Enhanced Tensile Strength of Acrylonitrile Butadiene Styrene Composite Specimens Fabricated by Overheat Fused Filament Fabrication Printing

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Abstract

In this study, we apply a simple but effective method to enhance tensile strength of carbon fiber (CF)/acrylonitrile butadiene styrene (ABS) and glass fiber (GF)/ABS specimens via fused filament fabrication (FFF). By employing a significant high printing temperature while turning off the cooling fan, the extruded ABS composite melt could be overheated, resulting in better diffusion process between composite rasters with reduced cooling rate and prolonged diffusion time. Consequently, the printed ABS composite specimens could achieve a porosity as low as 3.65%, corresponding to a decrease of up to 60% compared to those printed by a normal printing process. More importantly, the weld lengths formed between the adjacent rasters of the printed composite specimens increased by up to 122%, indicating a considerable enhancement in the raster interfacial bonding. Furthermore, the overheat printed composite specimens exhibited an increase of up to 20% in maximum bearing load, tensile strength, and Young's modulus compared to their normal printed counterparts. This work demonstrates that the overheat FFF printing has great potential to fabricate ABS composite specimens with enhanced structure and mechanical performance for end-use structural applications.

Key words: Fused filament fabrication, overheat printing, acrylonitrile butadiene styrene

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1. Introduction

Additive manufacturing (AM), also called 3D printing, has been developing rapidly and drawn substantial attention in the recent years [1]. Fused filament fabrication (FFF) or fused deposition modeling (FDM) is one of the most commonly used AM methods to process thermoplastics due to its simple process, reliability, high cost-effectiveness, and economic accessibility [2]. This method involves extruding a thermoplastic filament through a heated nozzle to deposit the polymer melt layer-by-layer and build up 3D parts based on their CAD models. By using this method, complex 3D parts made of different polymers or polymer matrix composites can be fabricated for a wide range of applications such as automobiles [3], aerospace [4], electronics [5], food [6], medical applications [7].

Since polymer matrix composites with reinforcing materials could offer better mechanical performance compared to neat polymer feedstocks, the composite specimens fabricated by FFF process are more promising for load-bearing structural applications [8-13]. However, their mechanical strength is still unsatisfactory owing to the inherent voids and poor interfacial bonding between the adjacent rasters [14]. During the layer-by-layer manufacturing, the temperature of the material melt decreases rapidly after its deposition on the underlying cold layer, leading to reduced flowability of the material melt as well as insufficient diffusion between the adjacent rasters [11]. Therefore, complete growth of neck formed between the rasters cannot be achieved, resulting in the formation of inter-raster voids and poor interfacial bonding [14]. Additionally, the reinforcing fillers could inhibit the mobility of the polymer chain [15] and alter the thermal conductivity of the material melt [16], leading to insufficient coalescence between the adjacent rasters.

Over the last decade, several approaches have been studied to improve the mechanical performance of the FFF printed composite specimens. They can be categorized into 4 main methods: process optimization [11, 17], process modification [10, 13], feedstock modification [12, 14], and post-treatments [9, 18]. Most methods involve complex and expensive modification of the feedstock materials and equipment or additional time-consuming post-treatment steps [9, 10, 12, 13, 14, 18]. Nevertheless, the process optimization method only requires the optimization of some important process parameters such as printing temperature, infill density, layer thickness, air gap, raster angle, extrusion flowrate, and cooling fan speed [11]. In fact, it is the most facile and cost-effective approach to fabricate FFF printed composite specimens with high mechanical performance [11].

Among the aforementioned process parameters, printing temperature and cooling fan speed have crucial effects on the diffusion process and cooling rate of the extruded material melt together with the mesostructures of the FFF printed composite parts [11, 17]. While a few studies reported the improved mechanical performance of the composite parts printed at high temperature [11, 17], the effects of overheat FFF printing with considerably high printing temperature and cooling fan turnoff on the mechanical properties of the printed composite parts have yet to be investigated. The overheat printing could prolong the elevated temperature of the deposited melt for better flowability and improved inter-raster diffusion [19]. Moreover, most research work on FFF printing of polymer composite in literature only reported the effects of different process parameters on the mechanical strength of the printed parts without studying their relationships with temperature profiles of the material rasters, mesostructures, fiber-matrix adhesion, and fracture behaviors [9, 10, 12, 13]. In fact, a comprehensive study of this process-structure-property correlation could provide insights into the process optimization strategy to fabricate the FFF printed composite specimens with desired structures and performance.

In this paper, we aim to enhance tensile strength of FFF printed carbon fiber (CF)/ acrylonitrile butadiene styrene (ABS) and glass fiber (GF)/ABS specimens by employing an overheat printing process. The overheat process was conducted by printing the composite specimens at the highest possible printing temperature of the printer used in this study as well as cooling fan turnoff to improve the flowability while decreasing the cooling rate of the extruded composite melt during the printing process. Furthermore, effects of the overheat printing on the tensile and impact strength of the printed specimens were discussed while their relationships with temperature profiles, mesostructures, fiber-matrix adhesion, and fracture behaviors were studied. The results suggest that the overheat FFF printing could be an effective approach to fabricate dense and high-performance printed ABS composite specimens.

2. Experimental section

2.1 FFF printing of the ABS composite specimens

The CF/ABS and GF/ABS filaments were purchased from 3DXTECH (USA). The ABS composite specimens were printed by employing a Raise3D Pro2 printer equipped with a 0.4-mm-diameter nozzle. The CAD models of the specimens were sliced by ideaMaker software to generate G-code files for the printing process. A build plate temperature of 110 ^{o}C and a printed raft with a thickness of 1.82 mm were used to minimize the warpage issue. An infill angle of [45°/-45°] was employed as it is one of the most widely used configurations for FFF printed structures. All parts were printed at a layer height of 0.25 mm and a printing speed of 50 mm/s. An infill overlap of 5% was used to provide good bonding between the infill and the shell. Notably, most printing parameters in the overheat process were similar to those in the normal process which were recommended by the printer's manufacturer. The major differences between the two processes were that the normal process used a printing temperature of 250 ^{o}C with a fan speed of 50%, whereas the overheat process employed the highest possible printing temperature offered by the printer (310 ^{o}C) while turning off the cooling fan to establish the overheat condition during the printing process.

2.3 Temperature profile measurement

The temperature profiles of the ABS composite materials in both normal and overheat processes were characterized by employing a K-type thermocouple connected to a temperature data logger (OMEGA, RDXL6SD-USB). The specimens printed for the measurement were rectangular prisms with 60 mm × 13 mm × 3.25 mm dimension, resulting in a total of 13 layers to complete a print (Fig. 1). Due to the heating effects of the build plate, the first few layers of the printed specimens were heated at a temperature slightly above T_g. As shown in Fig. 1a, the thermocouple was imbedded at the center of layer 9 to decrease the heating effects on the measured temperature profiles because the material temperature provided by the build plate at this layer was below T_g (~84 ^{o}C). Consequently, only temperature profiles generated by the ABS composite melt deposited from layer 10 to layer 13 were measured. The diffusion time and cooling time of the material at layer 9 with the surroundings were the total time when its temperature was higher than T_g and when its temperature reduced from peak temperature to T_g after the deposition of each subsequent layer, respectively.

2.4 Characterization and analysis

Thermogravimetric analysis (TGA, TA Instrument TGAQ500) of the ABS composite feedstocks was performed in synthetic air (oxygen 21%, hydrocarbon 5 vpm, moisture 2.00 vpm) from 25 °C to 800 °C at a heating rate of 10 °C/min. Differential scanning calorimetry (DSC, TA Instrument DSCQ200) was conducted in Nitrogen from 25 °C to 300 °C at the same heating rate. Melt flow index (MFI) of the ABS composite materials was characterized by employing an Instron melt flow tester (CEAST MF20), following ASTM D1238. The dimensions of the printed ABS composite samples were measured by a Vernier caliper. The cross-sections, cryo-fracture surfaces, and mechanical fracture surfaces of the printed composite samples were characterized by employing an optical microscope (Olympus SZ61) and a field emission scanning electron microscope (Zeiss UltraPlus FE-SEM). ImageJ software was used to analyze the cross-sections of the printed samples and determine their raster-to-raster weld lengths and porosity.

The tensile test of all printed samples was conducted by employing an Instron static tester (series 5982) equipped with a video extensometer for high accuracy strain measurements. According to ASTM D638, 24 tensile samples in total were tested at an elongation rate of 5 mm/min and a gage length of 50 mm. The sample stress was calculated by dividing the tensile force by the sample cross-sectional area. Regarding the impact test, a total of 40 printed samples were characterized by using a Zwick pendulum impact tester (HIT25P) with an impact load of 5.5 J, in accordance with ASTM D256-10A.

3. Results and Discussion

3.1 Thermal properties of the ABS composite feedstocks

Fig. 2a compares TGA results of the CF/ABS and GF/ABS feedstocks conducted in synthetic air. As can be seen, both materials started to decompose at approximately 375–378

^{o}C, indicating that it was feasible to print the materials at 310 ^{o}C using the overheat process. The derived weight curve of the GF/ABS samples showed two peaks at 402 ^{o}C and 529 ^{o}C, suggesting that the material experienced a two-step decomposition. This was a typical TGA behavior of neat ABS material in air, which was well-documented in literature [20]. Therefore, the total weight loss of 88.20% after the TGA test was mainly owing to the decomposition of the ABS matrix, suggesting that the GF filler content of the feedstock was approximately 11.80 wt.%. The CF/ABS samples, however, presented a three-step decomposition during the TGA test with three peaks observed at 403 ^{o}C, 529 ^{o}C, and 606 ^{o}C in their derived weight curve. The first two peaks were also from the decomposition of the ABS matrix [20], whereas the third peak was generated by the combustion of the CF fillers. Since the weight loss of the GF/ABS samples after the second peak was 90.52%, the estimated CF filler content of the feedstock was 9.48 wt.%.

According to the DSC curves shown in Fig. 2b, the glass transition temperatures (T_g) of the CF/ABS and GF/ABS feedstocks were approximately 98.76 ^{o}C and 92.72 ^{o}C, respectively. This result indicated that during the FFF printing, the ABS/GF feedstock could be softened for polymer diffusion or entanglement at lower temperature compared to the ABS/CF material. The MFI results of the ABS composite feedstocks at the temperatures used for the printing processes are presented in Fig. 2c. As observed, the MFI of the CF/ABS feedstock at 250 ^{o}C was 2.51 g/10min, whereas the measurement for the GF/ABS material was much lower (1.38 g/10min), suggesting that CF/ABS feedstock had lower melt viscosity and better flowability when being processed at this temperature. However, both materials showed a remarkable increase in the MFI at 310 ^{o}C, reaching 9.23 g/10min for the CF/ABS material and 9.10 g/10min for the GF/ABS material. Notably, there was only a slight difference between the MFI of both materials at 310 ^{o}C, indicating that their flowability at this temperature was comparable.

3.2 Temperature profiles of the ABS composite rasters

Fig. 3a presents temperature profiles of the material at layer 9 of the printed CF/ABS and GF/ABS specimens in the normal and overheat processes. As can be seen, all temperature profiles exhibited periodical increase after the deposition of each additional layer to the printed samples. Nevertheless, the temperature profiles of both composite materials in the normal process encountered sharp reductions before and after the peak temperatures during the deposition of the other four ABS composite layers. Due to the cooling fan used in the normal process, the material at layer 9 of the printed specimens was cooled down rapidly when the extrusion nozzle moved toward the center position of the ABS composite specimens, leading to the two sharp decreases in the temperature at each peak. In contrast, the cooling fan was turned off in the overheat process and, therefore, a more gradual decreasing trend was observed in the profile pattern at each peak during the deposition of the overheated ABS composite melt.

Fig. 3b shows peak temperature and diffusion time of the CF/ABS and GF/ABS materials at layer 9 during the normal and overheat printing processes. As can be observed, both processes of the two composite materials exhibited a gradual reduction in the peak temperature formed by each layer deposition. Specifically, the peak temperature of the CF/ABS material reduced from 105.3 to 93.4 ^{o}C for the normal process and from 141.3 to 120.3 ^{o}C for the overheat process. Similarly, the peak temperature in the normal and overheat processes of the GF/ABS material decreased from 100.1 to 91.1 ^{o}C and from 143.4 to 124.1 ^{o}C, respectively. This reducing trend was expected as heat transfer between the deposited composite melt to the material at layer 9 became less efficient at higher deposited layer number. In fact, thicker deposited composite material above the material at layer 9 acted as an insulator that lowered the heat transfer efficiency.

Besides, increased heat loss at the higher deposited layer number owing to the longer distance between the freshly deposited material and the material at layer 9 also contributed to the decreasing trend in the peak temperature of both processes. Notably, the peak temperatures in the normal printing process of both CF/ABS and GF/ABS materials were significantly lower than those in the overheat process. The differences in the peak temperatures of the two processes ranged between 26.9 ^{o}C (layer 13) and 36.0 ^{o}C (layer 10) for the CF/ABS samples and between 32.9 ^{o}C (layer 13) and 43.2 ^{o}C (layer 10) for the GF/ABS samples thanks to the overheating effects formed by using higher printing temperature and turning off the cooling fan in the overheat process.

Regarding the diffusion time, the normal printing process presented a decreasing trend from 4.3 s (layer 10) to 1.3 s (layer 11) for the CF/ABS samples and from 5.3 s (layer 10) to 0.7 s (layer 12) for the GF/ABS samples. At the deposition of the other subsequent layers, the peak temperatures of the composite material at layer 9 were below T_g due to insufficient thermal energy provided by the extruded composite melt at these layers. In fact, the total diffusion time of the composite material at layer 9 for the CF/ABS and GF/ABS samples was only 5.7 and 8.7 s, respectively, which was insufficient to achieve complete diffusion and entanglement with the surroundings. The low diffusion time was mainly owing to the low printing temperature and the cooling effects of the cooling fan used in the normal process together with the increased heat loss and the thicker insulating material formed at the higher deposited layer number.

Conversely, the diffusion time of the material at layer 9 in the overheat printing process presented an upward trend from 57.0 s (layer 10) to 80.0 s (layer 13) for the CF/ABS samples and from 112.0 s (layer 10) to 164.0 s (layer 13) for the GF/ABS samples. The increase in diffusion time of the overheat process suggested that the cooling fan turnoff and thicker insulating material formed at the higher deposited layer number could decrease the heat loss of the material at layer 9 substantially. Consequently, the temperature of the material at layer 9 could be maintained above T_g longer, leading to prolonged diffusion process with the surroundings. In addition, the higher printing temperature employed in the overheat process offered much higher peak temperature compared to those in the normal process, contributing to its higher diffusion time. As a result, the material at layer 9 in the overheat process could attain a total diffusion time of 277.3 s for the CF/ABS samples and 565.0 s for the GF/ABS samples, which was 49 and 65 times more than that of the normal process, respectively. The results suggest that better polymer diffusion and entanglement between the ABS composite rasters could be accomplished by the overheat process.

Fig. 3c compares the diffusion time and cooling time of the material at layer 9 in the overheat process for both ABS composite materials. As can be seen, while there was insignificant difference in the peak temperature attained by both ABS composites in the overheat process, the diffusion time and cooling time of the GF/ABS samples was nearly twice more than that of the CF/ABS samples. Since GF fillers have much lower thermal conductivity compared to CF fillers, the GF/ABS rasters were expected to transfer heat at a rate much lower than the CF/ABS rasters [21], resulting in the significant difference in the diffusion time between the two ABS composites. Consequently, the material at layer 9 of the GF/ABS specimens had lower heat loss and, hence, obtained much longer diffusion process.

3.3 Dimensions, mass, and cross-sections of the printed ABS composite parts

3.3.1 Dimensions and mass of the printed ABS composite parts

Fig. 4 presents the mass and dimensions of the tensile and impact samples fabricated by the normal and overheat processes. As can be observed, all samples printed by both processes had consistent dimensions and mass with low measurement variation. Notably, all dimensions of the printed samples were similar to the nominal dimensions. However, the overheat printed samples possessed slightly higher mass (~1-3 %) compared to those fabricated by the normal process, suggesting that the overheat printed samples might have more consolidated structure and encounter a slight over-extrusion possibly owing to the lower viscosity of the overheated material melt. Overall, there were insignificant differences in the printability between the normal and the overheat printing processes.

3.3.2 Cross-sections and mesostructures of the printed ABS composite parts

Figs. 5 a-d shows the cross-sections of the CF/ABS and GF/ABS samples printed by the normal and overheat processes. As can be seen, the internal structure of all printed samples consisted of 3 main regions: side, bottom, and middle & top. The two side regions of the printed parts possessed consolidated structures thanks to the infill overlap of 5% used in both printing processes. The bottom region (first 4-6 layers) also had consolidated structure as the build plate always heated the material at this region at high temperature (~T_g) while densification effects were provided by the mass accumulation and extrusion pressure of the subsequent deposited layers. In contrast, the structure of the middle & top region was the least consolidated with many voids observed. The void size in this region was obviously larger than that in the bottom region owing to the reduced heating effects of the build plate with increasing layer number. Notably, this is a typical issue of polymer parts fabricated by FFF printers equipped with only a heated build plate [22].

As shown in Figs. 5a and c, both ABS composite specimens printed by the normal process possessed many voids and gaps formed between the deposited rasters. Specifically, the porosity of the CF/ABS samples was approximately 6.87 %, whereas the measurement for the GF/ABS samples was 9.04 %. The difference in the porosity between the two ABS composite materials was mainly due to the lower melt viscosity and better flowability of the CF/ABS melt at 250 ^{o}C. However, the porosity of the CF/ABS and GF/ABS samples reduced to only 4.66% and 3.65%, corresponding to a decrease of 32.22 and 59.61%, respectively, when the overheat process was employed (Figs. 5b and d). The results were consistent with the longer raster-to-raster weld lengths achieved in the middle & top region of the overheat printed specimens, as shown in Fig. 5e.

While there was insignificant difference in the raster dimensions of all samples, the vertical weld lengths of the composite parts increased from 0.10 to 0.12 mm for the CF/ABS samples and from 0.09 to 0.13 mm for the GF/ABS samples after the overheat process was applied. Similarly, the horizontal weld lengths of the CF/ABS and GF/ABS parts printed by the overheat process were 14.75% and 122.00 % higher than those of the normal printed samples, respectively. This remarkable decrease in the porosity and increase in weld lengths of both ABS composite samples could be explained by the much lower melt viscosity and the prolonged diffusion time of the overheated composite rasters compared to those printed by the normal process. Consequently, better polymer diffusion could be achieved, resulting in the formation of lesser pores and voids together with larger side and bottom dense regions in the overheat printed composite samples.

3.4 Fiber-matrix adhesion of the printed ABS composite parts

Fig. 6 compares the cryo-fracture surfaces of the CF/ABS and GF/ABS samples printed by the normal and overheat processes. As can be observed, a large proportion of fractured CF fibers and gaps around the fibers could be observed on the surface of the CF/ABS samples (Figs 6a and b). In addition, there was a large amount of polymer residue on the CF fiber surfaces while some of the carbon fibers were "bean-like" with rough surfaces. The observed gaps around the CF fibers indicated that the fiber-matrix adhesion of the CF/ABS samples was intermediate. Regarding the GF/ABS samples, a large proportion holes as opposed to fibers were observed in Figs 6c and d, but on closer examination, several of these holes contained fractured fibers with a small gap around the fibers. Since GF had cylindrical shape with smoother surface, their fiber-matrix adhesion was slightly lower than that of the printed CF/ABS samples. More importantly, there were no remarkable differences between the cryo-fracture surfaces of the ABS composite printed by both processes, suggesting that the FFF overheat printing had insignificant influences on the fiber-matrix adhesion of the ABS composite specimens.

3.5 Tensile and impact properties of the printed ABS composite parts

Fig. 7 presents stress-strain curve, fractured samples, and tensile and impact properties of the CF/ABS and GF/ABS specimens printed by the normal and overheat processess. As can be observed, all tensile tests were valid with the samples breaking within the gage length (Fig. 7b). More importantly, all overheat printed samples showed better tensile performance compared to those printed by the normal process. In particular, the CF/ABS parts printed by the normal process possessed a maximum bearing load, tensile strength, and Young's modulus of 1,130 N, 26.54 MPa, and 2.12 GPa, respectively.

However, the overheat printed CF/ABS parts exhibited a 20% improvement in tensile performance with a maximum bearing load of 1,352 N, tensile strength of 31.94 MPa, and Young's modulus of 2.54 GPa. Regarding the GF/ABS printed samples, the maximum bearing load, tensile strength, and Young's modulus of the overheat printed parts could reach 1,377 N, 32.30 MPa, and 2.46 GPa, respectively, which were approximately 11% higher than those of their normal printed counterparts. Since there was no significant difference between the fiber-matrix adhesion of the samples printed by both processes, the better tensile performance of the overheat printed samples was mainly attributed to their more consolidated internal structures and, hence, better load transfer efficiency between the ABS composite rasters.

However, the strain at break and impact strength of the ABS composite parts printed by the two processess showed a different trend. In details, the strain at break of the composite parts printed by the normal process was 0.066 for the CF/ABS samples and 0.031 for the GF/ABS samples. By using the overheat process, the strain at break of the CF/ABS and GF/ABS samples decreased to 0.061 and 0.030, corresponding to a reduction of 8.63 % and 3.83%, respectively. Similarly, the overheat printed CF/ABS and GF/ABS samples had an impact strength of 45.37 J/m and 62.07 J/m, respectively, which was 6.51% and 9.82% lower than that of their normal printed counterparts. These findings indicated that FFF overheat printing had negative influences on the strain at break and impact strength of the printed ABS composite parts.

Fig. 8 presents fracture surfaces of the printed CF/ABS and GF/ABS samples after the mechanical tests. As the samples from both tensile and impact tests had similar failure morphologies, the following analysis and discussion were applicable to both types of loading.

A planar fracture surface without periodicity of the failure patterns was observed in the bottom region (denser structure) for the CF/ABS and GF/ABS samples printed by the normal process (Figs. 8a and c). However, with the reduced consolidation degree when layer number increased, a transition from planar failure to multiplanar serrated failure with a zig-zag pattern was observed. This mixture of trans-raster and inter-raster failure indicated a mixed-mode type which was dominated by the lower inter-raster failure. Failure initiated at the inter-raster interface isolating the different rasters that then failed independently at different failure planes. Inter-raster interface strength is the key parameter to control the strength of the material.

In contrast, all overheat printed samples largely exhibited a planar failure with a smooth single facture surface shown in Figs 8b and d. Similar length of the fiber pull-outs observed from both normal and overheat printed samples further indicated that the fiber-matrix adhesion of the CF/ABS and GF/ABS samples remained unchanged. The results were consistent with the findings obtained from their cryo-fracture surfaces, suggesting that the difference in the fracture patterns between the ABS composite samples printed by both processes could be attributed solely to the increased consolidation structure of the overheat printed samples. Since the tensile strength of the overheat printed samples exceeded that of their normal printed counterparts, tensile failure was, therefore, seen to be more sensitive to the stress concentrators arising at the contact between rasters. Eliminating such stress concentrators impacted positively on the tensile strength. Contrarily, the presence of the zig-zag pattern at the facture surface of the normal printed samples put in evidence an interaction between failure modes that resulted in an increased crack tortuosity. This could explain why these samples possessed higher impact strength and strain-at-break compared to their overheat printed counterparts.

3.6 Advantages of the overheat printing method for tensile strength improvement

Fig. 9 compares the achieved tensile strength and strength improvement percentage of FFF printed composite parts produced by the overheat printing and other methods, such as increase of reinforcing fiber length [12], post-treatment with laser heating [9] or annealing [18], and modification of extruder with auxiliary heating [13] or vibration motor [10]. Notably, all tensile samples in these works were printed at an infill angle of [45°/-45°]. As can be seen, the achieved tensile strength of the overheat printed ABS composite specimens in this study was in the range of printed ABS composite parts reported by the other methods and lower than that of the laser heated Al/ Polylactic acid (PLA) parts and annealed CF/Nylon parts. This result was expected as the achieved tensile strength depended on not only the printed structures but also the grades, types, and morphology of the material feedstocks as well as the volume or mass fraction of the reinforcing fillers. However, the strength improvement percentage of the CF/ABS specimens offered by the overheat printing was comparable to that of the Al/ PLA parts fabricated by the laser heating and much better than that of those fabricated by the other methods.

Among the other methods, only study of the extruder modified with vibration motor presented the improvements in mesostructures of the printed CF/ABS specimens with an achieved porosity of 10%, corresponding to a porosity reduction of 23% [10]. Nevertheless, our overheat printing process could establish better porosity reduction efficiency (up to 60%) with much lower achieved porosity (3.65%). More importantly, our developed method was the most facile and cost-effective among these approaches with no requirements of extruder modification, feedstock modification, or additional post-treatment steps. The results suggest that the developed overheat FFF printing process has great potential to fabricate dense polymer composite specimens with high mechanical performance. Notably, the cooling fan also plays crucial role in the FFF printing process, especially for the fabrication of small and complex features. Therefore, it should be flexibly controlled probably via G-code modification to offer both normal and overheat printing conditions for required applications.

4. Conclusions

In summary, the CF/ABS and GF/ABS specimens were successfully fabricated by the overheat FFF printing process. By printing the ABS composite specimens at significantly high temperature without using the cooling fan, the viscosity and cooling rate of the extruded ABS composite melt decreased considerably, leading to enhanced diffusion process between the composite rasters. Therefore, the porosity of the printed composite parts could reduce by up to 60% while their raster-to-raster weld lengths increased by up to 122%. Additionally, despite a slight reduction in strain at break and impact strength, the overheat printed specimens could attain an improvement of up to 20% in maximum bearing load, tensile strength, and Young's modulus compared to those fabricated by the normal process. This work suggests that the overheat FFF printing could be a promising method to fabricate high-performance ABS composite parts for end-use structural applications.

CRediT authorship contribution statement

Thang Q. Tran: Conceptualization, Methodology, Investigation, Writing – original draft, review & editing. **Carla Canturri**: Investigation, Writing – original draft, review & editing. **Xinying Deng**: Investigation, Writing – original draft, review & editing. **Chu Long**

Tham: Investigation, Writing – original draft. **Feng Lin Ng**: Resources, Project administration, Writing –review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Figure caption

Fig. 1. a) Schematic diagram showing experimental setup for temperature profile measurement, b) printed ABS composite sample with embedded thermocouple, and c) Tool-path of the printed ABS samples.

Fig. 2. a) TGA results, b) DSC results, and c) MFI results of the ABS composite feedstocks.

Fig. 3. a) Temperature profiles, b) diffusion time and peak temperature, and c) diffusion time and cooling time of the material at layer 9 of the ABS composite specimens during the printing process.

Fig. 4. Dimensions and mass of the tensile and impact samples printed by the normal and overheat processes.

Fig. 5. Cross sections of a) normal printed CF/ABS specimens, b) overheat printed CF/ABS specimens, c) normal printed GF/ABS specimens, d) overheat printed GF/ABS specimens. e) raster dimension and raster-to-raster weld lengths of the CF/ABS and GF/ ABS specimens printed by the normal and overheat processes.

Fig. 6. a) SEM images showing cryo-fractured surfaces of a) normal printed CF/ABS specimens, b) overheat printed CF/ABS specimens, c) normal printed GF/ABS specimens, and d) overheat printed GF/ABS specimens.

Fig. 7. a) Stress-strain curves, b) fractured tensile samples, and c) mechanical properties of the CF/ABS and GF/ABS parts printed by the normal and overheat processes.

Fig. 8. Representative SEM images showing facture surfaces of the impact and tensile samples. a) normal printed CF/ABS samples, b) overheat printed CF/ABS samples, c) normal printed GF/ABS samples, and d) overheat printed GF/ABS samples.

Fig. 9. a) Achieved tensile strength and strength improvement percentage of the printed composite parts achieved by different methods.