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EMPIRICAL EVALUATION OF POST TREATMENT EFFECT ON MECHANICAL AND SURFACE CHARACTERISTICS OF 3D FABRICATED FIBER REINFORCED POLYMER COMPOSITE

Material extrusion additive manufacuring (MEAM) is a universally adopted additive manufacturing (AM) process for fabricating custom-designed fiber-reinforced thermoplastic composite items; providing affordability, rapid production, and reduced material waste. However, the significant limitations are weaker mechanical performance and surface smoothness. This paper focuses on the optimization of different post-processing and thermal conditions to enhance tensile performance, hardness (shore D), and surface texture of carbon fiber-reinforced polylactic acid (CFPLA) objects. The novelty of this investigation is to systematically examine the effect of separate and combined post-processing treatment, applied in various cooling conditions and sequences, to evaluate their respective influence on overall performance including mechanical and surface attributes. The result demonstrates that different post-processing condition showed different effect on output responses, tensile strength, durometer hardness (Shore D), and roughness profile improved by 22%, 6.3%, and 90% in a corresponding sequence. The optimized condition for mechanical strength and surface quality is thermal processing after hot vapour surface modification with cooling inside the hot air oven, where tensile strength, hardness (shore D), and surface roughness were noted as 50.292 N/mm^2, 83, and 0.465 µm respectively, recorded a maximum tensile strength of 51.621 N/mm^2 for only heat treatment with oven cooling, while minimum surface roughness of 0.372 µm for only vapour treatment. Heat treatment enhanced mechanical strength, vapour exposure improved surface smoothness, while integrated post treatment enhanced both attributes. Post-fabrication state concurrently enhance all the output factors of end-stage products created by employing fused deposition modelling, thereby increasing the overall capabilities of the AM sector.

Keywords: Additive manufacturing; fiber reinforced polymer composites; post-processing; mechanical properties; surface roughness

1. Introduction

Additive manufacturing (AM) is a layer-based fabrication technology that allows the printing of intricately designed shapes component rapidly with economical material consumption [1]. Filament-based 3D printing is a highly preferred material extrusion (ME) strategy for fabricating different polymers and fiber-reinforced polymers [2]. This technology attracted attention across diverse fields such as automobile, electronics, biotechnology [3], medical [4], food, agricultural [5], aerospace, and aviation sectors [6]. ME process uses a CAD model to print 3D objects directly. This process invloves the extrusion of melted filament from the heated nozzle and deposit on a hot bed plate, plate moves down with a distance equal to layer thickness, and the additive layer fabrication strategy continues till the completion of the final item [7]. The main challenge with this technology is the lower mechanical characteristics and surface quality when evaluated against conventional manufacturing [8]. Another drawback is the presence of voids in the fabricated product [9]. The limitations can be resolved by performing post processing on the fabricated object. Various post processing techniques include chemical, thermal, and mechanical treatment. In thermal post processing, annealing was found to be the most influential technique in the enhancement of mechanical properties, crystallinity and reduction of voids and internal stresses [10-12]. Chemical treatment involves liquid chemical and hot vapour chemical treatment where vapour treatment was observed to be more substantial in enhancing the surface profile of the end product [13].

FFF fabricates inclusive array of printable polymers, namely polylactic acid (PLA), polycarbonate, polypropylene, polyether ether ketone (PEEK), polyamide, and acrylonitrile

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butadiene styrene (ABS). Within all the most frequently used filament is PLA due to its availability, low price, and trouble-free printing process [14]. PLA is commonly used in medical and Pharmacological units for its biocompatibility and biodegradability with exceptional environmental properties [15-17]. Also, mechanical characteristic of PLA ensures its suitability for functional applications in engineering [18]. Researchers determined that addition of carbon fiber (CF) to PLA contributes to enhanced performance which extends its applicability [19-21]. Studies of annealing and chemical exposure treatment by some researchers on structural performance and surface topology of neat PLA and carbon fiber-filled PLA are as follows: Radoslaw A. Wach et al. [22] noted that subjecting PLA samples to annealing for 70 minutes and 85°C resulted in 17% enhancement in flexural strength and an increase in crystallinity. Ali Ghasemkhani et al. [23] studied the annealing temperature effect over a two-hour period, and observed a notable improvement in tensile, impact, and flexural performance, crystallinity, and a reduction in porosity. N. Jayanth et al. [24] evaluated that thermal conditioning PLA at 120°C for 240 minutes caused a considerable 35.5% increase in tensile strength, minimizing voids and internally induced stresses, leading to improved tensile resistance throughout the material. Tomasz Kozior et al. [24] on the other hand, determined that annealing did not lead to a substantial advancement in the tensile performance of PLA objects but resulted in improved surface finish with a reduction in surface waviness. Behnam Akhoundi et al. [26] demonstrated that annealing treatment at 110°C for the time of 1 hour improves crystallinity, minimizes voids, and achieves a 9% improvement in tensile strength. Mhd Usama Alabd et al. [27] findings indicated that annealing at 110°C for 3 hour provided improved tensile strength. While, Pichai Janmanee et al. [28] identified 110°C for 1 hour and 30 minutes as optimal annealing condition.

Sridhar Rengisetty et al. [29] noticed that tensile and flexural strength were improved by annealing treatment, although the dimensions changes, the treated samples display higher thickness and smaller width and length of CFPLA items. Sunil Bhandari et al. [30] demonstrated that annealing PLA-CF at 90°C for 4 hours yields best tensile strength. Relative to untreated specimens, this process increased the strength under tension for carbon fiber-infused PLA and PETG to three and two times respectively. Further enhance modulus of elasticity and ductility. P. Arjun et al. [31] noticed that annealing of CFPLA specimens at 95°C for period of 120 minutes reduces internal stresses and improves tensile strength by 14%. Ribin Varghese Pazhamannil et al. [19] highlighted similar trends, revealing that CF-reinforced components had a 23% elevated tensile strength over unreinforced PLA, indicating increased crystallinity and inter layer bonding. K.K. Guduru et al. [32] performed post heat treatment in muffle furnace and liquid acetone treatment. In chemical treatment, specimens were immersed in chemical for different durations. The results indicated that post heat treatment at 120°C for 120 seconds and solvent exposure using acetone for the same time led to a 6% and 12% increase in the tensile strength of CFPLA, respectively. Marcus Ivey et al. [33] recorded a significant 30% rise in degree of crystallinity level, with the optimal tensile performance peaking at 115°C during annealing for CFPLA. Chuncheng Yang et al. [34] determined that different heat treatment approaches can induce considerable variation in material crystallinity and tensile behavior of AM PEEK specimens. Previous investigations have focused on the chemical vapour treatment of PLA Polymer. Fulvio Lavechia et al. [35] analyzed the impact of vapour treatment of ethyl acetate with varying liquid volume and exposure time. The result demonstrated that 5ml for 360 seconds yield high surface finish. Ana P. Valerga et al. [36] noticed that surface roughness reduced by 97% when treated with chloroform chemical. Vifan Jin et al. [37] observed 88% enhancement in surface finish when exposed for 300 seconds to dichloromethane vapour. Vifan Jin et al. [38] on the other investigation reported 83% reduction in tensile strength while surface finish and fracture toughness improved. Through the optimization of chloroform vapor treatment parameters, Bin Li et al. [39] determined that a 2-minute exposure to 22 ml of liquid with a 35% concentration enhanced the surface finish. Subham Sekhar et al. [40] noted that the surface roughness obtained from vapour chemical treatment is less when compared with the liquid chemical treatment, highest surface finish achieved with dichloromethane vapour exposure. Antonio Coppola et al. [41] demonstrated that the application of acetone vapour contributed to refined surface texture, highlighting its effectiveness as a post-processing technique. Alviar et al. [42] identifies vapour smoothening as an impactful approach for the surface smoothness. The reviewed literature is summarized in a schematic diagram, as presented in Fig. 1.

Research conducted earlier indicates that post treatment of objects significantly enhances the mechanical behavior and surface integrity, irrespective of the type of the filament material. Thermal treatment and chemical hot vapour exposure techniques are effective in improving mechanical properties and surface finish respectively. However, there remains a significant gap in earlier investigations concerning the influence of post-processing and integrated post-processing techniques, in different sequences and cooling conditions, on both mechanical properties and surface smoothness. Several research efforts focused on how individual post-processing influences particular output properties. Specifically, the effect of annealing on tensile properties and vapour treatment on surface texture, independent of the cooling conditions after thermal processing. This study is novel in that it systematically investigates the influence of distinct integrated and separate post-fabrication exposures under varied cooling modes and sequences, to evaluate their respective impacts on both mechanical and surface characteristics. The focus of this research is to optimize post-processing condition while considering various cooling conditions to produce high performance components. To acquire parts exhibiting greater mechanical strength and part quality, the various post-processing conditions considered include vapour treatment, annealing, annealing followed by vapor treatment, and vapor treatment followed by annealing, with cooling conducted both inside and outside a hot air oven to ambient temperature. The outcomes of this study will

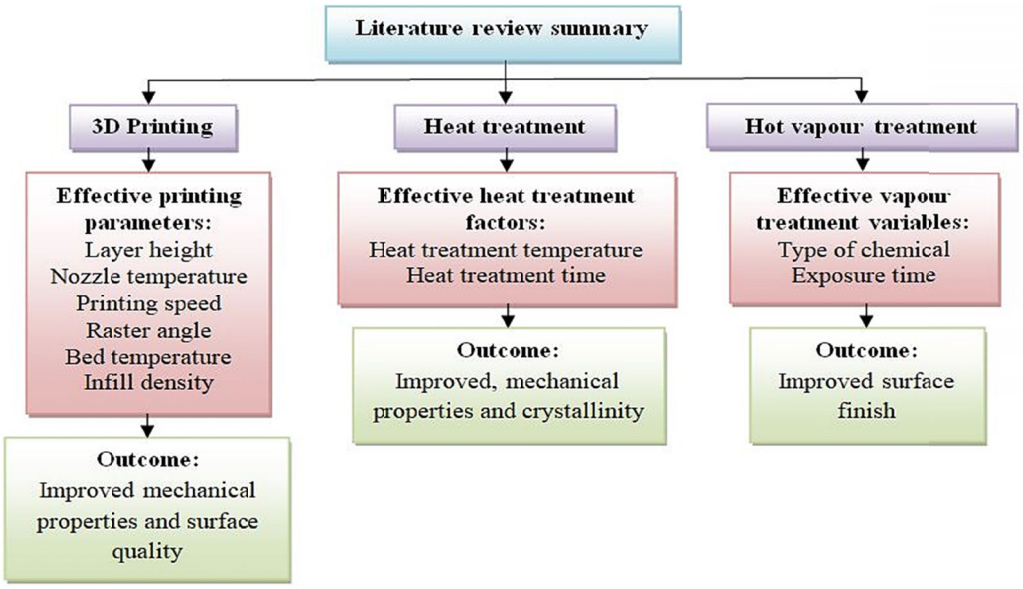


Fig. 1. Schematic diagram of literature review

significantly enhance the growing body of work conducted in this discipline, offering crucial actionable insights for design teams and industry leaders to guide their decision-making process.

2. Material and methodology

In the current study, the 1.75 mm diameter filament containing 85% PLA and 15% carbon fiber was provided by Enlight3d. To improve performance under mechanical stress 15% of reinforcement through short carbon fiber inclusion with PLA [19,20]. The items were fabricated on IEMAI3D MAGIC-HT-M 3D printer. This fused deposition modeling machine can print a wide range of fiber-reinforced polymers. The dimensions of the build plate were 280×250×300 mm with a maximum heat level of the extrusion nozzle 300°C. The CAD model of the ASTM D638 type IV tensile test specimen was developed through the Solid Works design tool and then exported in standard tessellation language (STL) format. The slicing software utilized. Before printing, calibration was done by adjusting the distance between nozzle outlet and the substrate of bed plate, along with leveling of the bed plate. The material is then introduced into the thermal chamber through rollers, where it is heated to a defined temperature and subsequently extruded out of the nozzle. The extruded material is deposited onto the bed plate with a specified layer thickness. This process of fabricating in a layer-by-layer fashion continues until the final object is fully printed. The various constant parameter settings are presented in TABLE 1 [43]. A detail methodology is shown in Fig 2.

TABLE 1

List of process parameters and their respective values

Printing parameters	Specifications
Printing temperature	225°C
Layer thickness	0.18 mm
Print speed	55 mm/s
Build plate temperature	70°C
Raster width	0.5 mm
Raster direction	0°
Infill percentage	100%
Build direction	0, XY-plane (flat)
Extruder nozzle size	0.4 mm
Material used for the nozzle	Brass
Environment temperature	24°C

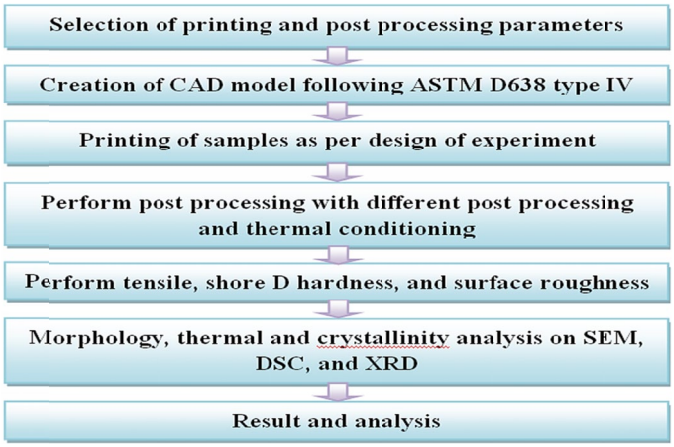


Fig. 2. Methodology flow chart

2.1. Post processing

In the post fabrication, two different Post-fabrication procedures comprising chemical vapor application and heat-based treatment were performed as per the experimental design. In hot vapour chemical application, the equipment required is a hot plate, 2000 ml beaker, liquid measuring jar, thermometer, chemical liquid, and holding stand. The treatment was

performed in the Nanotechnology laboratory in the Department of Nanotechnology, JNTU Hyderabad. The chemicals, with a 100% concentration, were bought from the U.V.SCIENTIFICS and were stored in a glass container with a secure seal. In this technique, a measuring jar was used to measure 50 ml of ethyl acetate, which was then transferred into a beaker with a 2000 ml capacity. The beaker had enough space to allow the object to be placed flat and horizontally inside. The liquid chemical-filled beaker was positioned on a temperature-controlled heating plate and heated until it reached its boiling point after which the temperature was set and exposure continued for the required duration. The stirrer was adjusted to a speed of zero RPM. and the reading of temperature was monitored using a thermometer. The specimen was then exposed to hot vapour for 50 seconds. The constant gap was maintained between part and liquid for all the specimens. After 40 seconds the object was removed from the vessel, which had been tightly covered from the top, and allowed to remove residual moisture. Hot air oven was utilized to perform thermal annealing in nanotechnology laboratory, JNTUH. A hot air oven was manufactured by DWARAKA Scientifics. The hot air oven operated across a temperature interval of 50°C-350°C. The annealing temperature must be set higher than the T_g value and lower than melting temperature. In this experiment, the components were heated to 95°C for 2 hours and submerged in solution of salt to ensure the work piece remained undistorted. The 48-hour duration was maintained between the two treatments.

2.2. Design of experiment

According to the findings from the previous study, the post processing factors selected for vapour and thermal treatments are ethyl acetate chemical, 40 seconds vapour exposure period, 95°C thermal annealing point, 120 minutes annealing time, 50 ml chemical, and 100% solution concentration, 24°C ambient temperature [44]. The design of the experiment with multiple surface treatment and cooling approaches is presented in TABLE 2. The pre- and post-processing experimental factors were selected based on the findings of the literature review and preliminary experimental trials, with the target of attaining optimal mechanical and surface attributes. The Printing variables, including heating temperature, print velocity, layer size, and raster direction, were selected based on the values reported in earlier findings to ensure stronger interlayer adhesion and fewer voids. Lower layer size improves mechanical characteristics and enhances surface attributes. A 0° raster angle facilitates higher tensile load resistance. Moderate nozzle temperature permits adequate material flow and stronger interfacial bonding without thermal degradation. Intermediate printing speed prevents fiber pullout and weaker bonding. Maximum infill percentage enhances structural integrity and strength [43]. Likewise, post-fabrication variables, including chemical solvent type, vapour exposure period, annealing temperature, and duration, were chosen according to their impact on mechanical strength and surface smoothness. Intermediate heating temperature with higher duration improves crystallinity and mechanical strength without degradation of properties, while higher exposure type enhances surface texture with more enclosure of surface irregularities and defects. All of these pre- and post-fabrication variables made sure that these factors are both practically attainable and scientifically validated for improving the overall performance of the CFPLA workpiece [44].

TABLE 2

Different post-processing and cooling conditions

Experiment Number	Post-processing procedure	Cooling method
1	Vapour treatment	—
2	Heat treatment before vapour treatment	Inside oven
3	Heat treatment before vapour treatment	Left outside the heated oven, at ambient temperature condition
4	Heat treatment	Left outside the heated oven, at ambient temperature
5	Heat treatment	Inside oven
6	Vapour treatment before heat treatment	Left outside the heated oven, at ambient temperature
7	Vapour treatment before heat treatment	Inside oven

2.3. Testing

The Tensile strength was evaluated adhere to ASTM D638 type IV guidlines on computer controlled numerical testing machine. The equipment is capable of handling a load of 100 KN. The movement rate was 5 mm/minute. The printed tensile test components before and after testing are shown in Fig. 3. Shore D hardness numbers were recorded on the shore D scale utilizing shore D digital hardness measurement device. ASTM D220 standards were followed for the test. The durometer will determine hardness in the range of 0 to 100 HD. The other

Fig. 3. Tensile test samples before and after testing

specification of the tester includes 0-0.25 mm indenter depth, resolution of 0.5 HD, and 0.45 N pressure. In this process, an object is positioned on a flat platform and the needle applies downward force. The degree of surface irregularity of post processed work pieces was obtained using a Mututiyo SJ-210 surface roughness tester. The values were noted on three different surfaces and average was taken.

2.4. Morphology analysis

Surface morphology study was under taken on HITACHI S-3700N SEM. Upon completion of the tensile test, the fractured surface was examined and imaged with a machine.

2.5. Differential scanning calorimeter (DSC)

The Thermal characteristics of the CFPLA test specimen were studied utilizing a DSC-60 at Osmania University, India. The temperature range and the rate of heating during the test were 20-400°C and 10°C/min respectively. A portion of the specimen, consisting of a few inner layers, was collected from the cross-sectional part. T_g and Tm values were obtained from the DSC measurements.

2.6. X-Ray diffraction (XRD)

The diffraction peak curve of the tested items was obtained using an advanced X-ray diffraction machine (BRUKER AXS / D8 FOCUS). Crystallinity characteristics were analyzed using intensity counts obtained from 3 to 80° scanning range.

3. Results and discussion

The following section presents in detail analysis of the influence of different post processing and cooling conditions on tensile strength, hardness on the Shore D scale, and surface irregularities of the 3D fabricated components. TABLE 3 presents the result obtained for the considered output factors

TABLE 3

Results of output factors

Experiment number	Tensile strength (N/mm^2) ± deviation	Shore D hardness ± deviation	Surface roughness (μm) ± deviation
1	40.083 ± 0.3	77 ± 1	0.372 ± 0.012
2	44.452 ± 0.25	79 ± 1	0.493 ± 0.019
3	42.710 ± 0.32	78 ± 1	0.581 ± 0.017
4	49.177 ± 0.41	82 ± 1	1.625 ± 0.021
5	51.621 ± 0.37	84 ± 1	1.266 ± 0.015
6	47.959 ± 0.29	81 ± 1	0.561 ± 0.011
7	50.292 ± 0.22	83 ± 1	0.465 ± 0.012

3.1. Tensile strength

The findings reveal that 51.621 N/mm^2 is the maximum tensile strength achieved for experiment number 5. The optimum post processing and cooling condition to acquire this strength is post-heat treatment with cooling of the post-processed components inside the hot air oven to 24°C. The primary factor behind the tensile properties improvement is the corresponding increase in crystallinity. The crystalline structure of the polymer enhance as the polymer chains reorganize when raised to a heat level between the glass transition and point of phase transition to liquid. Conversely, the heat treatment fails to affect the crystallinity of carbon fiber but the bond between the fiber and polymer improves by enhanced Interfacial adhesion and molecular alignment of molecular chain within the matrix. The hot vapour chemical treatment on the printed specimen gives lower tensile strength among all the post-treated experiments. The chemical treatment weakens the interaction between the polymer matrix and carbon fiber and reduces adhesion strength. When samples are exposed to polar vapour solvent the reduction in adhesion strength is caused by the changes in the surface characteristics of the carbon fiber and the breakdown of the polymer chain. The poor interaction bonding between fiber and polymer reduces the resistance of the material to stretching stresses and weakens its overall tensile strength.

It is also noticed from the post processing condition of vapour treatment after heat treatment that the tensile characteristics reduce compare to that of subsequent heat treatment following vapour exposure. It is also clear from the experiment that the loss in the tensile properties by the vapour exposure is regained further by thermal treatment, while the gain in strength after heat treatment will reduce upon vapour deposition. With little literature on integrated post processing treatment on CFPLA, in comparison to untreated samples annealing after vapour deposition enhances the tensile strength but the enhancement is less when compared to single post processing thermal treatment [44]. The present study supports the previous research that annealing enhances tensile strength. However, the researchers did not state other properties like surface finish [19,31]. With this study, it is stated that the enhancement of thermal treatment is limited to tensile strength whereas with integrated post processing of thermal treatment following vapour treatment, there is the enhancement of tensile strength and surface finish.

It is observed for all the post processed specimens that the samples cooled inside the hot air oven have more tensile strength than that of the objects cooled outside the hot air oven. The gradual cooling in the hot air oven allows more controlled cooling that helps to avoid internal stresses and further promotes the development of superior crystallinity that produces products with high tensile strength. Controlled slow cooling within the oven facilitates controlled crystallization of the matrix, enabling the polymer chains to reorganize into more ordered structures before solidification. Conversely, rapid air cooling tends to lock the amorphous structure, resulting in elevated residual stresses and lower mechanical consistency. Additionally, in the long term,

the increased crystalline phase contributes to greater thermal stability, reduced warpage, and maintains dimensional integrity during severe conditions. These performance merits are vital for aerospace structural components, including unmanned aerial vehicles' frames, mechanical housing, and support brackets, which demand consistent load-bearing capability under varying operational stresses. The crystalline rich structure is gained by thermal treatment. The tensile strength improved by 22% after heat treatment when compared to the untreated item.

From Fig. 4, it is observed that Different post-processing conditions resulted in different tensile strength values; the sequence starting with the operation achieves the highest tensile strength is as follows: Thermal heat treatment with cooling inside a hot air oven, thermal heat treatment following vapour exposure with cool-down phase in a heated air oven, thermal treatment with temperature reduction outside hot air oven, thermal heat treatment after vapour treatment with air over oven cooling, subsequent vapour deposition following heat treatment with air-cooling process in a hot air oven, thermal treatment following vapour treatment with air-based cooling outside heated oven, and vapour exposure treatment.

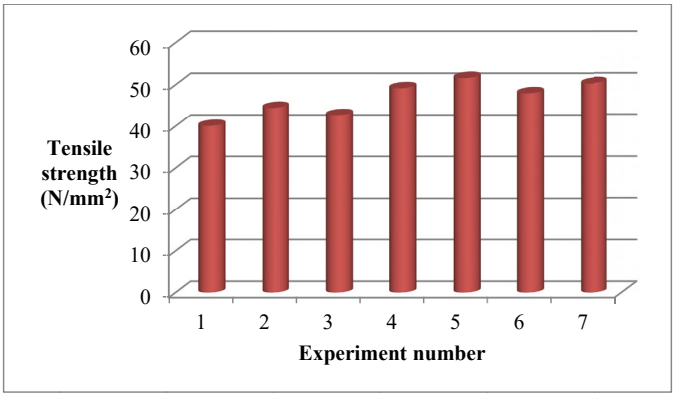


Fig. 4. Comparison of tensile strength against different experiments

The stress versus strain graph displayed in Fig. 5 reveals that among all the post-fabrication treatments, the more ductile characteristics were observed in vapour exposure treatment, followed by heat exposure, then vapour before heat, and heat before vapour treatment. The crystalline structure after vapour deposition remains nearly unchanged as the deposition of vapour

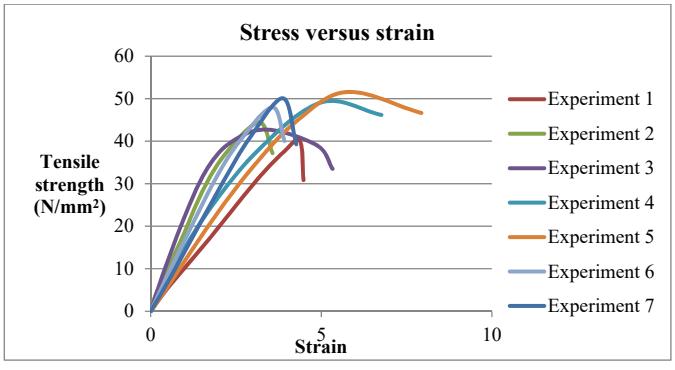


Fig. 5. Stress versus strain graph for tensile strength

closes microcracks, layer lines, and small notches on the surface, which leads to little variation in ductility. The improvement in the crystallinity after the post-heat exposure reduces chain mobility throughout the material, which results in more brittle behavior despite high load resistance. When compared to either treatment alone, the highest brittle characteristics were recorded for integrated post-treatment.

3.2. Shore D hardness

The outcome of the experimentation illustrates that thermo treatment of the CFPLA specimens with a reduction of temperature of a thermal treated object within a hot air oven produced a high hardness of 84. This treatment improved hardness by 6.3% when compared with samples that remain untreated. Parallel findings were recorded for hardness and tensile strength. Heat treatment improves crystallinity, polymer chain alignment, adhesion between matrix and fiber, and ductility, and reduces internal stresses that result in a high hardness samples. Hardness values are more for the items treated with reduction of temperature inside the hot air oven when compared to that of rapid cooling outside the heated oven. Fig. 6 reveals that shore D hardness values differed under various post-processing conditions, and the sequence that starts with the operation that produced the highest hardness is as follows: Thermal heat treatment with the air-cooling process in a heated air chamber, thermo treatment after vapour exposure with temperature reduction in a heated air chamber, thermal treatment with air over oven cooling, thermal heat treatment following vapour exposure treatment with air-based cooling outside a heated oven, subsequent vapour deposition following heat treatment with cooling inside hot air oven, vapour exposure following thermal treatment with cool-down phase in an outside heated air oven, and vapour treatment.

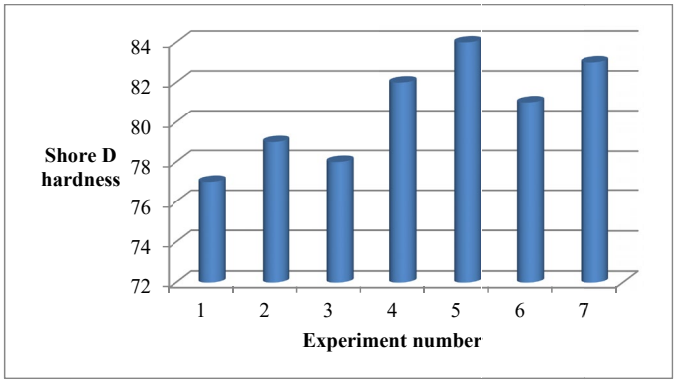


Fig. 6. Comparison of shore D hardness against different experiments

3.3. Surface roughness

The result indicates that the lower surface irregularities of 0.372 μm value is recorded for experiment number 1. The optimum post treatment condition for a higher surface finish is

vapour exposure operation. A 90% enhancement in the surface finish of the CFPLA object was noted when treated with hot vapour. The reaction with ethyl acetate vapor leads to a minor melting of the object and slightly softens the exterior layer helping to smooth out small voids, flaws, surface irregularities, and reduce the layer lines visible on the surface. The samples cooled inside the hot air oven show a better surface finish when compared to sudden cooling outside in ambient conditions. Rapid cooling may cause the exterior of the CFPLA item to contract faster than the inner layers, leading to uneven shrinkage and surface flaws like warping, cracks, and surface protrusions. The result of heat treatment is less impactful on surface characteristics.

The findings of this study support those of earlier studies that Influence of vapor-phase processing on PLA samples improves the microscale surface structure [35-37]. However, those studies focus more on surface topography and less on mechanical behavior. Little literature found on the alterations in strength and surface morphology due to vapor conditioning of CFPLA samples. This study demonstrates that the surface finish improves by vapour treatment, while it has a negative consequence for mechanical response, the little drop in tensile performance and hardness was primarily due to localized surface melting and lowered interfacial bonding. For applications where surface appearance and aesthetic appeal are of greater importance, such as prosthetic shells, biomedical implants, and ergonomic structures, a minor reduction in the strength is acceptable, as these elements are not subjected to higher mechanical loads.

When compared to alternative post-fabrication strategies like laser polishing, the enhancement in the surface merits acquired in this investigation is comparable. For instance, prior research on Al/PLA composites recorded surface improvement of 91.5% and 86.6% following laser treatment [47,48], while this study obtained 90% enhancement. When considering mechanical performance, laser treatment enhances the tensile strength of Al/PLA by about 20%-25% [48,49]. There is a noticeable rise in dynamic mechanical characteristics after laser treatment [48]; however, the corresponding behavior needs to be studied for vapour and thermal treatment. Although there is a significant enhancement in surface finish and moderate enhancement in tensile attributes following laser polishing, rapid heating and cooling cycles during laser polishing at the localized region may induce thermal gradients, ultimately degrading the matrix materials and resulting in microcracks at the interface of fiber and polymer matrix. In contrast, the combined vapour and thermal treatment considered in this work facilitates a more balanced improvement of both surface and mechanical merits. However, heating at elevated temperatures and prolonged exposure to vapour may lead to dimensional distortion and thermal degradation. Furthermore, the integrated post-fabrication strategy is cost-effective, eco-efficient, and readily scalable, minimizing energy usage and equipment costs as it requires neither significant energy nor special equipment.

Fig. 7 demonstrates that the optimized post processing condition for both surface finish and tensile strength is vapour treatment before heat treatment and cooling inside the hot air oven. Each post processing condition demonstrates different results. The different post-treatment conditions, ordered from highest to lowest surface finish are as follows: Chemical hot vapour exposure, vapour deposition before heat treatment with cooling inside the hot air oven, thermo-treatment with temperature reduction inside the hot air oven before vapour exposure treatment, vapour treatment before thermal treatment with cool-down phase outside heated air oven, thermal heat treatment before vapour exposure treatment with air-based cooling outside heated oven, thermal heat treatment with air-cooling process in a hot air oven, thermal treatment with the air over oven cooling.

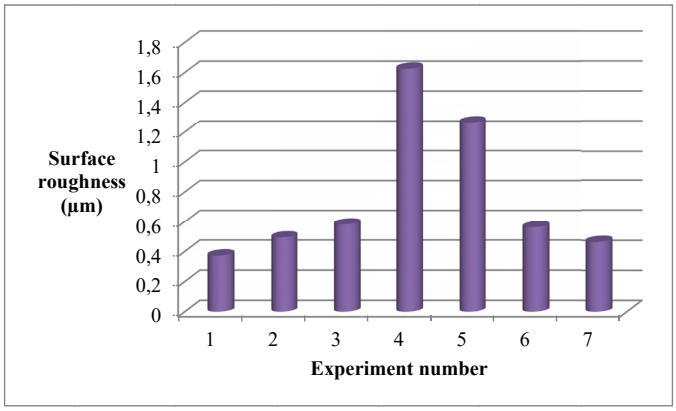
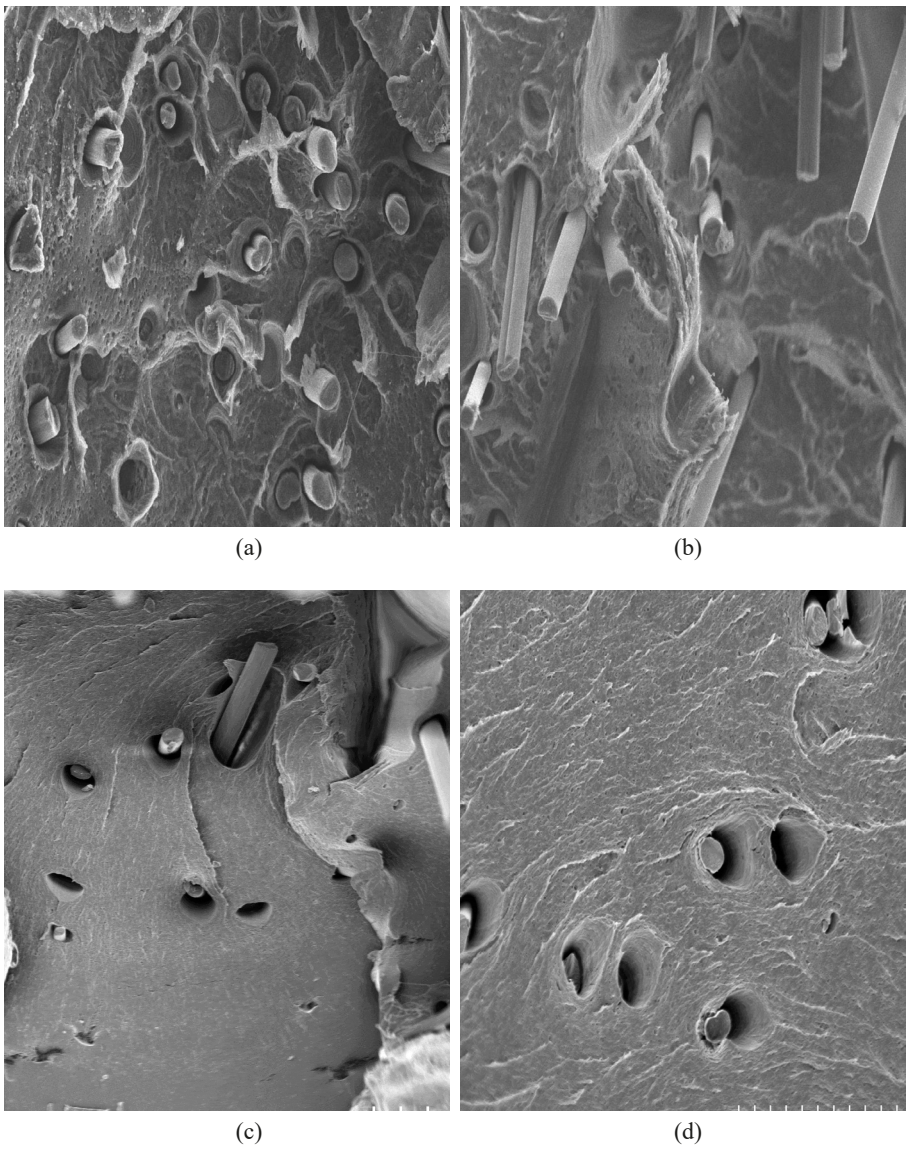


Fig. 7. Comparison of surface roughness against different experiments

3.4. SEM analysis

SEM was used to capture SEM images of tensile tested objects to analyze surface morphology. Images were captured for different post processed and untreated specimens with different magnifications. Fig. 8(a) shows that the higher tensile strength specimen was achieved after heat treatment, where a more compact structure was observed with more diffusion and interlayer bonding. The carbon fibers are well embedded within the PLA matrix, indicating an effective load transfer under tensile loading. Localized regions of high strain exhibited partial fiber pullout, attributed to interfacial debonding. However, the separations of fibers are minimal, demonstrating stronger bonding and interfacial adhesion between the PLA matrix and reinforcement to maintain efficient transfer of stress. SEM analysis further revealed no apparent deterioration of the fiber, confirming that the treatment conditions were not severe enough to degrade the reinforcement. The reinforcement mechanism attributed to the effective load transfer between the matrix and enhanced fiber, facilitated by the high stiffness and aspect ratio of carbon fiber. These fibers act as a resisting element that bridges microcracks and restricts their growth. Additionally, carbon fiber serves as an effective nucleating agent during PLA crystallization, facilitating crystal growth and enhancing the overall crystallinity, which further contributes to improved mechanical strength. Heat treatment improves the polymer chain alignment, tightens the polymer chain structure to seal fine voids, and strengthens



(a) (b)

(c) (d)

Fig. 8. SEM images of (a) untreated (b) vapour treated (c) heat treated with hot air oven cooling (d) heat treated after vapour treatment with coollng inside hot air oven

the inter-chain bonds. Figs. 8(a) and 8(b) shows tightly packed structures with fewer voids and higher inter diffusion bonding when compared to images of Figs. 8(c) and 8(d) where minor voids are more and specimen failure is largely due to ejection of fibers as a result of low interfacial interaction with the matrix material. Vapour treatment did not permit the material to softening and reorientation needed to fill the internal voids, a process that heat treatment allows for effectively. There is not much difference in the structure identified in the components after heat treatment and heat treatment after vapour treatment with cooling inside the hot air oven.

3.5. XRD analysis

After the DSC, the samples were analyzed through XRD. The diffraction pattern acquired by XRD is shown in Fig. 9. Diffraction patterns of crystallites are observed only in the heat treated sample, which contain a notable crystalline portion, while the untreated sample show only a wide amorphous halo with no distinct crystal peaks. Thus, the heat treatment enhances the crystallinity of the printed item. The highest diffraction peak of pattern of crystallites for post treated is observed at 16.756 with 3004.475 intensity counts, while for untreated samples it is observed at 16.859° with 600 intensity counts as shown in Figs. 10 and 11.

4. Conclusion

The present research explores the impact of various post processing and cooling condition on ultimate tensile strength, hardness measured on the Shore D scale, and surface topography were analyzed. The different post treatment and thermal condition considered were vapour treatment, heat treatment, vapour treatment before heat treatment, and vapour treatment

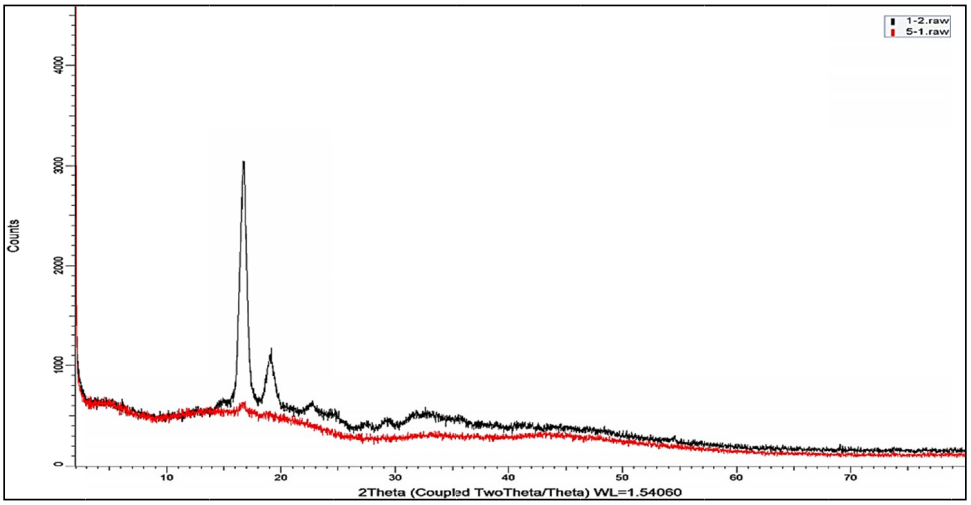


Fig. 9. X-Ray diffraction pattern for heat treated and untreated CFPLA samples

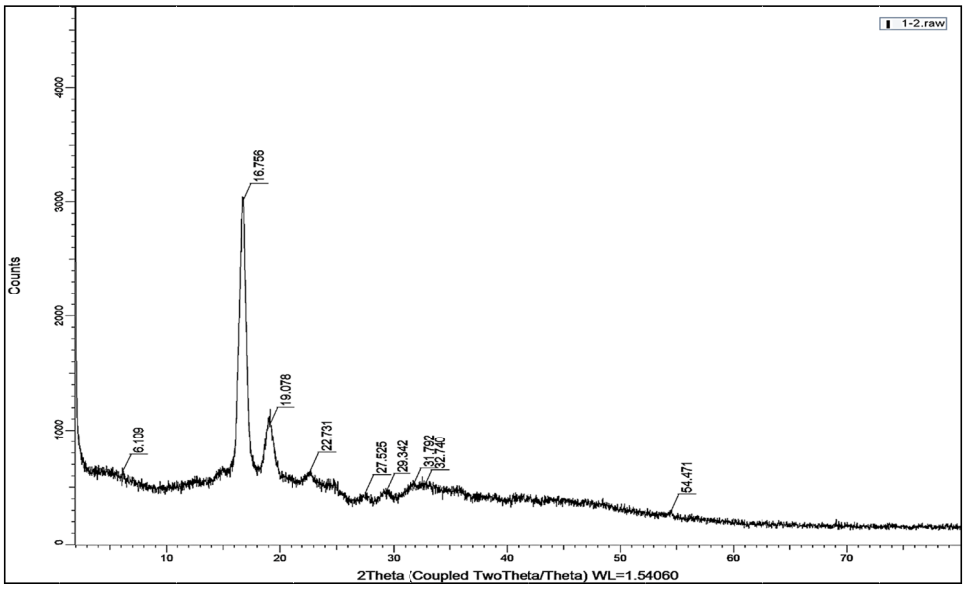


Fig. 10. X-Ray diffraction pattern for heat treated samples

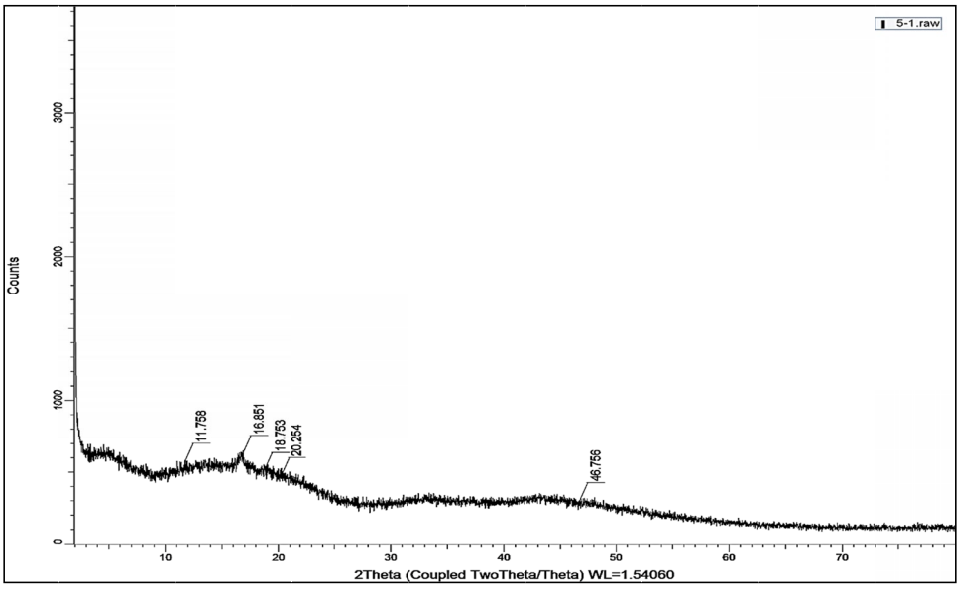


Fig. 11. X-Ray diffraction patterns for untreated samples

following thermal treatment with cooling both inside and outside the hot air oven after heat treatment. The study concludes that mechanical characteristics and surface finish are affected differently by different post-treatment conditions. The tensile performance, hardness and surface finish are enhanced by by 22%, 6.3%, and 90% respectively, yielding corresponding values of 50.292 N/mm^2, 83, and 0.465 µm. The optimum conditions for resistance to tensile forces, and hardness (Shore D) are heat treatment with air-cooling process in a heated air chamber with the corresponding values of 51.621 N/mm^2 and 83, while vapour treatment is an optimum post treatment technique for lower surface roughness of 0.372 µm. Heat treatment helps to improve the mechanical properties by improving the crystallinity and polymer matrix and fiber adhesion, while vapour treatment improves the surface finish by softening the surface and removing visible layer lines, surface irregularities, and voids. XRD analysis reveals that crystallinity improves with heat treatment. SEM analysis shows that heat-treated samples exhibit higher diffusion, stronger interlayer bonding, and fewer voids. Vapour treatment negatively impacted the tensile strength and hardness. The decrease in tensile strength due to vapour deposition can be restored through thermal treatment, but the tensile strength gain from heat treatment declines with subsequent vapour exposure. Reduction of temperature inside the hot air oven gives better mechanical properties and surface finish than rapid cooling as gradual cooling allows reducing induced internal stresses.

The optimum condition for both mechanical strength and surface quality is vapour treatment before heat treatment with cooling inside hot air oven. Properties lost in the vapor treatment process were regained with heat treatment. The findings of this study offer key insights that unlock greater potential for advancement in additive manufacturing industries. However, the study is limited to static mechanical and surface performance aspects. Dynamic performance merits like fatigue resistance, impact durability, and long-term environmental stability remain unexplored and recommended for future evaluation. Additionally, the findings of the current study are specific to CFPLA. Due to the variation of mechanical properties, the ideal configuration should not be transferable to other polymers without further experimentation and validation; future investigation should extend this optimization approach to other filaments to establish wider applicability. Additional studies are required to evaluate the impact of post-treatment on the geometrical deformation of the components. Furthermore, future studies may explore the alternative fiber type, fiber percentage, orientation, and distribution to expand the scope of fabricated items in the aerospace and medical sectors.

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