THE EFFECTS OF OVER-EXTRUSION ON THE IN-SITU CONSOLIDATION OF ADDITIVELY MANUFACTURED COMPOSITES

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ABSTRACT

Additive manufacturing of continuous fiber reinforced thermoplastic composites using the fused filament fabrication (FFF) process is of growing interest due to the technology's low cost and simplicity; however, the printed materials typically exhibit high void contents, and consequently poor mechanical performance. To counter this, a discrete in-situ consolidation (DISC) process has been developed wherein a heated flat-bottomed tool is pressed into and run along the length of each bead after it has been deposited via FFF. When consolidated using the DISC process, the bead undergoes significant spreading and compaction, leading to an extensive rearrangement of the internal fiber network. It was observed that when the fibers exhibit in-plane waviness prior to DISC, the post-consolidated fiber network becomes highly disorganized and poorly packed, leading to the development of voids. This initial waviness is found to be the result of over-extrusion, wherein the length of filament extruded during the FFF process exceeds the distance traveled by the nozzle, causing the fibers in the filament to buckle. An experimental analysis was performed in which beads were deposited and consolidated with varying levels of over-extrusion, and their macro- and micro-scale morphologies were analyzed. It was found that at over-extrusion values less than 0.1%, consolidated beads exhibited little waviness and highly rectangular cross-sections which is optimal for maximizing inter-bead packing efficiency. Furthermore, the internal fiber networks exhibited high packing efficiencies, minimizing the available space for void development. However, over-extrusion values greater than 0.1% were found to result in poorly packed fiber networks with high residual stresses, leading to severe deconsolidation and void growth once compaction pressure was removed. Due to the extreme sensitivity of the DISC process to over-extrusion, methods for accurately controlling this parameter need to be developed.

1 INTRODUCTION

Additive manufacturing (AM) technologies have the potential to greatly increase the accessibility of continuous fiber-reinforced polymer composites (FRPCs) by automating otherwise costly and labor-intensive manufacturing processes. Fused filament fabrication (FFF) has received significant interest from the research community as a suitable AM process for continuous FRPCs due to its simplicity, widespread usage, and the ease of incorporating continuous fibers into the extrudate. FFF differs from most other automated composite processing methods in that it uses material extrusion (MEX) rather than a tension-driven deposition method, e.g., automated fiber placement (AFP) or filament winding. The FFF process works by extruding a preimpregnated continuous fiber-reinforced thermoplastic filament through a heated nozzle which deposits beads layer-by-layer to construct a part (Fig. 1a). For this process to work correctly, the feed rate of the filament, controlled by the drive roller, must be closely matched to the velocity of the nozzle relative to the substrate. If the material is fed at a lower rate than the nozzle velocity, or "under-extruded", the tension created in the material may cause it to pull off from the substrate, thus interfering with the deposition. If the material is fed at a higher rate than the nozzle velocity, or "over-extruded", the continuous fibers will be placed under compression during deposition, resulting in buckling and the development of waviness (Fig. 1b). Over-extrusion is defined here as the percentage of additional filament length extruded with respect to the distance traveled by the nozzle during deposition of the bead (Eq. 1). As an example, if a bead is 100 mm long and 101 mm of filament had been extruded, the over-extrusion value would be 1%.

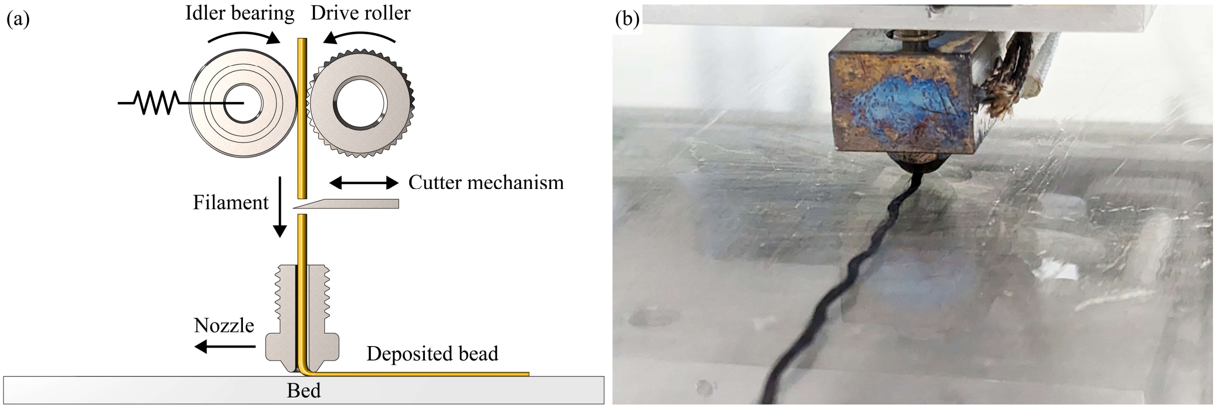

Fig. 1: (a) Schematic diagram of the FFF process. (b) FFF process showing significant waviness in the deposited bead as a result of over-extrusion.

$$\text{Over-extrusion} = \frac{L_{extruded\,filament} - L_{bead}}{L_{bead}} \times 100\% \tag{1}$$

In-plane fiber waviness has been observed in numerous studies on the continuous fiber FFF process [1–7]. This waviness is likely due to over-extrusion of the filament, a topic which has not yet been addressed in literature. Over-extrusion can be attributed to many underlying issues in current FFF systems. The radius of the drive roller at the point of contact with the filament (Fig. 1a) must be known with a high level of accuracy to calibrate the feed length (circumference) per revolution parameter in the control system. This becomes complicated when using a toothed roller as the contact radius is dependent on how far the teeth dig into the filament, or when using an elastomeric roller as the contact radius is dependent on how much the elastomer deforms. In both cases, the contact radius is dependent on the compression force between the roller and filament which must be precisely maintained. Wear or the build-up of polymer on the drive roller further complicates matters. Another significant issue is filament slippage due to insufficient or inconsistent grip between the filament and the drive roller. The drive roller must be able to consistently overcome any frictional or inertial (unspooling) resistances encountered in pulling the filament into the print head, as well as any compressive forces required to push the filament through the nozzle.

Composite parts manufactured using the FFF process typically suffer from high void contents, substantially reducing mechanical performance [8]. Voids are prone to developing in two areas: within the beads (intra-bead), and between the beads (inter-bead). Intra-bead voids can be a result of porosity existing in the filament prior to deposition or can develop due to rearrangement of the matrix and internal fiber network during processing. Inter-bead voids develop when the material does not completely fill in the gaps between adjacent beads during deposition. One of the main factors contributing to the porosity in parts produced using FFF is the lack of consolidation pressure imparted on the material during deposition. Depositing material with the nozzle closer to the substrate has been found to increase consolidation pressure; however, this also significantly increases the risk of clogging of the nozzle which results in an unreliable process [9,10]. Discrete in-situ consolidation[1] (DISC) has been introduced as a simple method for consolidating beads in a secondary step after deposition [11]. The DISC process works by applying heat and pressure to the bead by running a flat-bottomed consolidation tool along its length (Fig. 2). Prior work demonstrated this process' ability to decrease average void content from over 40% to around 4% in a continuous carbon fiber-reinforced polyamide 12 (PA12) with a fiber volume

[1] Patent-pending process.

fraction of 50% [11]. It was noted in this study that over-extrusion of the material had led to significant in-plane fiber waviness and a substantial drop in fiber packing efficiency during consolidation, posing the question addressed here as to how great an effect over-extrusion has on consolidation quality with the FFF and DISC processes.

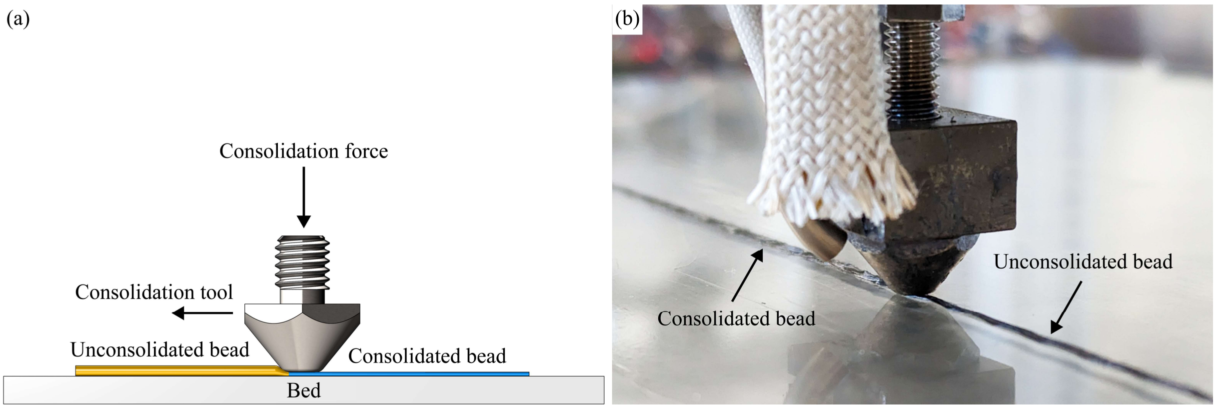

Fig. 2: (a) Schematic diagram of the DISC process. (b) Deposited bead undergoing DISC process.

The detrimental effects of fiber waviness on the mechanical properties of composites are well documented [12]. However, the relationships between over-extrusion, fiber waviness, and consolidation quality in the FFF and DISC processes have not yet been investigated. In this study, these effects are examined via experimental analyses. Beads processed via FFF alone as well as FFF followed by DISC, with varying levels of over-extrusion, are analyzed using macro photography and optical microscopy to identify the effects on intra-bead fiber packing efficiency and void content.

2 MATERIALS AND METHODS

2.1 Sample preparation

Beads of a continuous carbon fiber-reinforced polyamide 12 (PA12) 3D printer filament (11590, Suprem, Yverdon-les-Bains, Switzerland) with a nominal fiber volume fraction of 58% were deposited onto an unheated glass bed using a 2 mm diameter stainless steel nozzle (Fig. 1b). The settings used were a nozzle temperature of 280 °C, a deposition height of 0.3 mm, and a speed of 300 mm/min. A stepper motor actuated polyurethane drive roller was used to feed the filament. Samples were deposited with varied programmed over-extrusion values starting at positive 2%, where clear waviness was visible in the bead, and lowering this value incrementally by 0.2% until visible waviness was eliminated at around negative 1%. Further reductions to negative 2% were made to ensure minimally over-extruded samples were produced, relying on the adhesion between the deposited bead and the glass bed to pull the filament out of the nozzle and to cause the filament to slip against the drive roller when not enough was length was supplied. G-codes for the manufacturing process were created using a custom MATLAB script.

For each of the 21 programmed over-extrusion variations representing values between -2% to +2%, 4 samples were manufactured using FFF only, and 4 samples were manufactured using FFF followed by DISC. Each sample was 30 mm in length. To perform the DISC process, a conical stainless steel consolidation tool with a flat tip diameter of 4 mm was used (Fig. 2b). The edges of this tip were rounded to an approximate radius of 0.5 mm to reduce abrasion of the fibers. The settings used were a temperature of 280 °C, a speed of 100 mm/min, and a constant force of 10 N applied using a pressure regulated pneumatic cylinder.

2.2 Measurement of over-extrusion

Prior to microscope cross-sectioning, measurements of over-extrusion were taken for each sample as the programmed over-extrusion values were not accurate. Top view photographs of the beads were captured using a digital camera (D850, Nikon, Tokyo, Japan) with a macro lens (AF-S Micro NIKKOR 105mm, Nikon) and ring flash (ML-150, Godox, Shenzhen, China) mounted on a copy stand (RSP rePRO, Kaiser Fototechnik, Buchen, Germany). This setup was designed to minimize optical distortion. Each sample's photograph was imported into a computer graphic software (Rhino 7, Robert McNeel & Associates, Seattle, USA), where the paths of three distinct and spaced-apart fibers were traced over a 10 mm length, centered around the microscope cross-section plane (Fig. 3). The lengths of the three paths were added together and divided by the sum of their longitudinal spans to determine an average over-extrusion value. It was assumed that fiber waviness occurs primarily in-plane and that out-of-plane waviness had a negligible effect on the measurements.

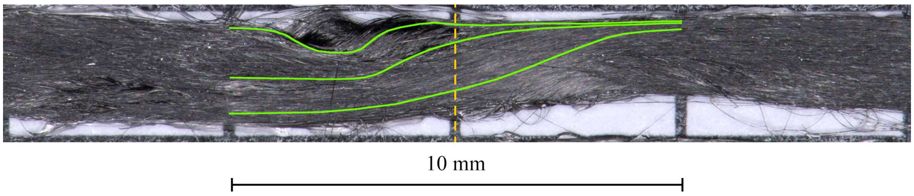

Fig. 3: Top view macro photograph of a bead with three traced fiber paths (green) for measurement of average over-extrusion. The yellow dashed line represents the approximate location where the cross-section micrograph will be taken. This sample used a programmed over-extrusion value of 1.8% and exhibited a measured over-extrusion value of 2.36%.

2.3 Fiber packing efficiency analysis

All samples were embedded in a cold mounting epoxy (EpoFix, Struers, Ballerup, Denmark), ground, and polished using a materialographic grinder/polisher system (GPX200, LECO, St. Joseph, MI, USA) to obtain transverse cross-sections. An optical microscope (DM6000 M, Leica Microsystems, Wetzlar, Germany) with a 10 MP camera (MC190 HD, Leica Microsystems) was used to photograph the samples under bright-field illumination (Fig. 4a). Fiber packing efficiency was calculated for each sample by dividing the total fiber area by the bounded area of the fiber network in the transverse cross-section of the bead (Eq. 2). The total fiber area was determined from measurements of the filament in Adobe Photoshop. The bounded area was determined by selecting the fibers via thresholding in Adobe Photoshop (Fig. 4b), expanding this selection by 20 µm to fuse neighboring selections (Fig. 4c), and contracting the selection by 20 µm to obtain the final bounded area (Fig. 4d). An estimate of intra-bead void content was calculated for each sample by subtracting the filament cross-sectional area from the bounded area of the bead fiber network and dividing by the bounded area of the bead fiber network (Eq. 3). While this void content measurement provides good data for comparative purposes, it is not fully accurate in that it does not account for any matrix that is outside of the fiber network bounds (see isolated matrix-rich regions on the right side of Fig. 4).

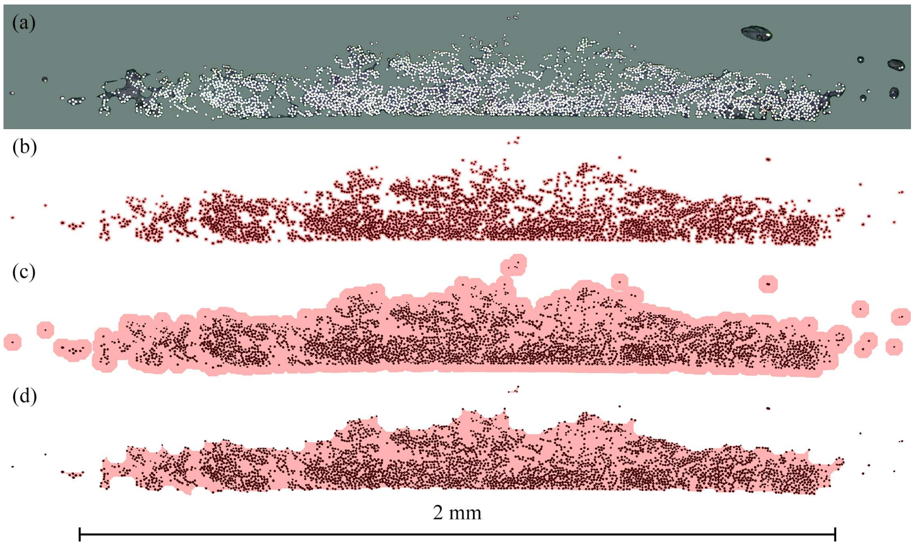

Fig. 4: Determination of bounded area of fiber network in a bead for fiber packing efficiency calculation: (a) Transverse cross-section micrograph of a bead showing the carbon fibers (white), PA12 matrix (dark gray), and mounting epoxy (green). (b) Thresholding to select fibers. (c) Expansion of selection by 20 µm to fuse neighboring selections. (d) Contraction of selection by 20 µm to obtain the final bounded area.

$$\text{Packing efficiency} = \frac{A_{fibers}}{A_{bounds}} \times 100\% \tag{2}$$

$$\text{Intra-bead void content} = \frac{A_{bounds} - A_{filament}}{A_{bounds}} \times 100\% \tag{3}$$

3 RESULTS AND DISCUSSION

3.1 Filament microstructure

Fig. 5a shows a partial cross-section optical micrograph of the filament, which exhibits excellent impregnation and negligible porosity. The average cross-sectional area and fiber volume fraction was determined to be 0.191 ± 0.005 mm^2 and 55.0% ± 1.4% respectively by analyzing five complete cross-sections in Adobe Photoshop. Using micro-computed tomography (Xradia Versa XRM-520, Zeiss, Oberkochen, Germany), the fibers were found to be aligned in parallel with some very minor localized waviness (Fig. 5b).

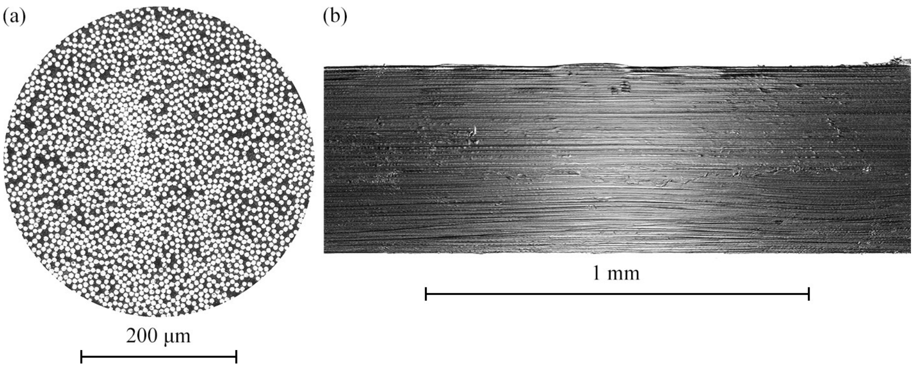

Fig. 5: (a) Partial cross-section optical micrograph of the filament. (b) Side view of the filament, taken via micro-computed tomography, showing parallel fibers and some very minor localized waviness.

3.2 Over-extrusion variability

Fig. 6 shows the relationship between programmed and average measured over-extrusion values for all samples in the experiment. As can be seen, measured over-extrusion exhibits significantly more variability at higher values of programmed over-extrusion than at lower values. At -0.8% programmed over-extrusion and lower, the measured over-extrusion becomes negligible indicating that the process has transitioned from extrusion-driven to tension-driven deposition. Interestingly, the average measured values do appear to trend towards the programmed values while above 0% programmed over-extrusion.

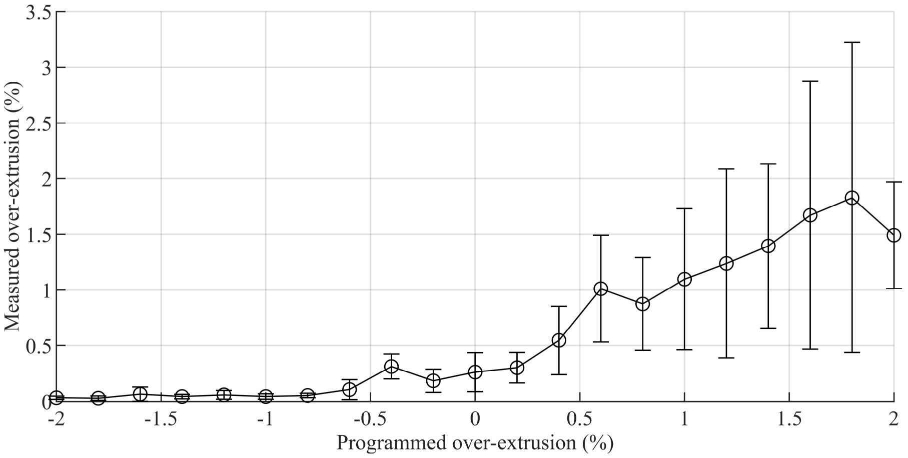

Fig. 6: Relationship between programmed and measured over-extrusion values.

Fig. 7 shows a flatbed scan of beads processed via FFF only and FFF followed by DISC with measured over-extrusion values of 0% and 1.4%. The programmed over-extrusion values for these beads were -1.8% and +1.4% respectively. The beads processed with minimal over-extrusion (Fig. 7a and b) exhibit consistent width and straight profiles, while beads processed with 1.4% over-extrusion (Fig. 7c and d) exhibit inconsistent width and varying in-plane waviness along their length. This variation in waviness indicates that the amount of over-extrusion varied as the bead was deposited. This can likely be attributed to a fluctuating build-up of buckled filament in the nozzle that exits at an inconstant rate. At higher programmed over-extrusions, more fluctuation would become possible leading to the increase in variability of measured values seen in Fig. 6 while also maintaining an average value similar to the programmed one.

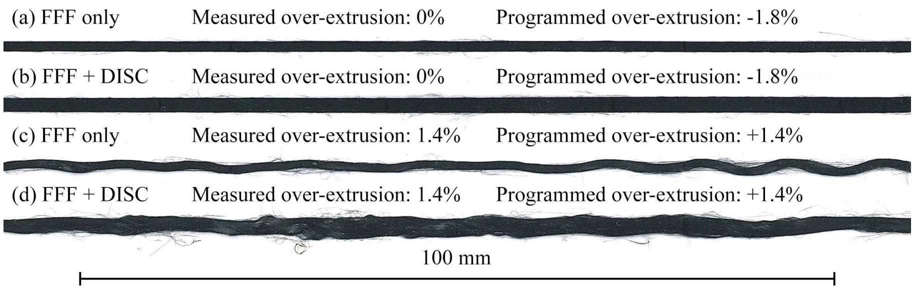

Fig. 7: Flatbed scan of beads processed via FFF only and FFF followed by DISC with measured over-extrusion values of 0% and 1.4%. In over-extruded samples, variation can be seen in the waviness along the length, indicating fluctuations in the amount of over-extrusion.

3.3 Experimental analysis

The macro photographs in Fig. 8 show beads processed via FFF only and FFF followed by DISC with measured over-extrusion values of 0%, 0.4%, and 1.8%. Beads processed with DISC exhibit significantly more spreading than those processed with FFF alone. When processed with minimal over-extrusion (0%), beads exhibit straight, parallel fibers and a consistent width along their length (Fig. 8a and b). Slight in-plane waviness can be seen in the beads with 0.4% over-extrusion (Fig. 8c and d), which will result in lowered inter-bead packing efficiency. Waviness becomes quite severe in the beads with 1.8% over-extrusion (Fig. 8e and f), which will be highly detrimental to inter-bead packing efficiency and lead to considerable inter-bead porosity. Furthermore, significant rearrangement of the bead structure occurred during the consolidation process as a result of the excess fiber lengths and the shear forces imparted by the DISC tool, leading to a highly disorganization fiber network which exhibits twisting, folding, and frequent fiber crossings.

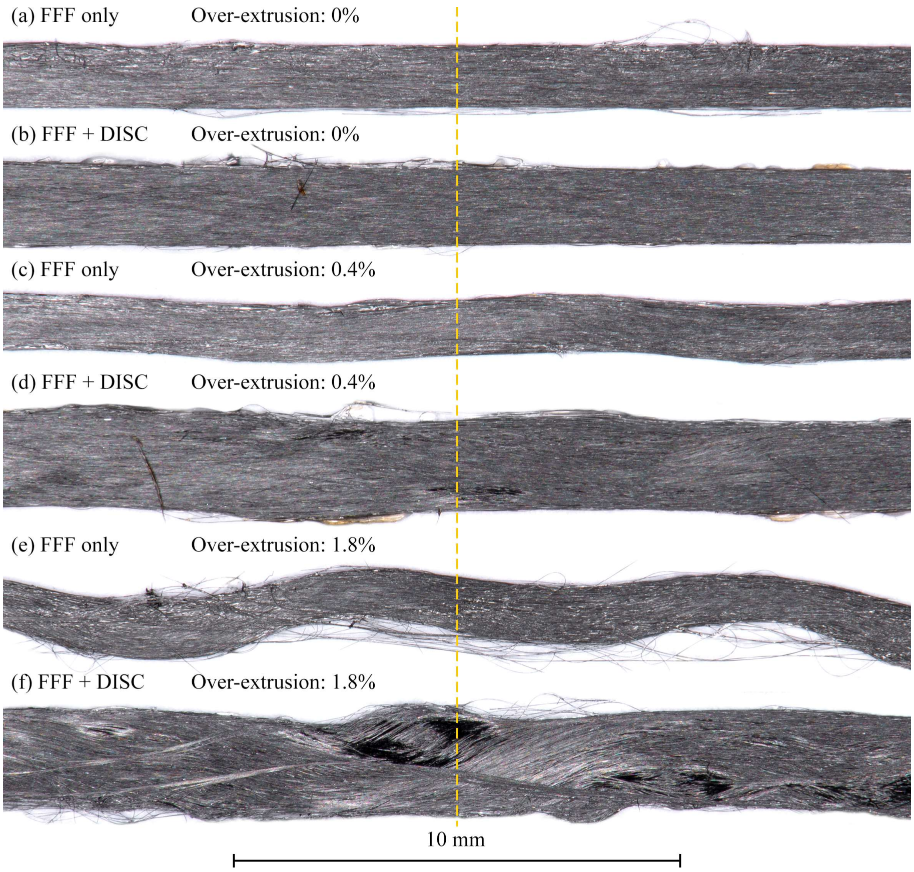

Fig. 8: Top view macro photographs of beads processed via FFF only and FFF followed by DISC with measured over-extrusion values of 0%, 0.4%, and 1.8%. The yellow dashed line represents the approximate location where the cross-section micrographs in Fig. 9 were taken.

The yellow dashed line in Fig. 8 represents the approximate location where the transverse cross-section micrographs in Fig. 9 were taken. With minimal over-extrusion (0%), the cross-sectional profiles were typically lenticular when processed via FFF only, often with matrix rich regions forming at the sides (Fig. 9a). While these beads exhibited excellent longitudinal straightness, the lenticular cross-sectional profile will limit the achievable inter-bead packing efficiency, leading to inter-bead porosity. Once consolidated, the 0% over-extrusion samples consistently exhibited a densely packed, rectangular fiber network (Fig. 9b) which, in combination with the straightness of the bead, will result in excellent inter-bead packing efficiency. When processed at 0.4% over-extrusion, the cross-sections of the FFF only samples became slightly thicker and more rectangular (Fig. 9c); however, inter-bead packing efficiency becomes limited by the bead's in-plane waviness. Interestingly, the fiber packing efficiency of the DISC samples became notably worse with this small increase in over-extrusion. As can be seen in Fig. 9d, the fiber network in the right half of the bead exhibits a more compact form, while the left half appears to have deconsolidated. This is likely due to the generation of high strain energies in the fiber network during compaction, resulting in decompaction once the consolidation pressure was removed. When over-extruded at 1.8%, the fiber network in the FFF only samples became significantly less organized, resulting in intra-bead porosity (Fig. 9e), and DISC samples exhibited severe deconsolidation (Fig. 9f).

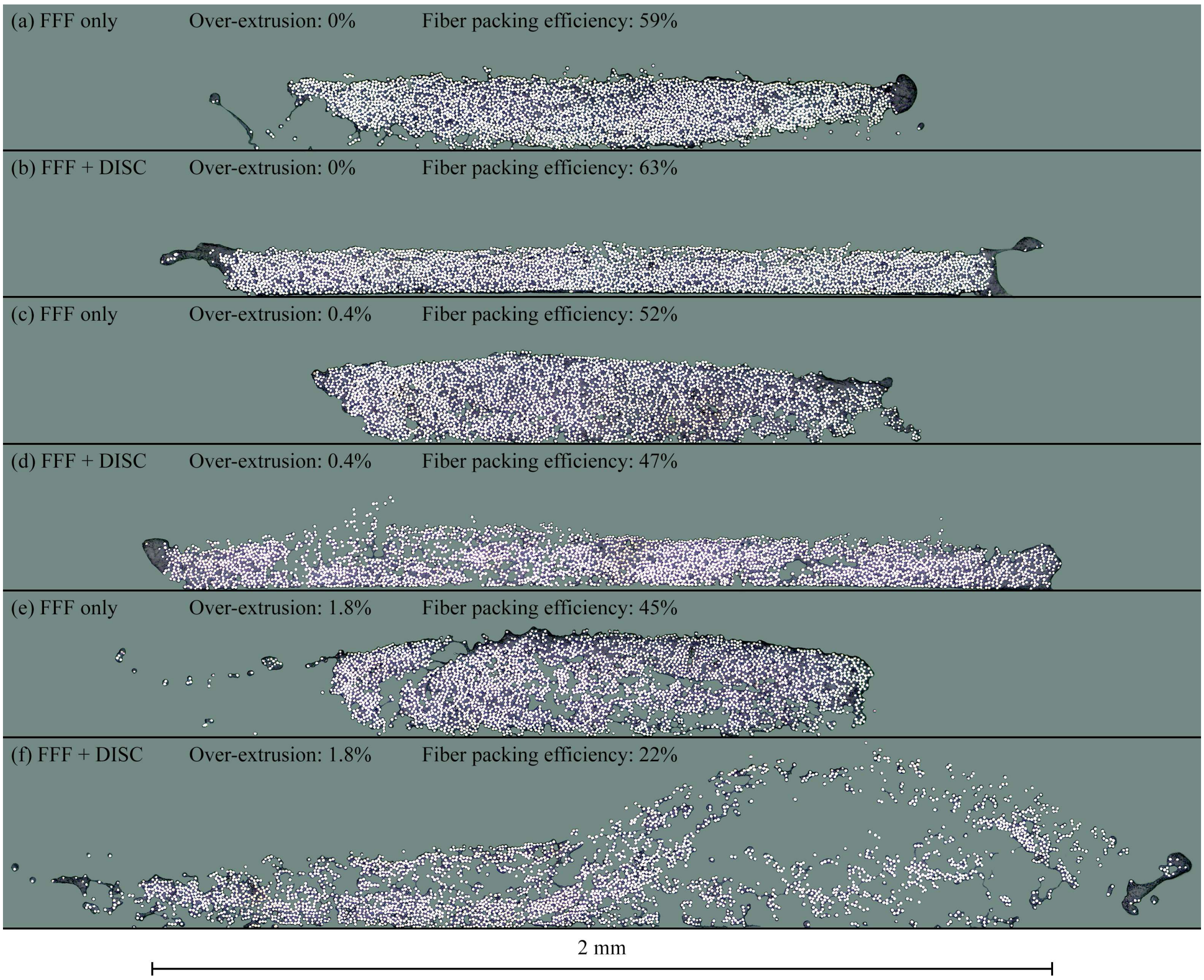

Fig. 9: Transverse cross-section micrographs of the beads in Fig. 8, showing the carbon fibers (white), PA12 matrix (dark gray), and mounting epoxy (green).

As packing efficiency is defined as the volume of fibers to the total volume of the composite, then it must necessarily be equal to, or greater than, the fiber volume fraction of the filament (55% in this case) to achieve a void-free bead. Packing efficiencies exceeding the fiber volume fraction indicate that matrix squeeze-out has occurred. It should also be noted that packing efficiencies meeting or exceeding the fiber volume fraction do not guarantee an absence of voids, as porosity can still exist if insufficient matrix is present inside the fiber network bounds. Fig. 10a plots the experimental relationship between measured over-extrusion and fiber packing efficiency in beads processed via FFF only. As can be seen, packing efficiencies were typically below 55% throughout the tested over-extrusion range. Interestingly, packaging efficiencies exceeding 55% did occur more frequently at over-extrusion values below 0.1%. Fig. 10b plots the relationship between measured over-extrusion and intra-bead void content and demonstrates that even at low over-extrusion values, samples commonly exceeded the 2% limit often stated for aerospace use, indicating an unreliable process.

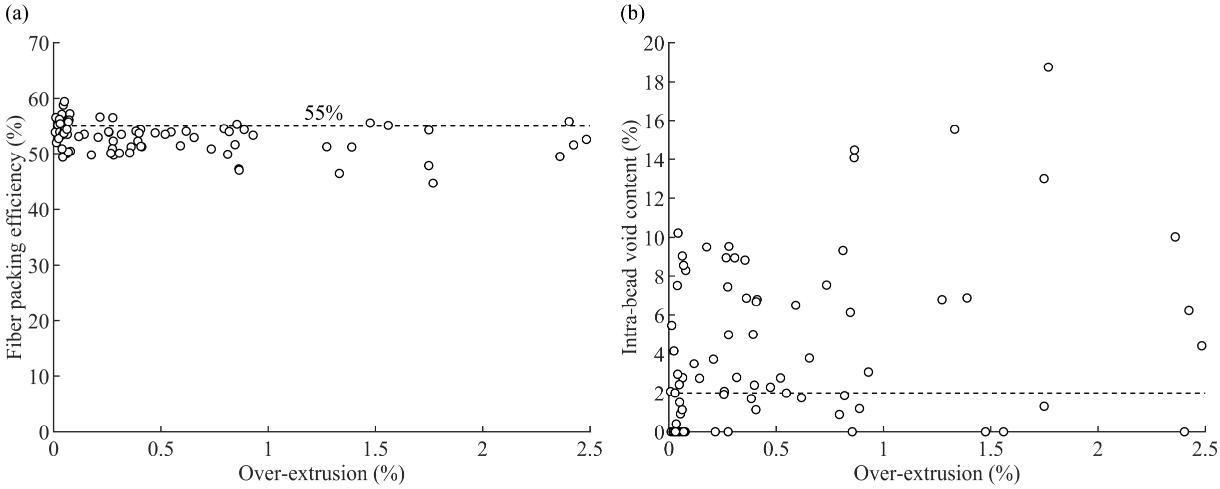

Fig. 10: Experimental results for beads processed via FFF only: (a) Relationship between measured over-extrusion and fiber packing efficiency. (b) Relationship between measured over-extrusion and intra-bead void content.

The experimental data for beads processed via FFF followed by DISC is shown in Fig. 11. It can be seen that the DISC process is extremely sensitive to over-extrusion, exhibiting much more severe drops in packaging efficiency than beads processed via FFF only. However, beads processed with less than 0.1% over-extrusion demonstrated excellent performance, achieving an average fiber packing efficiency of 57.7% ± 2.8% and an average intra-bead void content of 0.4% ± 1.5%. Performance rapidly drops with higher over-extrusion values, suggesting that over-extrusion is one of the most critical parameters to control when using the DISC process. Interestingly, the upper bound of the intra-bead void content data appears to follow the same trend as the theoretical waviness curve derived in section 3.4.

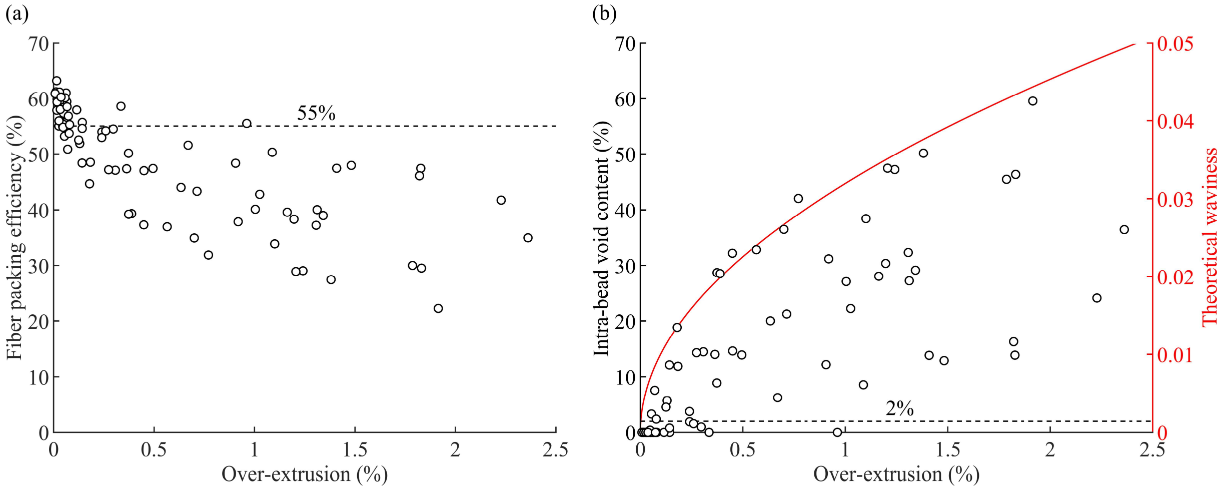

Fig. 11: Experimental results for beads processed via FFF followed by DISC: (a) Relationship between measured over-extrusion and fiber packing efficiency. (b) Relationship between measured over-extrusion and intra-bead void content. A scaled theoretical waviness curve has been overlaid to show its similarity to the data's upper bound.

3.4 Mechanisms of fiber packing efficiency loss

Over-extrusion of filament leads to compressive stresses in the fibers, inducing buckling in the form of waviness. Waviness can be quantitatively defined as wave amplitude normalized by wavelength. By approximating the fiber waveform as sinusoidal, the relationship between over-extrusion and waviness can be derived. A MATLAB script was written to numerically determine this relationship by discretizing a sine wave and summing segment lengths, iteratively modifying amplitude until converging on a given over-extrusion value. Fig. 12a shows the sinusoids for five different over-extrusion values between 0% and 2%, incremented by 0.5%. A significant geometric change occurs between 0% and 0.5%, followed by a more gradual increase in amplitude with further over-extrusion. The relationship between waviness and over-extrusion is plotted in Fig. 12b, clearly showing this initial rapid increase followed by more gradual growth after around 0.2% over-extrusion.

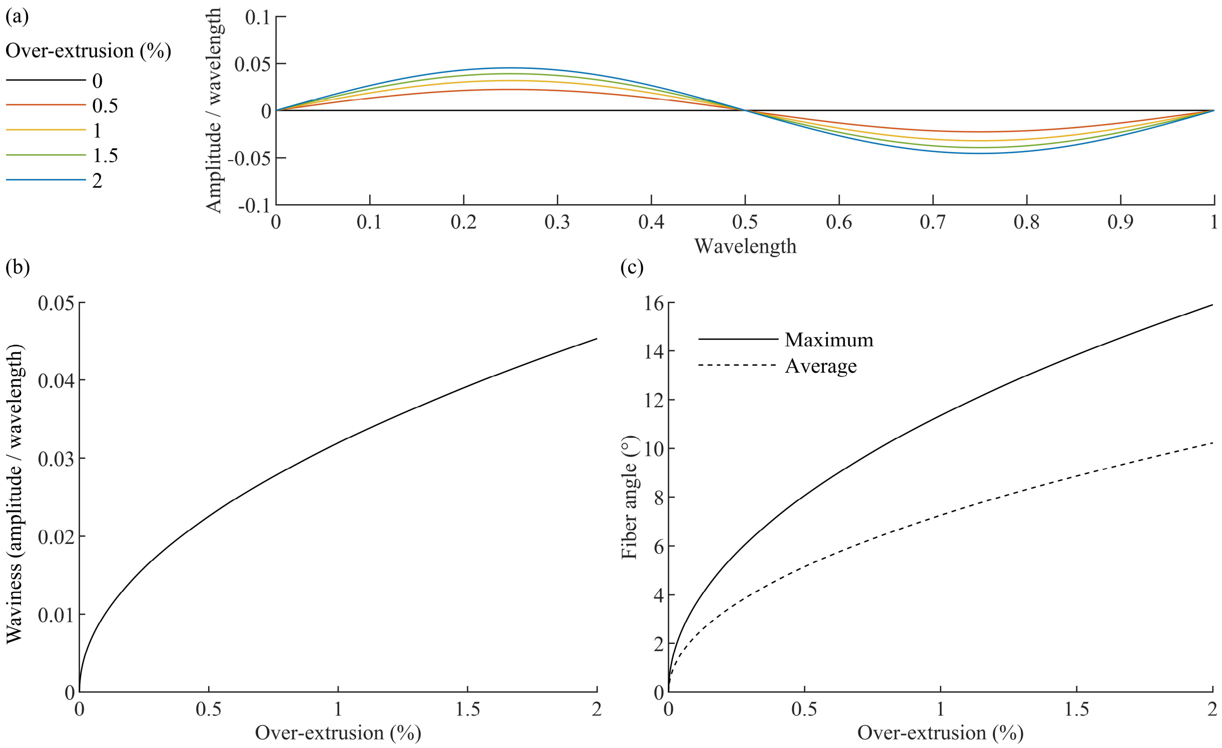

Fig. 12: (a) Sinusoidal waves resulting from various over-extrusion values. (b) Relationship between over-extrusion and fiber waviness. (c) Relationship between over-extrusion and the maximum and average absolute differences in fiber angles relative to the nominal fiber direction.

Fig. 12c shows the relationships between over-extrusion and the average and maximum absolute differences in fiber angles relative to the nominal fiber direction, following nearly identical trends to waviness. Maximum fiber packing efficiency is achieved when all fibers are straight and parallel to each other. The rapid increase in misaligned fibers with even small amounts of over-extrusion greatly increases the chances of fiber crossings occurring in the fiber network, which are highly detrimental to packing efficiency and consolidation quality [13]. It is likely for this reason that the upper bound of the DISC intra-bead void content data appears to follow a similar trend to the theoretical waviness and fiber angle curves (Fig. 11b). Furthermore, the development of misaligned fibers will also result in significant degradation of mechanical properties of the composite [5,12].

The increase in frequency of fiber crossings with increasing over-extrusion is problematic for two reasons. Firstly, whenever two fibers cross, they create a region which cannot be compacted to less than two fiber diameters in thickness (Fig. 13a). This limits the displacement of the DISC tool, affecting compaction of neighboring fibers. Secondly, every fiber crossing has the potential to create arrangements in which fibers can become deformed, storing up strain energy during consolidation, and decompacting once pressure is removed (Fig. 13b). Another source of strain energy development is the shear force of the DISC process buckling the already wavy fibers into tighter bent configurations. Once consolidation pressure is removed, the bent fibers can release the residual stresses by deconsolidating in- or out-of-plane.

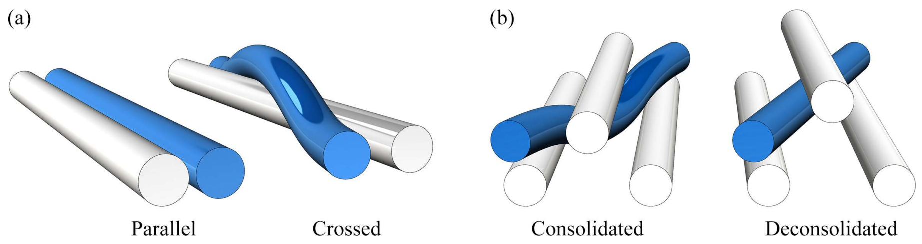

Fig. 13: (a) Doubling of compacted thickness that occurs when fibers cross. (b) Example of fiber arrangement caused by fiber crossing resulting in deconsolidation once compaction pressure is removed.

Three strategies to counter the severe deconsolidation behavior seen with over-extruded beads processed using DISC can now be proposed. Firstly, higher accuracy filament feed systems should be developed to better meter extrusion length and minimize over-extrusion. Secondly, deconsolidation occurs when an area of the bead without any consolidation pressure applied to it exceeds the melting temperature of the matrix. It may be possible to ensure that only regions under the DISC tool exceed the matrix melting temperature by increasing consolidation speed or lowering consolidation temperature. Lastly, as fiber packing efficiencies above the fiber volume content of 55% were difficult to achieve (Fig. 11a), perhaps the use of lower fiber volume fractions, e.g., 40%, may be more ideal for ensuring void-free composites.

4 CONCLUSIONS

This study has performed the first analysis of the effects of over-extrusion on the continuous fiber FFF and DISC processes. It was found that over-extrusion is the likely cause for in-plane fiber waviness commonly seen in continuous fiber FFF literature. Beads processed by FFF alone were seen to exhibit less sensitivity to over-extrusion in terms of intra-bead fiber packing efficiency and void content; however, their irregular cross-sectional profiles and any in-plane waviness is likely to result in poor inter-bead packing efficiency. At over-extrusion values less than around 0.1%, beads processed by DISC exhibited high intra-bead fiber packing efficiencies and low void contents, as well as rectangular cross-sections which should result in optimal inter-bead packing efficiency. However, the DISC process was found to be highly sensitive to greater over-extrusion values, exhibiting severe deconsolidation when exceeded a value of around 0.1%. Due to this extreme sensitivity, significant emphasis should be placed on controlling this parameter. Higher accuracy filament feed systems may need to be developed as even small amounts of error could result in a significant drop in material quality.

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