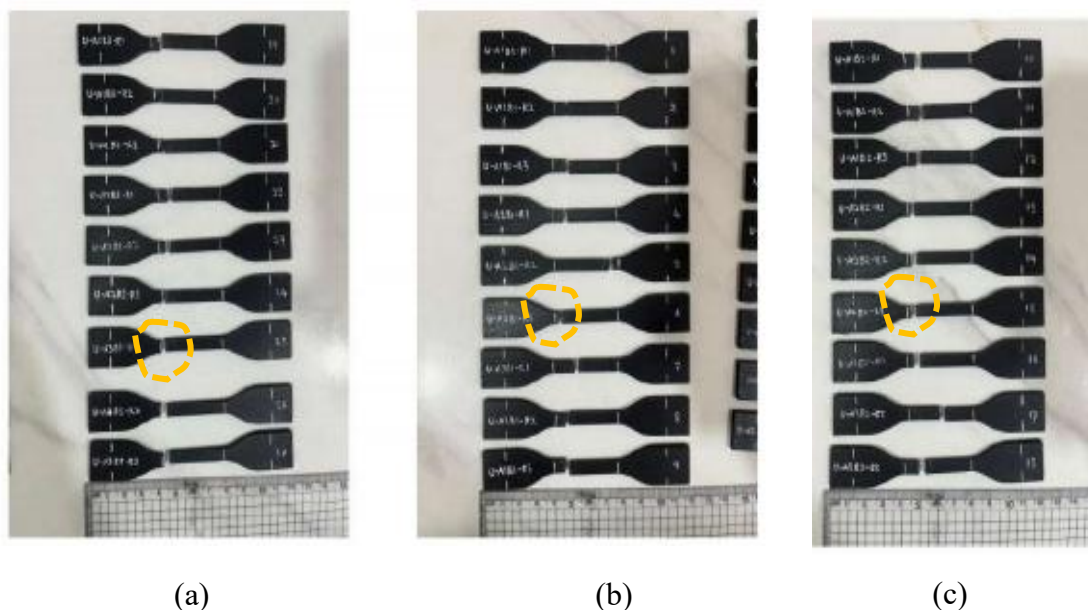


Figure 6. Representative annealed PLA-CF specimens after tensile testing, grouped by annealing temperature: (a) 80 °C, (b) 100 °C, (c) 120 °C. Fracture occurred within the gauge section in all groups.

The untreated specimens exhibited a mean UTS of 31.55 ± 2.43 MPa and served as the baseline condition for comparison. Following post-processing, both annealed and UV-treated specimens generally maintained the same failure location, with no visible evidence of premature fracture outside the gauge region. This observation suggests that neither post-processing method adversely affected the validity of the tensile testing procedure. Fracture-surface observations further suggested improved interlayer adhesion and reduced void-related defects in the treated specimen's layers (Bahrami et al., 2024), particularly after annealing, where thermal relaxation and molecular diffusion may have promoted stronger bonding between adjacent layers.

For the annealed specimens, fracture surfaces appeared relatively uniform across all treatment conditions, particularly at higher annealing temperatures. Furthermore, the specimens annealed at 120 °C exhibited the highest tensile-strength values recorded in the study, reaching 36.53 MPa. Although the present work did not include detailed microstructural characterization, the increased tensile strength combined with the consistent fracture behaviour suggests that annealing did not introduce observable macroscopic defects that would compromise tensile performance. Previous studies reported (Bhandari et al., 2019; Seok et al., 2023). Similar improvements in the tensile properties of annealed FDM-produced PLA and fibre-reinforced composites.

The UV-treated specimens also failed within the gauge section and generally exhibited tensile strengths higher than the untreated condition. However, a larger variation in tensile performance was observed among the UV treatment parameter combinations compared with the annealing treatments. This observation is consistent with the statistically significant interaction between exposure time and lamp distance identified by ANOVA. The specimen treated at 40 min and 8 cm exhibited the highest UTS among the UV-cured groups

(35.01 MPa), whereas lower values were recorded for other parameter combinations. Similar sensitivity of mechanical performance to UV-processing conditions has been reported by (Pandžić et al., 2023).

The fracture observations support the tensile-test results obtained in this study. Both annealing and UV treatment improved the tensile performance of PLA-CF compared with the untreated condition, while maintaining consistent failure within the gauge section. Among the two post-processing methods, annealing produced the highest tensile-strength improvement and a more consistent response across the investigated parameter range. Further characterization using scanning electron microscopy (SEM) would be beneficial in future work to relate the observed tensile behaviour to fracture features and microstructural changes resulting from the different post-processing treatments.

CONCLUSION AND RECOMMENDATIONS

Thermal annealing and UV treatment were evaluated as post-processing strategies for improving the tensile performance of FDM-printed PLA-CF composites containing 10 wt.% short carbon fibre. Using two independent 3² full-factorial DOE analyses, the study demonstrated that both treatments enhanced tensile strength relative to the untreated condition. The highest UTS of 36.53 MPa was achieved through annealing at 120 °C for 60 min, corresponding to a 15.78% improvement over the baseline value of 31.55 ± 2.43 MPa. For UV treatment, the optimum condition was obtained at 40 min exposure and an 8 cm lamp distance, resulting in a UTS of 35.01 MPa and an improvement of 10.97%.

Statistical analysis revealed that annealing temperature significantly affected UTS, whereas the UV-treatment response was governed by lamp distance and its interaction with exposure time. Annealing produced the higher observed mean UTS and the more predictable response across the investigated processing range. Compared with UV treatment, annealing produced a greater strengthening effect and a more consistent response across the study. The findings confirm that post-processing is an effective approach for enhancing the mechanical performance of PLA-CF components fabricated by FDM, with thermal annealing representing the more effective strategy under the conditions examined in this study.

To build upon these findings and further advance the application of post-processed PLA-CF composites, future work should focus on:

Extended Characterization: Measuring additional mechanical properties, including elastic modulus, elongation at break, flexural strength, dynamic fatigue, and dimensional shrinkage post-treatment.

Advanced Microstructural Diagnostics: Utilizing Scanning Electron Microscopy (SEM) to inspect fracture surfaces, Differential Scanning Calorimetry (DSC) and X-ray Diffraction (XRD) to quantify crystallinity (χ_c), and micro-computed tomography (μ -CT) to map internal void distribution.

Material and Process Scope: Testing a broader range of carbon fiber loadings (e.g., 5 wt.%, 15 wt.%, and 20 wt.%) and investigating hybrid post-processing regimes combining thermal annealing and UV surface curing.

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