HORIZONTAL FORMING IN ADDITIVE MANUFACTURING: DESIGN AND ARCHITECTURE PERSPECTIVE

ALEXANDER GEHT[1], MICHAEL WEIZMANN[2],
YASHA JACOB GROBMAN[3] and EZRI TARAZI[4]
[1,2,3,4]*Technion - Israel Institute of Technology*
[1]*geht@campus.technion.ac.il* [2,3,4]*{wmichael|yasha|ezri.tarazi}@technion.ac.il*

Abstract. Extrusion based three-dimensional additive manufacturing technology forms objects by driving the material through a nozzle depositing a linear structure through vector-building blocks called roads. In a common 3-axis system, the roads are stacked layer upon layer for forming the final object. However, forming overhanging geometry in this way requires additional support structures increasing material usage and effective printing time. The paper presents a novel Horizontal forming (HF) approach and method for forming overhanging geometry, HF is a new extrusion-based AM approach that allows rapid and stable forming of horizontal structures without additional support in 3-axis systems. This approach can provide new design and manufacturing possibilities for extrusion AM, with emphasis on medium and large-scale AM. HF can affect the outcome's aesthetic and mechanical properties. Moreover, it can significantly accelerate the production process and reduce material waste. The present paper maps the influence of various parameters employed in the HF method, providing a deeper understanding of the printing process. Additionally, it explores and demonstrates the potential functional and aesthetic characteristics that can be achieved with HF for industrial design and architectural products.

Keywords. Additive manufacturing; Support; Horizontal forming (HF); Extrusion-based system; Fused granulate forming (FGF).

1. Introduction

Additive manufacturing (AM) is considered the next fabrication revolution, with its emphasis on customization, decentralization, and rapid production. In less than four decades since their introduction, AM technologies have made impressive progress. Nonetheless, issues associated with poor material properties, slow fabrication, expensive cost, and scaling constraints limit many AM approaches to rapid prototyping for early modeling, education and research fields.

One of the most popular types of AM technologies is extrusion-based modeling (3D Hubs 2018). In this technology, the material is driven through the nozzle and deposits in a linear structure through vector-building blocks called "roads"

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 1, 203-212.

(Bellini, Guceri, and Bertoldi 2004). The roads are usually stacked layer upon layer (Figure 1, left) to form the final object. In this way, each new layer must be supported by the layer beneath it. Overhanging geometry over a certain degree (about 60°) (Figure 1, middle), or free-space segments (Figure 1, second from right) can be very challenging, if not impossible.

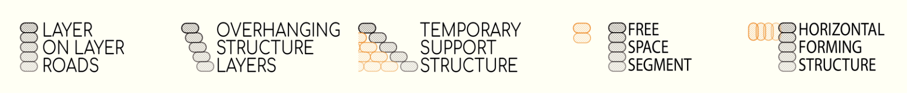

Figure 1. Figure 1: Material deposition types, using extrusion-based AM.

The current research explores and develops an additional method for forming overhanging structures, in an attempt to expand the capabilities of complex models forming in 3-axis extrusion-based AM, with emphasis on fabrication speed and manufacturing processes.

The paper begins with a background section that presents several common methods of forming overhanging geometries and describes the benefits and drawbacks of each. The main part of the research is presented in the following section, which maps Horizontal Forming (HF) basic criteria such as horizontal printing distance and the material amount by various experiments in overlapping printing. The last part of the paper presents a software tool that generates a G-code tool path and several case studies that compare printing with a regular slicer and the new HF oriented software tool.

2. Background

2.1. COMMON APPROACHES TO OVERCOMING OVERHANGING GEOMETRY IN 3-AXIS MACHINERY

2.1.1. Support structure

The most common approach to avoiding overhanging geometry failure is printing support structure. This is an additional structure generated under the overhanging geometry to prevent it from collapsing (Zhao and Xu 2019). Like a scaffold, it is a temporary structure, usually formed from the base up to the overhanging geometry. In some cases, when large areas of overhanging geometries are needed, the supports can become larger than the model itself in terms of volume, printing time, and amount of material used. As support is an additional structure, it required additional printing movements and increases the probability of failure. Moreover, removing the support is highly labor-intensive and time-consuming, and can damage the model’s surface.

2.1.2. Avoiding overhanging geometry

In some cases, complex shapes with large overhanging geometries are divided into several parts and printed in different orientations in order to avoid the need for support. As a result, the assembly process needs to be considered and integrated into the design, making the design and production more complex. Moreover, gaps between parts can appear during the printing process, due to material deformation and the different printing orientations.

2.1.3. Freeform 3D printing

Freeform is a technique of forming spatial structures without the need for support (Huang et al. 2016). It is based on a very slow printing process and material cooling. As a result, the extruded material solidifies in the course of the movement to create free-standing strands of material in space (Oxman et al. 2013). Although this method allows complex forming, it requires custom machinery adaptations and a high level of control over software and hardware (Molloy and Miller 2018). Moreover, the outcome of the freeform process tends to be less consistent with the design model, depending on material properties and printing parameters. Finally, as the material cools, fusion quality between the cross-sections can be poor.

3. Horizontal Forming

Horizontal Forming is a new approach to creating overhanging structures using common, 3-axis machinery without relying exclusively on direct layering methods. HF is based on Fleximatter's method for fabricating hollow objects (Meshorer and Vasilevski 2017). HF based methods were developed especially for medium and large-scale fused granular fabrication (FGF) aiming to simplify and accelerate extrusion-based AM processes by cutting the need of support or infill at the manufacturing process.

The method comprises deposition of modeling material in parallel horizontal contours, wherein at least one of the contours is extruded horizontally above a three-dimensional region devoid of any solid support (Figure 1, right). The structure solidifies during the forming process and allows forming horizontal surfaces in mid-air without any support. HF provides new design complexity and can be more effective in material usage and manufacturing time, which are extremely important factors in manufacturing considerations (Austern, Capeluto, and Grobman 2018).

FGF may use industrial-grade, low-cost, and highly diverse materials. Moreover, this technology can be easily scaled up, for example by being mounted on a mobile platform, expanding the printing boundaries and providing almost limitless printing size (Keating and Wallace 2016). Thanks to simple machinery and affordable materials, this technology has a huge potential in the industrial and architectural design fields.

4. Research Aim

The main aim of this research is developing a new approach (HF) to printing self-supporting horizontal structures and examining the effects of the overlap and material amount parameters on the performance of a new approach. The study was conducted in two phases. In the first, experimental phase, we defined and mapped the HF method parameters by examining the effect of overlap and material amount as the most significant parameters in this method (Meshorer and Vasilevski 2017). In this phase, we observed and analyzed the material's behavior and formation, providing basic insights for developing the new approach as well as the database for future research.

In the second phase of the research a G-code path generator software tool was developed based on the data and conclusions from phase 1 experiments. The tool was tested in case study experiments that were designed to explore and demonstrate potential functional and aesthetic characteristics of HF from industrial design and architectural perspectives.

5. Phase 1: Mapping and Examination

5.1. DESCRIPTION OF MACHINERY

Initial testing was carried out with a medium-scale Fleximatter (850×750×1000 (X-Y-Z)) FGF system, using a 2mm nozzle. This technology was chosen given its ability to print medium-scale products and architectural fragments. Granulate ABS material was chosen as the most common and affordable industrial material for commercial objectives. For this study, we applied transparent ABS also known as MABS (methacrylate-acrylonitrile-butadiene-styrene (LG MABS TR557)). The raw material was mixed with pigments to provide immediate visual feedback, enabling us to examine contour fusion quality, as detached material leaves a white mark on the fused area (Bellehumeur and Li 2004) (Figure 5).

One of the most important HF parameters is contour overlap, defined as the distance between two adjacent contours (Figure 3, bottom). To define the overlapping distance range, we printed the same structure with overhanging geometry, observing the effect of the overlap distance. The overlap resolution was defined for the experiment as 0.1mm, with the experiment starting from zero overlap (no contact between contours), and reaching up to an overlap equal to nozzle diameter.

5.2. PHASE 1: EXPERIMENT

The experiment's aim was to map and define the influence of various parameters on contour-overlap and material-amount on the printed result. Contour-overlap is defined as the distance between two adjacent contours (Figure 3, bottom). To define and map the printable overlapping distance range, we printed 200X50mm rectangle with 90 deg overhanging surfaces every 10mm (in the z-axis) with overlapping parameter increased by 0.1mm every following overhanging surface until the structure failed to form. The experiment started from zero overlap (no contact between contours) and reached up to an overlap equal to nozzle diameter (2mm). A rectangle modeled with varied rounded edges was used to observe forming behavior at round and sharp geometry.

To investigate the effect of the material amount on HF the process was done with different amounts of material. Material amount range defined between cross-section area of 1.196mm2 that equivalent to a cross-section of 0.5mm layer height and 2.5mm road width up to 4.141mm2, equivalent to a cross-section of 2mm layer height and 2.5mm road width.

5.3. RESULTS

5.3.1. Layer-on-layer vs. horizontal forming

The results show a significant difference between traditional layered roads (Figure 2A) and horizontal contour cross-section (2B), as the material forms under different conditions. Traditional layered road height is defined as that between the previous layer and the nozzle, providing constant boundaries due to the deposition process. While layer height is constant, the amount of extruded material affects road width. Both parameters affect the road cross-section shape, forming a symmetric road cross-section that can be calculated and predicted (Comminal et al. 2018).

Horizontal contours form, however, as the extruded material has enough overlap with the previous contour and fuses. Since the previous contour is the only boundary, the contour forms as an asymmetrical shape (Figure 2, right). Furthermore, predicting the contour cross-section is challenging as there is no material beneath the extruded layer and contour forming depends on material solidification, which is affected in turn by cooling and material characteristics. Unlike roads, contour width (Cw) depends on nozzle diameter (Nd) and overlap (O) (Cw=Nd-O). Our observations show that nozzle diameter limits the maximum contour width. Contour height is more complex to predict as it depends on material amount and solidification.

Based on the observation of the printed roads and contour cross-section shapes (Figure 2), it seems that the standard slicer used in the layer-on-layer method is unsuitable for working with the HF method, which requires a different approach due to the difference between roads and contours.

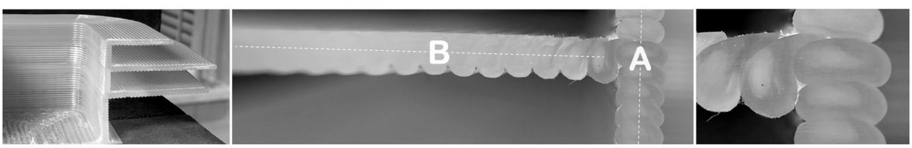

Figure 2. Figure 2: Layer on layer and horizontal forming cross-section. Left: Printed model with stable HF. Middle A: Roads cross-section. Middle B: Contour cross-section. Right: Cross-section close-up.

5.3.2. Horizontal forming parameters

HF's success and mechanical characteristics depend on the overlap distance and material amount. The results of the different overlapping distances were classified into three main classes, based on contour fusion quality: "fail", "stable" and "over-overlap" (Figure 3): low overlapping distance will fail to form horizontal geometry due to low or non-fusion between two adjacent contours (Figure 6: overlap=0.0mm). Increasing the overlap will increase fusion quality providing a stable and constant horizontal structure since the extruded material will have enough surface to be attached to (Figure 6: overlap=0.2-0.5mm). Using stable HF parameters will enable forming a neck growth fusion providing a stable structure

(Bellehumeur and Li 2004).

There is a point of over-overlapping, however, where the material will accumulate excessively, and the designed geometry will be deformed, similarly to the over- extrusion effect in the layering method (Figure 4). It is complex to predict material deformation caused by over-overlapping, as in some cases, the material is not fully solidified, and the overhanging geometry bends up during the forming process (Figure 4, left). In other cases, with solidified geometry, the material starts to generate natural random patterns (Figure 4, middle). Still, other cases involve a combination of random patterns and bending (Figure 4, right) (O'Dowd et al. 2015).

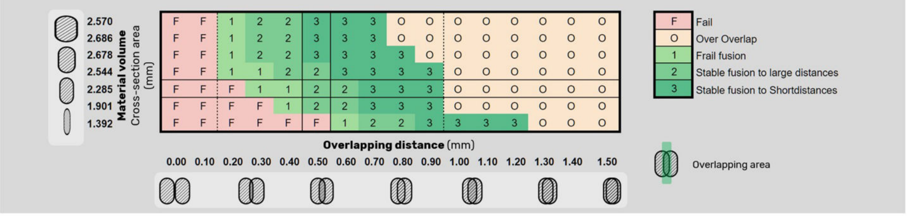

Figure 3. Figure 3: Mapping of the effect of overlapping and material amount. "F" refers to failure to fuse. "O" refers to over-overlapping. 1 - Frail contour fusion. 2 - Stable fusion for long HF. 3 - Stable fusion for short HF, after which it becomes over-overlapping.

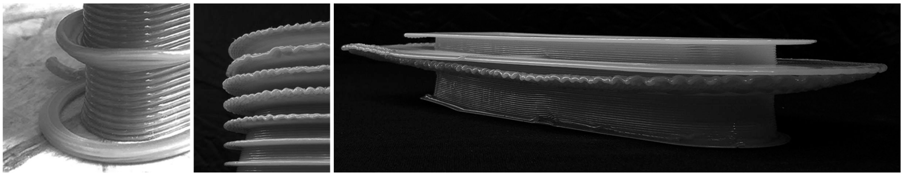

Figure 4. Figure 4: Over-overlapping parameters. Left: Material banding upward; Middle: random texture; Right: Material bending with random texture.

Stable fusion parameters, in this setup, have a range of around 0.6mm, providing a constant horizontal structure with differential fusion quality (Figure 3, 1-3). Parameters with low relative overlapping will form frail fusion (Figure 3, 1; Figure 4, left). Frail fusion can be used as a design and manufacturing tool: those areas can be used as a new opportunity to redesign material properties, 4D structures, or detachable areas (Tibbits 2014). For example, frail fusion areas can be set as an interface between the model and support structure)that can be easily removed(or be defined as foldable areas.

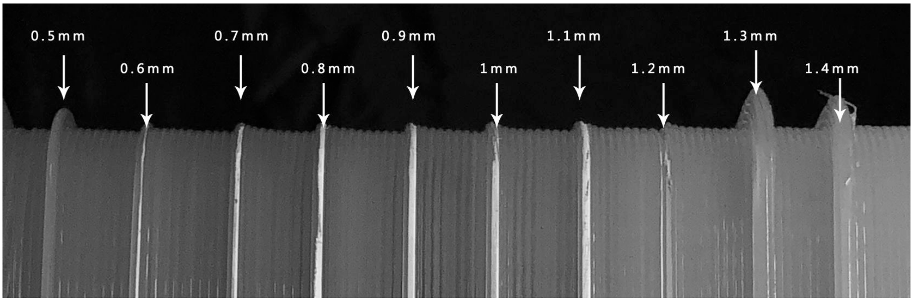

Figure 5. Figure 5: The white linear mark represents the fusion area between two contours after detachment. Left: 0.5mm overlap distance - providing frail fusion; contours were easily detached. Right: 1.3mm overlap distance - neck-growth fusion; impossible to detach manually.

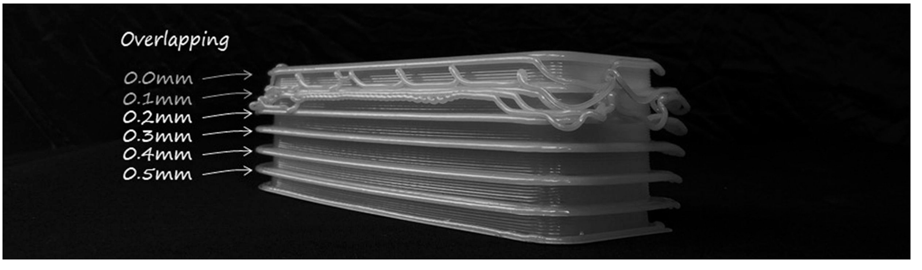

Figure 6. Figure 6: HF affected by overlapping parameters. 0.5mm overlap: stable forming; 0.0mm overlap: failure to form a horizontal structure.

5.3.3. Material effect

Common industrial materials have a shrinkage rate that adds complexity to the deposition process (Wang, Xi, and Jin 2007). Formed material continually deforms due to the deposition process. Forming horizontal geometry will take more time between two consecutive layers, and the layer with HF may shrink and deform while printed. Furthermore, as the layer has more overhanging contours, it will take more time to form, hence greater deformation. Additionally, as more contours are formed in the same layer, shrinkage forces will be stronger, leading to significant deformation; in some cases, a layer might fail to print due to the deformation of the previous one. Whereas forming failures due to material shrinkage can be predicted in the modeling stage, this is very complex due to the multiple parameters affecting deformation.

6. Phase 2: Case study - Freeform HF

Since the invention of AM, there has been a separation between the machinery (3D printer) and design tools. Technological advancements have concentrated on the manufacturing process, developing new materials, scale, and optimizing the machinery performance. The gap between the machinery and CAD was bridged by third-party software, known as a slicer. Although the slicer makes the design model printable, it limits the technology's potential. As a result, most of extrusion-based AM parameters set as a constant parameter in the course of the printing process to simplify and ensure a stable and successful manufacturing process.

Yet, extrusion-based AM is a continuous process of material extrusion and machinery motion, which can be used similarly to a craft process, where the outcome is affected by the material's behavior and the motion of the tool. Tacit knowledge of expert operators can predict the effect of motion, material quantity, and temperature on the material's behavior. Having the designer's knowledge embodied in the technology allows designing unique artifacts just by having the vision of material behavior driven by the machinery. The most interesting part is to be able to translate this knowledge into a design tool everyone will able to use (Bilotti, Norman, and Rosenwasser n.d.).

Next, we provide examples of applying freeform modeling rather than the slicer method using HF, and present other areas with potential for applying this method.

6.1. SLICER-GENERATED HF

The Fleximatter slicer uses 3D models to automatically generate paths for the printer and adds horizontal contours by generating offset contours at the required layer (model height). This method is effective in structures that require uniform horizontal reinforcement with horizontal ribs (Figure 7), forming horizontal support scaffolds for free-space objects and for other applications. However, this slicer generates horizontal structures only, as model offsets and the same overlap parameter are defined for the whole layer, without the ability to define variable overlapping within a single layer.

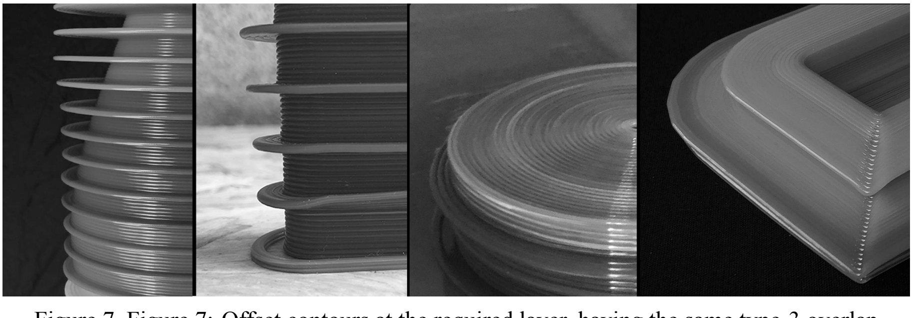

Figure 7. Figure 7: Offset contours at the required layer, having the same type-3 overlap parameter, which have become over-overlapping after a few contours.

6.2. HORIZONTAL FREEFORM

In order to control the overlapping parameters over the forming process, a G-code path generator software tool was developed. The tool allows defining the overhanging structure as a tool path, with full control of deposition motion and direction. The tool was developed in Rhino and Grasshopper environments. It was based on the tested parameters from phase 1 and developed to fit the Fleximatter machinery.

Figure 8. Figure 8: HF design tool types.

The tool was used for generating several examples to explore the new possibilities for HF. The first example introduces local HF on the model surface - we were able to form horizontal contours on the specific areas of the model, without having to form an offset of the entire model, saving printing time. Using this method, we can reduce model damage caused by printing offset contour over the whole model. Moreover, we are able to control the shape and size of the structure.

The second example is based on fusion behavior driven by overlapping distance. Mechanical and aesthetic properties can be applied to the design model on the horizontal structure: Breaking point (Figure 8) - frail fusion contours can be set in a stable horizontal structure, providing a predicted breaking point as a design and manufacturing feature.

An additional example is a deferential HF (Figure 9). The overlap parameter can be applied in more complex shapes, controlling contour behavior between full fusion, frail fusion or fail areas to represent deferent aesthetics and functional properties, such as airflow, transference, and flexibility. This very basic tool helps us show a new way to think and design using this method. It is an important basis for future research.

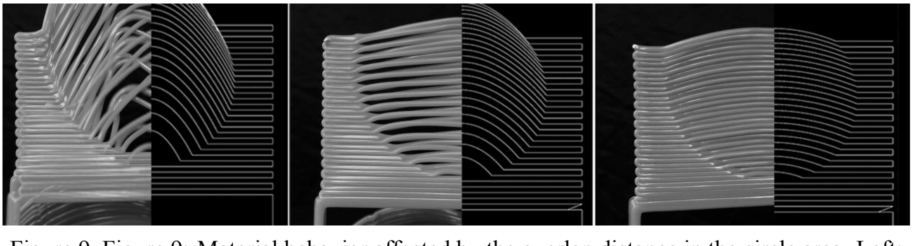

Figure 9. Figure 9: Material behavior affected by the overlap distance in the circle area. Left: 5mm overlap; Middle: 2.5mm overlap; Right: 1.6mm overlap.

7. Conclusion

The research explores the potential of horizontal forming (HF) for fabricating complex overhanging structures without the need for additional support or post-processing. Literature suggested that employing HF can accelerate the manufacturing process and reduce material waste - advantages that are particularly critical in medium - and large-scale AM. The paper focused on mapping the overlap distance relative to extruded material volume and developing and examining the potential of a new software tool for HF, presenting new possibilities of using HF.

Mapping the effects of overlap distance and material amount allows predicting and programming the fusion type between contours, thus adding another layer of complexity to the HF method. The case study models demonstrated that the HF structures are stable for medium-scale products and architectural fragments.

FGF AM technology seems to have significant potential for desktop, large-scale and architectural manufacturing. Moreover, this method may be suitable not only for fused extrusion, but also when using other materials.

References

Austern, G., Capeluto, I.G. and Grobman, Y.J.: 2018, Rationalization methods in computer aided fabrication: A critical review, *Automation in Construction*, **90**(December 2017), 281-293.

Bellehumeur, C. and Li, L.: 2004, Modeling of Bond Formation Between Polymer Filaments in the Fused Deposition Modeling Process, *Journal of Manufacturing Processes*, **6**(2), 170-178.

Bellini, A., Guceri, S. and Bertoldi, M.: 2004, Liquefier Dynamics in Fused Deposition, *Journal of Manufacturing Science and Engineering*, **126**(2), 237.

Comminal, R., Serdeczny, M.P., Pedersen, D.B. and Spangenberg, J.: 2018, Numerical modeling of the strand deposition flow in extrusion-based additive manufacturing, *Additive Manufacturing*, **20**, 68-76.

Huang, Y., Zhang, J., Hu, X., Song, G., Liu, Z., Yu, L. and Liu, L.: 2016, FrameFab: robotic fabrication of frame shapes, *ACM Transactions on Graphics*, **35**(6), 1-11.

Hubs, initials missing: 2018, “3D Printing Trends Q1/2018” . Available from <https://f.3dhubs.com/tpeFNMnNBD83pKJYnSHpne.pdf>.

Keating, S.J.: 2016, *From Bacteria to Buildings: Additive Manufacturing Outside the Box*, no thesis type given, no school given.

Meshorer, Y. and Vasilevski, A.: 2017, “METHOD AND SYSTEM FOR FABRICATING HOLLOW OBJECTS” . Available from <https://patentimages.storage.googleapis.com/f3/28/e7/35f082462ab539/US20170274575A1.pdf>.

Molloy, I. and Miller, T.: 2018, Digital Dexterity, *ACADIA*, 266-275.

O’Dowd, P., Hoskins, S., Walters, P. and Gelsow, A.: 2015, Modulated extrusion for textured 3D printing, *International Conference on Digital Printing Technologies*, 173-178.

Oxman, N., Laucks, J., Kayser, M., Tsai, E. and Firstenberg, M.: 2013, Freeform 3D printing, *Green Design, Materials and Manufacturing Processes*, 479-483.

Sabin, J.: 2018, Robosense 2.0, *ACADIA*, 276-285.

Turner, B.N., Strong, R. and Gold, S.A.: 2014, A review of melt extrusion additive manufacturing processes: I. Process design and modeling, *Rapid Prototyping Journal*, **20**(3), 192-204.

Wang, T.M., Xi, J.T. and Jin, Y.: 2007, A model research for prototype warp deformation in the FDM process, *International Journal of Advanced Manufacturing Technology*, **33**(11-12), 1087-1096.

Zhao, P. and Xu, M.: 2019, *Lecture Notes in Electrical Engineering 543. Advances in Graphic Communication , Printing and Packaging*, S.