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Failure Analysis of Bi-Material FFF Parts

P. Fernández[a], F. Pelayo[a], D. Ávila[a], N. Beltrán[a], D. Blanco[a]*

[a]*IPFResearch Group, University of Oviedo, Gijón, 33203, Spain*

Abstract

Fused Filament Fabrication (FFF) is a popular additive manufacturing process where parts are built as a superposition of flat layers of material. The nature of this process allows for the use of more than one extruder within a single layer. This means that FFF can be used under a multi-extruder architecture which enables the manufacturing of multi-material parts. Examples of this type of parts can be found in mechanical and bioengineering fields. When designing this type of parts, bonding between different materials becomes a key issue, since the intention is that the part works as a whole while advantage is taken from dissimilar properties of materials. One of the main goals in this type of analysis is to determine the resistance that the part shows in the frontier between materials. This work aims on the analysis of failure behavior of bi-material FFF joints.

Keywords: FFF; Bi-Material; Failure Behaviour;

1. Introduction

Additive Manufacturing (AM) comprises a widening range of processes that use a layer-upon-layer deposition strategy in order to obtain three-dimensional objects. Fused Filament Fabrication (FFF) is the most popular group of AM processes because of its simplicity and potential. In FFF, a thermoplastic filament is extruded through a heated nozzle, so that it can be deposited following bi-dimensional trajectories upon a base tray to form a layer of solid material. Once a particular layer has been completed, the vertical distance between nozzle and tray is increased a value equal to the layer height, and this sequence goes on until the whole part has been completed.

* Corresponding author. Tel.: +34-(98)-5182444
E-mail address: dbf@uniovi.es

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The nature of this process allows for the use of more than one extruder within a single layer. This means that FFF can be used under a multi-extruder architecture which enables the manufacturing of multi-material parts. Multi-extruder designs include heads that are not only capable of simultaneously handling two or more materials, but even of combining materials by modifying their proportion on a single head [1]. Nevertheless, the use of this configuration has been very limited to this date, while the architecture that uses multiple independent extruder in a single machine remains the most popular. If this configuration is used in multi-material parts, one extruder should usually be waiting to do its task on a particular layer while other extruder is working. This limitation is mainly due to accessibility and it is preferable in order to avoid collisions between heads.

Multiple-material parts are expanding the possibilities of design in a wide range of uses. Ma et al. [2] studied the possibilities of Hybrid Deposition Manufacturing (HDM) in order to create multi-material parts with embedded components, pointing out the benefits of using this approach to reduce manufacturing and assembly time. They even provide examples of simple robotic mechanisms manufactured by HDM. Nevertheless, in this work one of the materials is deposited through AM, whereas the other is a resin poured in the existing gaps. Amin et al. [3] analyse the possibilities of combining additively manufactured frames with matrix made of silicone or PU foam for impact force and energy absorption. Raviv et al. [4] provide a method for designing self-evolving structures through the combination in one single body of two different materials: one rigid and other highly hydrophilic, so that the late is going to form an hydrogel and expand up to a 200% of the original volume when exposed to water.

Some researchers have focus their work in understanding the mechanical behaviour of multi-material parts. Thus, Roger and Krawczak [5] analyse the possibilities of designing structures that takes advantage of FFF possibilities, including heterogeneous infill of the part and multi-material parts. In their work, completely rigid multi-material parts made of “pure” ABS and carbon black-filled ABS have been tested. Spatial orientation of both volumes within the same part and material overlapping has also been considered in this work. Their results show that the existence of a frontier between both volumes weakens the part as a whole, so that the UTS values are significantly lower in the multi-material part with respect to equivalent “pure” ones. Moreover, no overlapping causes brittle fracture and no UTS value is provided for this case. Additionally, it should be noted that vertical orientation is less resistant than horizontal one. Nevertheless, images from this work reveal that the authors have used shells and probably other reinforcement structures, and that the workpiece have been already considered as two parts side-by-side instead of a real multi-material single part.

Moreover, the importance of bonding conditions in multi-material parts has been highlighted by Vaezi et al. [6] as one of the main challenges for multi-material manufacturing. It has to be concluded that, when designing this type of parts, bonding between different materials becomes a key issue, since the intention is that the part works as a whole while advantage is taken from dissimilar properties of materials.

Following this approach, the work of Lopes et al. [7] evaluates combinations of PLA, TPU and PET printed with a zebra-crossing pattern. They demonstrate that mechanical properties weaken when boundaries are introduced (even when the same material is placed at both sides of the frontier) with respect to the properties of continuous “solid” specimens. More relevant is their finding that chemical affinity between materials do also affects the strength of the part, with multiple zones and multiple-materials parts being weaker that multiple zones single-material specimens. Nevertheless, the images in this work show that the authors had included a shell feature during the CAM step (a usual procedure in FFF), and its possible reinforcement effect could affect the results. Similarly, they hadn´t considered the possible effect of overlapping between materials in the vicinity of the frontier. This circumstances could explain the fact that almost all failures during testing are reported to be produced exactly on the interface between materials. Once again, the selected approach tends to consider the multi-material parts as connected independent blocks instead of proper continuous volume. In other words: there is not a continuous transition between materials (in terms of geometry), but an abrupt one.

Taking all this into account, this work aims on the evaluation of failure behavior of bi-material FFF joints, considering continuous geometry transition between zones. This analysis will be particularized for parts combining rigid and flexible zones through tensional test.

2. Methodology and experimental planning

In this work, behaviour under load of bi-material additively-manufactured parts has been analysed. Two materials with different properties have been considered: PLA has been used for manufacturing rigid zones, whereas a commercial elastic TPU (Filaflex) has been used for flexible ones. Additionally, two configuration parameters that were expected to have an influence upon bond strength have been considered: the relative orientation of fibers (***α***) with respect to the direction of the force, and the degree of overlapping between rigid and flexible materials (***O***). Since there is a lack of standardization regarding part design and test specifically referred to additive manufacturing parts, the methodology described in ISO 6922:187 to test tensile strength in butt joints [8] has been adapted.

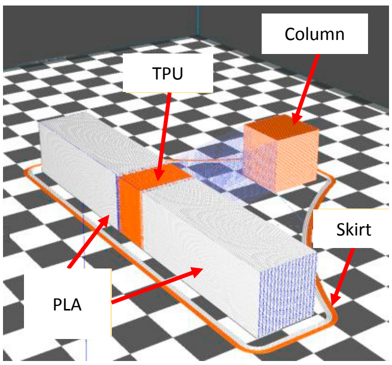
2.1. Design and manufacturing considerations of tests specimens

According to [8], a prismatic test specimen with rectangular section (10mm x 8mm) has been designed, so that both ends are built in rigid PLA with respective lengths of 50 mm, and it includes an intermediate section (10 mm long) built in flexible TPU. This model defines the basic shape and dimensions of test specimens used in this work, so that the same CAD file is used for all of them since the external dimensions and overall geometry are the same. Therefore, differences between specimens correspond to different combinations of the experimental factors (***α*** and ***O***) within the experimental range. Since both factors are related to manufacturing options, they are established during the CAM step.

Manufacturing of bi-material test specimens raised a series of practical issues that required some adjustments in the procedure. The main difficulties were related to the behaviour of flexible TPU during hot extrusion through the nozzle. Though fine adjustment of extrusion parameters of TPUs is an important issue itself, this task is even more complicated when building bi-material structures within the same layer. In this situation, while the head printing the PLA is working, the head with the TPU has to stand still, and through all the time lapse high temperatures in both the nozzle and the heater contribute to downgrade the TPU. Moreover, elastic materials present problems related to retraction movements: during retraction, flexible materials are prone to be drawn and their diameter reduced. This situation causes a reduction in the effective flow ratio when the extrusion movement restarts. Adjustment of flow ratio to get a proper infill is also a problematic issue, since inadequate low ratios prevent the material to fill the theoretical or desired area (causing isolated wires); on the other hand, inadequate high flow ratios cause the material to accumulate, locally increasing the actual height of the layer. To prevent this type of problems, a 0 mm retraction and 130% flow ratio had been used for TPU extrusion, whereas an auxiliary column (with no physical connection to the test specimen) is used to stabilize material flow.

Printing conditions are presented in Table 1, and they are common for every test specimen manufactured within the scope of this work. It also contains a graphic representation of the arrangement of these specimen and column on the manufacturing tray.

Table 1. Printing Conditions.

Parameter		PLA	TPU	Arrangement of specimen and column on the tray
Quality	Layer Height (mm)	0,4	0,4	
	Shell thicknes (mm)	0	0	
	Fill Density (%)	100	100	
Filaments	Diameter (mm)	2.85	2.85	
	Flow Rate (%)	100	130	
	Nozzle diameter	0.4	0.4	
Temperatures (ºC)	Extrusion	210	240	
	Waiting	210	240	
	Bed	65	65	
Retraction	Speed (mm/s)	50	40	

Distance (mm)	4	0

2.2. Experimental design

Two steps have been considered regarding experimental design: firstly, test have been conducted in order to compare bonding strength dependence with α; finally, overlapping influence is analysed.

The significance of α would be analysed considering four alternative disposition: three "linear" fibre orientations (0°, 45° and 90º) and a single "grid" disposition (with fibre in both 0º and 90º orientations) under no-overlapping conditions. The same conditions regarding manufacturing configuration and lack of reinforcement structures (shell, etc.) has been imposed in the case of this specimens. A graphic representation of the different dispositions for α are provided in Figure 1, were the rigid zones are represented in white colour and the flexible intermediate zone has been orange-coloured.

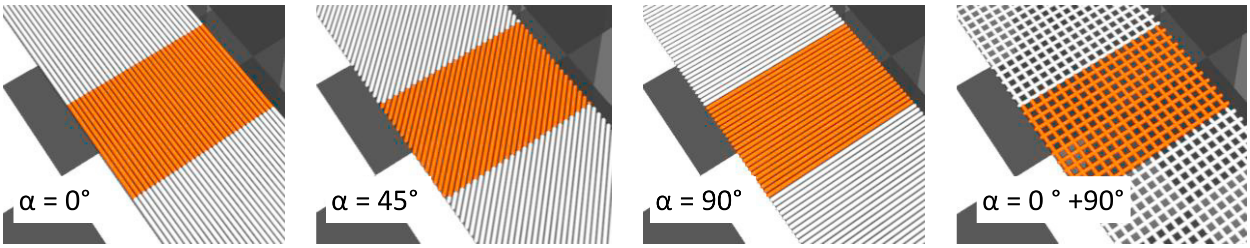


Fig. 1. Relative orientation of fibres within a layer for both linear and grid deposition strategies.

Finally, overlapping between materials would be analysed under three different conditions: 0 mm (which means that rigid and flexible zones share an ideal frontier; a plane, in the proposed design), 1 mm and 2 mm (both implying that a small frontier volume is shared by both materials). It has to be explained that overlapping does not imply extruding both materials on the same area, but alternatively displacing the limit from layer to layer. In a given layer, frontier between materials A and B is shifted in one direction, whereas in the following layer frontier is shifted in the opposite direction and so on. Since a value shall be given for the relative orientation of fibres, this last step in the experimental design has been analysed under two conditions: "linear" (α = 0°) and "grid" (α = 0º and 90º). A graphic representation of the different levels of overlapping for the particular case of "grid" fibre disposition can be found in Figure 2.

Five replicas of each particular test specimen designed according to each combination of test parameters have been manufactured using a double-head FFF BCN3D machine (Fig. 3). Each head has been loaded with rigid PLA and flexible TPU, respectively. Software Cura 1.0.3 for BCN3D has been used for configuration of manufacturing parameters and G-Code generation. Once the parts have been manufactured, they were measured using callipers and micrometres in order to check that the dimensions fulfil the rule of not exceeding the nominal values ± 0,1 mm. Tensional test were performed using a MTS Synergy machine (Fig. 3), equipped with a 5 kN load cell. Using the TestWorks software, values of test speed, specimen dimensions and initial distance could be fixed. In this case, a 5 mm/min displacement ratio has been used during test.

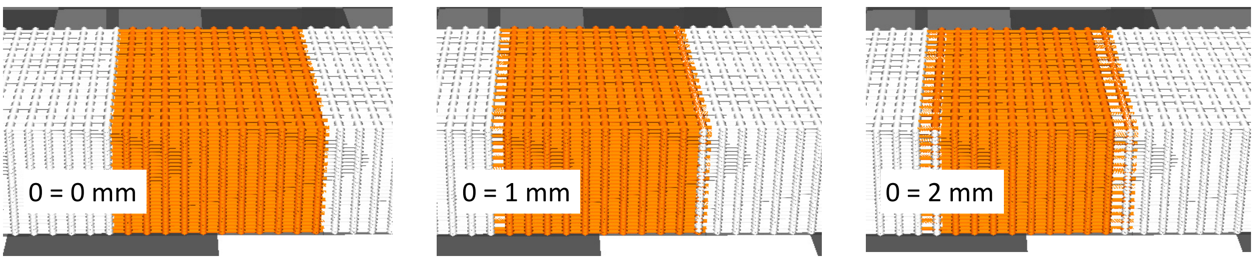


Fig. 2. Different levels of overlapping particularized for a "grid" fibre disposition.

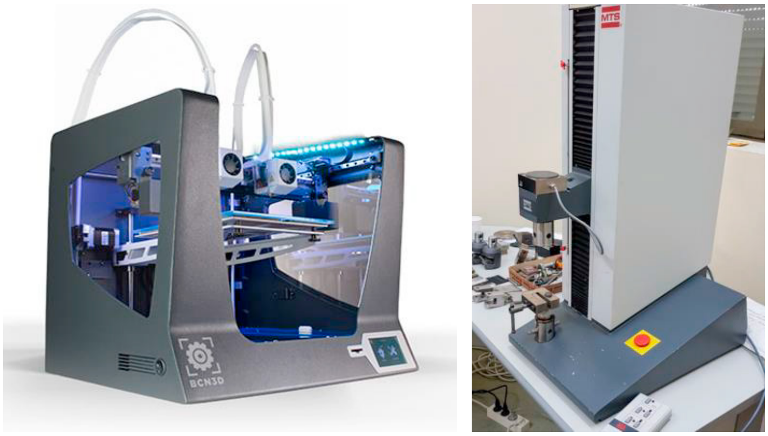


Fig. 3. BCN3D FFF machine with double independent heads (left) and MTS Synergy tensional test machine (right).

3. Results and discussion

3.1. Tensile strength and breaking behaviour dependence with O for no-overlapped bi-material parts.

From the results, it can be inferred that usual failures, when no-overlap exist between the bi-materials parts, are delamination-like process (45° and 90° patterns) inside the rigid volume and fibre breakage along the boundary (0° and 0º-90º grid patterns). In figure 4, it is shown the observed failure for specimens with 45° and 90° linear fibre orientations. The delamination mechanism occurs inside the rigid volume built on PLA, whereas TPU volume and the transition zone between both materials remain almost intact (Fig. 4). Fibre trajectories are superposed along Z manufacturing direction (layer upon layer).

The fail at the trajectory turning point of one of the unions between fibres, produces the initiation of the failure, which cause a peeling effect along the contact zone and the complete delamination-like failure observed. Then, the stresses are concentrated in another union between fibres being the failure procedure repeated again in the rigid material creating a zig-zag delamination pattern (see Figure 4).

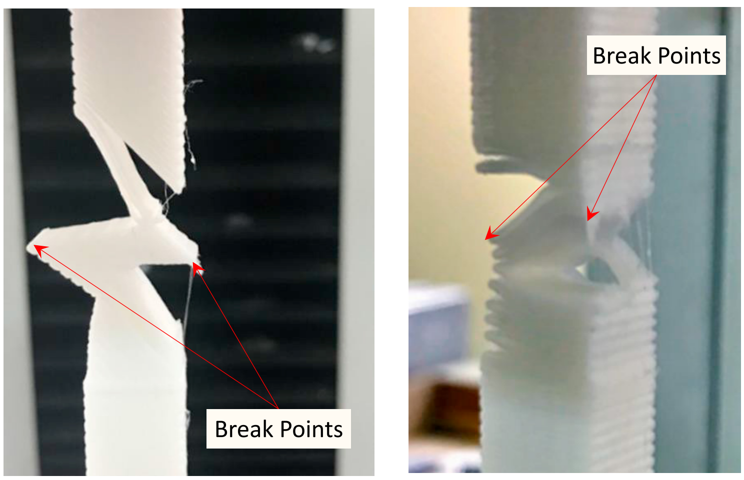


Fig. 4. Failure examples of non-overlapped 45° (left) and 90° (right) specimens

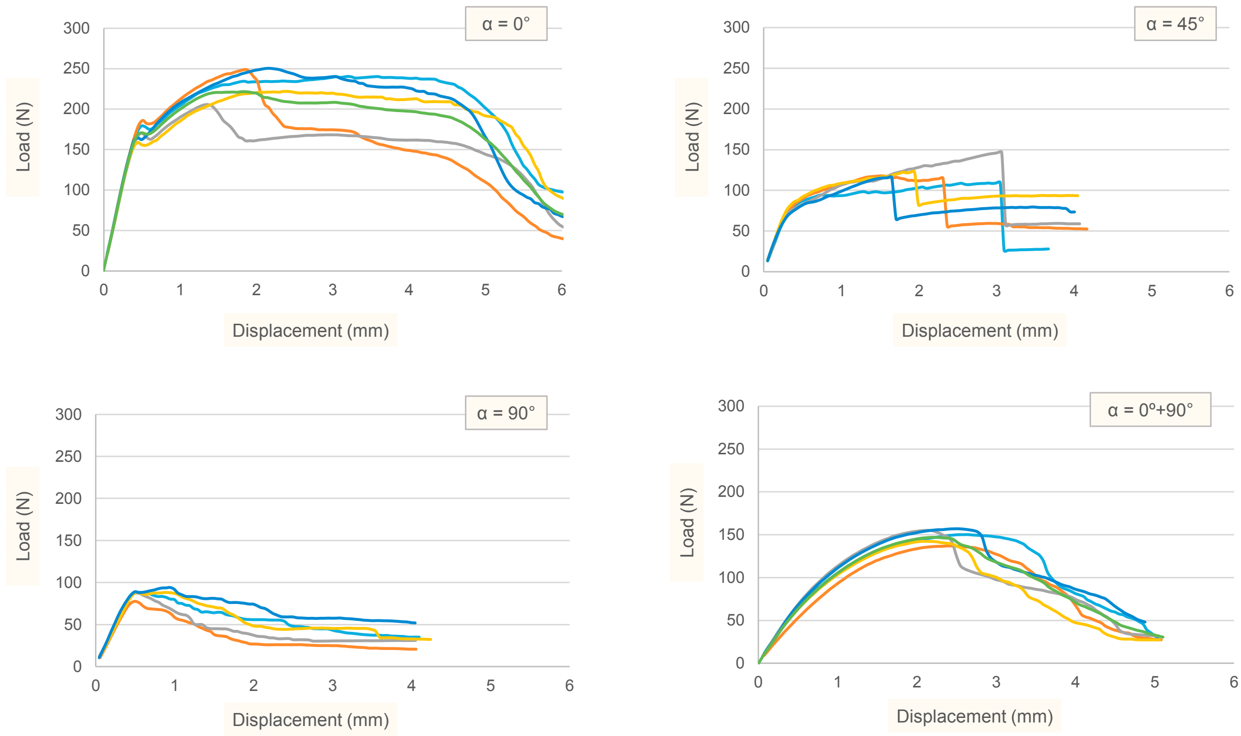


Fig. 5. Load-displacement graphics of non-overlapping 0º (top left), 45º (top right), 90º (bottom left) and grid (bottom right) test specimens.

Regards to the strength, the force-displacement curves obtained in the tensile tests for each α orientation are presented in Figure 5. Although the initial breakage of the specimens would set the practical design curve for the strength of each α orientation, the complete curves until 4-6 mm are shown in Figure 5. This allows to show the progress and the degree of the delamination-like failure in each orientation. For the tested orientations, the 45º orientation would be the "brittle" case where a large drop in load is produced after first delamination. On the other hand, the 0º-90º grid specimen presents a more continuous or "ductile" curve.

In order to compare the strength of each orientation, the value at 0.5 mm displacement was taken. This value corresponds with the initial failure of the 90º linear patter (the lowest). The lower strength values are obtained for the 45º and 90º orientations with an average force of 90 N and 80 N, respectively. Among both cases, the 45º orientation presents a plastic or creep zone being the maximum load before breakage around 110 N. However, no plastic (or creep) zone is clearly presented in the 90º orientation. For the linear patterns with 0º orientation is observed the highest strength with a maximum force of 175 N (at 0.5 mm displacement). In this orientation, after the first initiation of the failure, a plastic (or creep) zone is also observed (see Figure 5), being the maximum load before complete failure about 210 N. On the other hand, the 0º-90º grid patterns presents a totally different behaviour with a load of about 60 N for 0.5 mm displacement. Although the stiffness of the 0º-90º pattern is the lowest, the average maximum load was 160 N. Moreover, the 0º-90º grid specimens present the largest deformation before failure, followed by those corresponding to the 0º orientation.

3.2. Tensile strength dependence for overlapped bi-material parts.

To simplify the comparison in the overlapped bi-materials parts, the results of the average curves for the five tests in each configuration are presented in this section. The force-displacement curves are presented in Figure 6 where the cases: Overlap 0 mm, correspond with the average curves of 0º orientation and 0º-90º grid, presented previously in Figure 5.

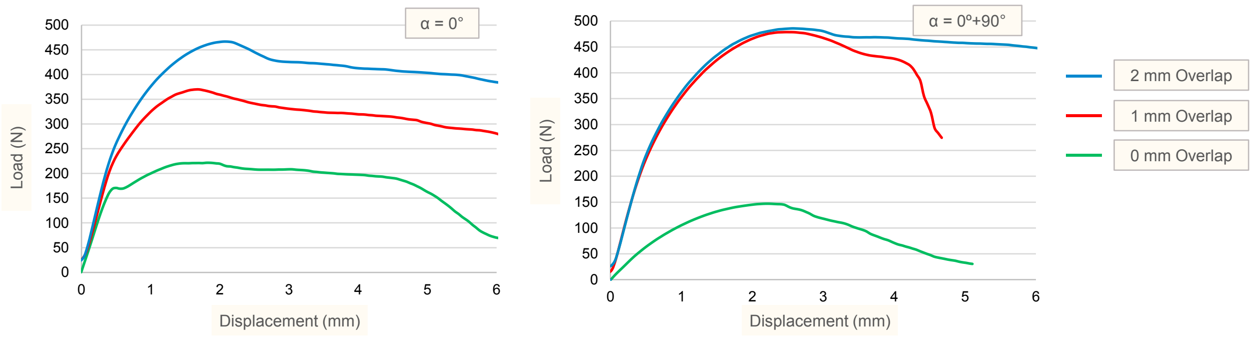


Fig. 6. Averaged load-displacement graphics of 0º linear pattern (left) and grid (right) test specimens for different degrees of overlapping.

From test results, it can be observed that using an overlap between both materials increases the final strength of the bi-material parts. The strength increment in the 0º fibre orientation specimens is about 33% for each millimetre of overlap. On the other hand, the strength increment is approximately a 200% when using overlap in the 0º-90º grid orientation. However, no significant increment was observed between using 1 or 2 mm overlap in these specimens. With respect to the fibre orientation, similar values are obtained for both configurations when 2 mm overlap is used. However, the 0º-90º grid specimens presents a higher strength than the 0º specimens for 1 mm overlap. Finally, it can be observed (see figure 6) that the failure initiation occurs for higher strains in the 0º-90º grid specimens. This could be identified as a great plasticity or creep capacity of the 0º-90º grid specimens.

Figure 7 provides a sequence of the failure process for a 1 mm overlapped grid pattern specimen. It can be clearly seen that the material in the proximity of the boundary (overlapped section) is progressively drawn till it reaches the corresponding UTS. The, TPU fibres maintain links between both materials, until they are finally broken.

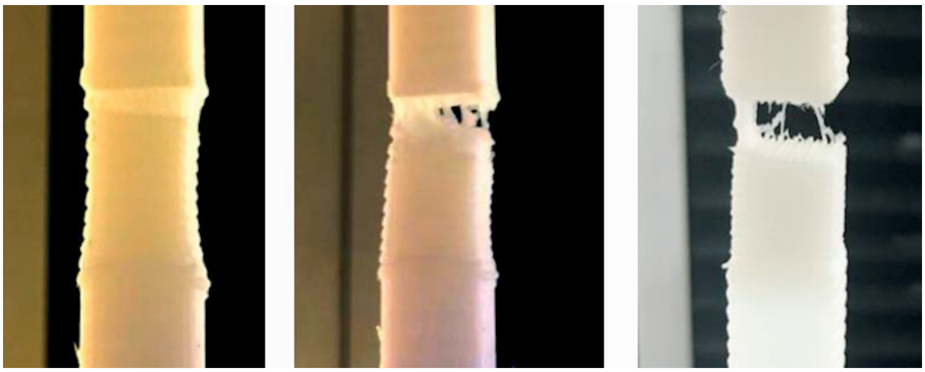


Fig. 7. Failure sequence of a 1 mm overlapped grid pattern specimen.

4. Conclusions and future work

This work has focused on describing and characterizing failure behaviour of FFF bi-material parts. In order to achieve this objective, parts have been designed and manufactured avoiding all possible sources of “artificial” reinforcement (such as shell or top/bottom solid layers) and frontier-like structures. This means that, instead of thinking of bi-material parts as individual parts that share a boundary, present work has considered the part as a single one with zones built on different materials. Under this approach, and considering no overlapping between materials, fibre orientation reveals itself as an important issue, since 45° and 90° linear fibre patterns provoke the parts to fail by delamination within the rigid PLA zone. Results show that a 0º orientation should be preferable if no overlapping is included in the design. Nevertheless, it is also clear that a minimum degree of overlapping causes a significant increase in the strength of the part (1 mm overlapping shall double this strength). Additionally, if overlapping is considered, orthogonal ($\boldsymbol{\alpha}$ = 0º and 90º) grid deposition strategies are preferable to linear patterns, since a slight improvement in strength can also be observed. Summarizing, our recommendation is that designers should use overlapping between materials and grid strategies in order to obtain higher values of strength, whereas grid strategies shouldn´t be recommended if, forced by design restrictions, no overlapping is applied.

Bonding conditions between materials in bi-material parts should be carefully analysed, and further work in this area should be carried on. Process improvements alongside with the development of enhanced engineering materials, suitable for FFF, will expand the possibilities of design and functionalities of bi-material parts. Bonding between different pairs of materials should be tested and characterized, taking into account the particularities of AM processes, like the multiple options available, regarding layer deposition strategies. Simultaneously, geometric characteristics of transitions should also be analysed.

References

[1] M. Khondoker, D. Sameoto. Design and Characterization of a Bi-Material Co-Extruder for Fused Deposition Modeling. ASME International Mechanical Engineering Congress and Exposition, Volume 2: Advanced Manufacturing, (2016)

[2] R.R. Ma, J.T. Belter, A.M. Dollar. Hybrid Deposition Manufacturing: Design Strategies for Multimaterial Mechanisms Via Three- Dimensional Printing and Material Deposition. Journal of Mechanisms and Robotics. (2015). 7: 021002

[3] A.R. Amin, Y.T. Kao, B.L.Tai, J. Wang. Dynamic Response of 3D-Printed Bi-Material Structure Using Drop Weight Impact Test. Proceedings of the ASME 12th International Manufacturing Science and Engineering Conference, MSEC 2017

[4] D. Raviv, et al. Active printed materials for complex self-evolving deformations, Scientific Reports, 4, 7422 (2014).

[5] F. Roger, P. Krawczak . 3D-printing of thermoplastic structures by FDM using heterogeneous infill and multi-materials: An integrated design-advanced manufacturing approach for factories of the future. 22ème Congrès Français de Mécanique. Lyon, (2015)

[6] M.Vaezi, S. Chianrabutra, B. Mellor, S. Yang. Multiple material additive manufacturing – Part 1: a review, Virtual and Physical Prototyping, 8:1, 19-50 (2013)

[7] L.R. Lopes, A.F. Silva, O.S. Carneiro. Multi-material 3D printing: The relevance of materials affinity on the boundary interface performance. Additive Manufacturing. 23 (2018) 45-52

[8] ISO 6922:187. Adhesives -- Determination of tensile strength of butt joints (1987)