PARAMETRIC ZIGZAG TOOLPATH GENERATION FOR THIN-WALLED STRUCTURES IN WIRE LASER ADDITIVE MANUFACTURING: A GRASSHOPPER-BASED APPROACH

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Abstract - This paper proposes a parametric approach for generating zigzag toolpaths for thin-walled structures in wire laser additive manufacturing using Grasshopper. Three zigzag types - sinusoidal, sharp-angle, and square-angle - were developed with adjustable parameters such as width and spacing, and applied to various path shapes including lines, arcs, and curves. Experiments were conducted by fabricating 6 mm wide, 50-60 mm long, and 16 mm high walls using a 5-axis wire laser additive manufacturing system with 316L stainless steel wire. Results revealed clear differences in dimensional accuracy and surface finish, with the sinusoidal pattern showing the closest match to design and smoothest surface. The proposed parametric method provides a flexible tool for toolpath generation in wire laser additive manufacturing.

Key words - Zigzag toolpath; Thin-walled structure; Wire Laser Additive Manufacturing; Grasshopper; Parametric method.

1. Introduction

Wire Laser Additive Manufacturing (WLAM) represents a promising approach for fabricating metallic components with high material efficiency and reduced production costs compared to powder-based methods [1]. However, generating optimal toolpaths for additive manufacturing remains challenging, particularly for thin-walled structures that require precise deposition strategies to maintain dimensional accuracy and structural integrity [2, 3].

Traditional toolpath generation methods often rely on pre-defined patterns with limited customization capabilities [4, 5]. The development of parametric approaches that allow for flexible pattern generation and application to various geometric paths could significantly enhance the capabilities of additive manufacturing processes [6]. Computational design tools such as Grasshopper, a visual programming environment for Rhinoceros 3D, offer promising platforms for developing such parametric toolpath strategies [7].

The zigzag toolpath pattern is particularly effective for both thin-walled and infilled structures. The traditional zigzag approach has been found to be computationally efficient, and it achieves optimal overlapping distances that enhance the quality of the printed object.

This research presents an innovative methodology for generating customizable zigzag toolpaths using Grasshopper, with specific focus on thin-walled structures. Three zigzag pattern variants - sinusoidal curves, sharp-angled curves, and square-angled curves - were developed with parametric control over key characteristics including zigzag width and spacing. The methodology allows for applying these patterns to arbitrary path geometries, thus providing a versatile framework for toolpath generation in WLAM applications.

2. Related works

Toolpath generation strategies for additive manufacturing have evolved significantly in recent years. Initial approaches predominantly utilized simple raster or zigzag patterns with fixed parameters [8, 9]. More recent research has focused on adaptive strategies that adjust toolpath characteristics based on geometric features [5, 10].

For thin-walled structures specifically, Ding et al. [11] demonstrated that toolpath design significantly impacts the final part quality, with oscillatory patterns showing advantages for maintaining consistent wall thickness. The integration of computational design tools in toolpath generation has gained traction in recent years. Ashrafi et al. [12] utilized Grasshopper to generate toolpaths in the additive manufacturing of concrete.

Despite these advances, limited research exists on fully parametric zigzag pattern generation for WLAM of thin-walled structures. The present work aims to address this gap by developing a versatile Grasshopper-based framework that enables the creation of customizable zigzag patterns applicable to arbitrary path geometries.

3. Methodology

3.1. Parametric Zigzag Pattern Generation in Grasshopper

Grasshopper is a visual programming language integrated with the Rhinoceros 3D CAD software, allowing users to create complex parametric designs and geometries. Its intuitive interface enables the modeling of intricate shapes through mathematical representations, making it an ideal tool for applications in additive manufacturing, particularly in generating toolpaths for 3D printing.

The proposed methodology leverages Grasshopper's visual programming environment to create parametric zigzag toolpaths. Three distinct zigzag pattern types were developed:

1. Sinusoidal zigzag (Figure 1.a): Utilizes sine wave functions to create smooth, curved oscillations;

2. Sharp-angled zigzag (Figure 1.b): Creates triangular patterns with sharp turning points;

3. Square-angled zigzag (Figure 1.c): Produces rectangular patterns with 90° turns.

For each pattern type, the following parameters were made customizable:

- Zigzag width, W (mm);

- Inter-path spacing (distance between consecutive zigzag lines), S (mm);

- Base path geometry (straight line, curve, circle, etc.).

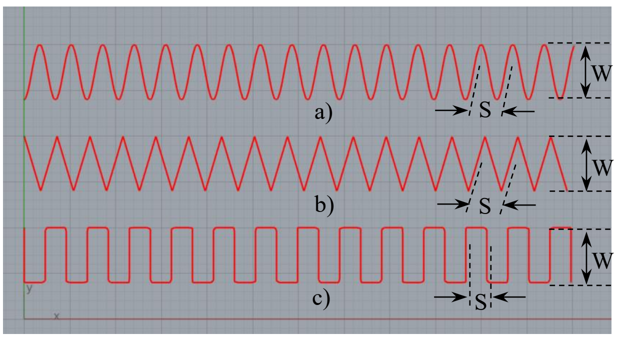


Figure 1. *Three parametric zigzag patterns in straight lines generated in Grasshopper: a) Sinusoidal zigzag, b) Sharp-angled zigzag, c) Square-angled zigzag*

3.2. Pattern application to arbitrary path geometries

A key feature of the developed methodology is the ability to apply zigzag patterns to arbitrary path geometries. This was achieved through the following steps:

1. Creation of the base path geometry (straight line, curve, circle, etc.);

2. Generation of the parametric zigzag pattern;

3. Mapping the zigzag pattern onto the base path using Grasshopper's "Flow Along Curve" component;

4. Adjustment of the pattern based on local curvature of the base path.

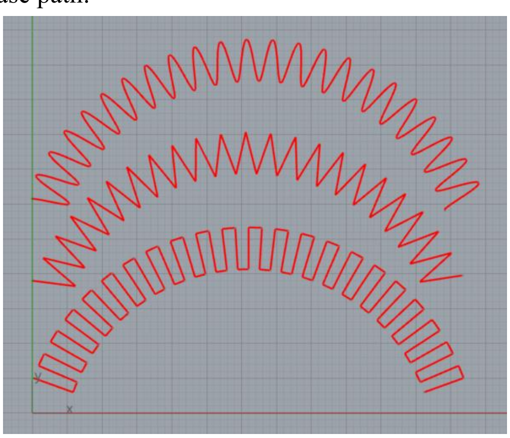


Figure 2. *demonstrates examples of the three zigzag patterns applied to a curved path*

3.3. Thin-walled structure design

For experimental validation, three straight thin-walled structures with the following parameters were designed:

Zigzag width: W = 6mm

Inter-path spacing: S = 3.45mm (This value is determined based on the welding bead width and the overlap ratio between them).

Length: 50-60mm

Height: 16mm (equivalent to 10 layers at 1.6mm layer height).

The zigzag patterns in successive layers will be arranged to overlap each other, the concave part of the zigzag in one layer will be built up by the convex part of the zigzag in the next layer.

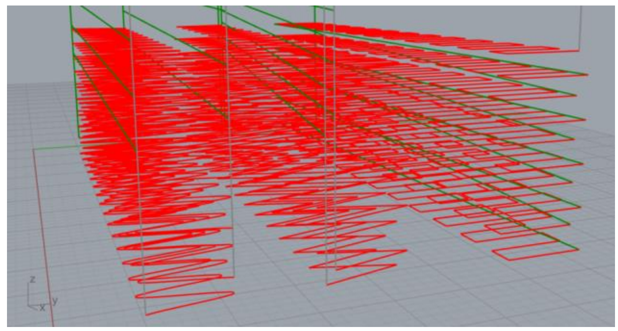
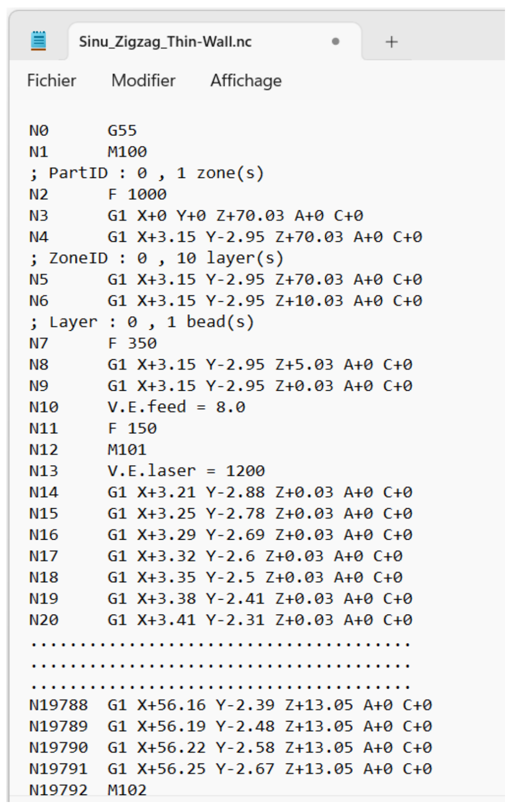


Figure 3. *Straight thin-walled structures with three parametric zigzag patterns in Grasshopper*



```
Sinu_Zigzag_Thin-Wall.nc
Fichier   Modifier   Affichage

N0      G55
N1      M100
; PartID : 0 , 1 zone(s)
N2      F 1000
N3      G1 X+0 Y+0 Z+70.03 A+0 C+0
N4      G1 X+3.15 Y-2.95 Z+70.03 A+0 C+0
; ZoneID : 0 , 10 layer(s)
N5      G1 X+3.15 Y-2.95 Z+70.03 A+0 C+0
N6      G1 X+3.15 Y-2.95 Z+10.03 A+0 C+0
; Layer : 0 , 1 bead(s)
N7      F 350
N8      G1 X+3.15 Y-2.95 Z+5.03 A+0 C+0
N9      G1 X+3.15 Y-2.95 Z+0.03 A+0 C+0
N10     V.E.feed = 8.0
N11     F 150
N12     M101
N13     V.E.laser = 1200
N14     G1 X+3.21 Y-2.88 Z+0.03 A+0 C+0
N15     G1 X+3.25 Y-2.78 Z+0.03 A+0 C+0
N16     G1 X+3.29 Y-2.69 Z+0.03 A+0 C+0
N17     G1 X+3.32 Y-2.6 Z+0.03 A+0 C+0
N18     G1 X+3.35 Y-2.5 Z+0.03 A+0 C+0
N19     G1 X+3.38 Y-2.41 Z+0.03 A+0 C+0
N20     G1 X+3.41 Y-2.31 Z+0.03 A+0 C+0
.......................................
.......................................
.......................................
N19788  G1 X+56.16 Y-2.39 Z+13.05 A+0 C+0
N19789  G1 X+56.19 Y-2.48 Z+13.05 A+0 C+0
N19790  G1 X+56.22 Y-2.58 Z+13.05 A+0 C+0
N19791  G1 X+56.25 Y-2.67 Z+13.05 A+0 C+0
N19792  M102
```

Figure 4. *G-code segment of thin-walled additive program with sinusoidal zigzag pattern generated in Grasshopper*

Toolpath generation and G-code export

The process of converting the parametric designs into machine-executable G-code involved the following steps:

Slicing the 3D model into 10 layers of 1.6mm height each.

1. Generating zigzag toolpaths for each layer using the developed Grasshopper definitions;

2. Converting the toolpaths into machine coordinates;

3. Adding process parameters (laser power, feed rate, etc.) to the toolpath data;

4. Exporting the complete toolpath as G-code using Grasshopper's custom scripting components.

The G-code generation process incorporated specific commands for the WLAM system, including positioning, laser power control, and wire feed rate adjustments.

4. Experimental setup and fabrication

4.1. WLAM system configuration

Experiments were conducted using a 5-axis WLAM system with the following specifications:

- Laser source: 6 coaxial lasers with maximum power of 1200W;

- Motion system: 5-axis CNC controller (3 translational axes along X, Y, Z and 2 rotational axes around X and Z);

- Wire feeder: wire feeding system for 1mm diameter wire;

- Material: 316L stainless steel wire (1mm diameter);

- Substrate: 316L stainless steel plate (5mm thickness).

4.2. Process parameters

The following process parameters were used for fabricating the thin-walled structures:

- First layer: 1200W laser power;

- Subsequent layers: 800W laser power;

- Inter-layer cooling time: 30 seconds;

- Wire feed rate: 8 mm/s;

- Travel speed: 150 mm/min;

- Shielding gas: Argon at 7L/min.

4.3. Fabrication process

The fabrication process followed these steps:

1. Preparation of the substrate by cleaning and fixing on the machine bed;

2. Loading of the generated G-code into the machine controller;

3. Setting up the process parameters according to the specified values;

4. Execution of the fabrication process with monitoring of each layer;

5. Cooling of the final structures before removal from the substrate;

6. The entire fabrication process was monitored to ensure consistent deposition quality across all layers.

5. Results and discussion

5.1. Analysis

After fabrication, the three thin-walled structures were measured to determine their width and height.

ImageJ software was also used to quantitatively analyze the surface quality for three types of zigzag toolpath patterns. ImageJ is an open-source image analysis software developed by the National Institutes of Health (NIH), which is suitable for rapid surface assessment of 3 additively machined samples based on the "Plot Profile" tool. This methodology constitutes a rapid approach to surface quality analysis and assessment through image processing techniques, particularly applicable when evaluating specimens where surface roughness parameters do not necessitate highly stringent measurement precision.

a) Sinusoidal zigzag thin-walled structure

b) Sharp-angled zigzag thin-walled structure

c) Square-angled zigzag thin-walled structure

Figure 5. *Three straight thin-walled structures*

Figure 5 shows the images of three straight thin walls generated by three zigzag patterns and the analysis results are summarized in Table 1.

Table 1. *Systematic comparison of three zigzag toolpath patterns*

Assessment Criteria	Sinusoidal zigzag	Sharp-angled zigzag	Square-angled zigzag
Measured Dimensions (width × height)	6.30mm × 16.70mm	5.75mm × 15.65mm	6.85mm × 15.30mm
Dimensional Deviation from Design (6mm × 16mm)	+0.30mm × +0.70mm	-0.25mm × -0.35mm	+0.85mm × -0.70mm
Gray Value Range	30-210	10-250	30-250

Average Oscillation Amplitude	150-170	220-240	200-220
Oscillation Frequency	Low	Extremely high	Moderate
Oscillation Characteristics	Smooth, rounded	Sharp, pointed	Flat regions with steep transitions
Regional Homogeneity	High	Moderate	Low
Density of High Peaks (>200) per Unit Length	Low	High	Moderate
Valley Depth	Shallow	Very deep	Moderate
Peak-to-Valley Transition Characteristics	Gradual, smooth	Abrupt, sharp	Abrupt with flat sections
Microstructural Features (small oscillations)	Few	Abundant	Moderate
Presence of Material Accumulation Points	Low	Moderate	High

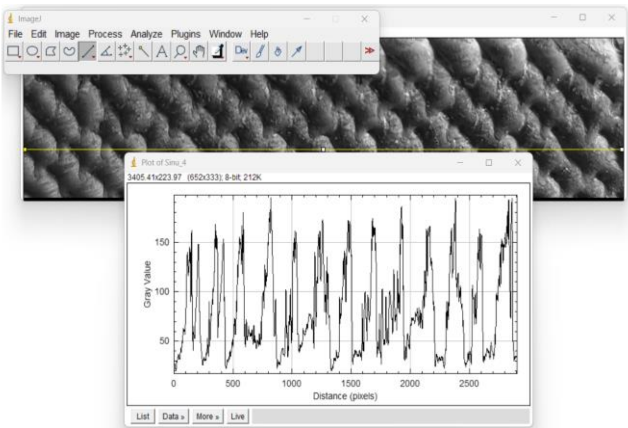


***Figure 6.** Example of thin-wall surface analysis using ImageJ software*

Figure 6 shows the surface image of the selected straight thin-walled specimen, and the "Plot Profile" graph exported from ImageJ software. The graph and analysis results provide the following information about the analyzed surface:

Horizontal Axis (X): Distance (pixels) - represents the pixel distance from the starting point to the endpoint of the analysis line.

Vertical Axis (Y): Gray Value - represents the grayscale intensity values, ranging from 0 (black) to 255 (white).

Significance of the graph:

Surface characteristics: The graph illustrates the variation in grayscale values along a cross-sectional profile of the specimen surface. Each peak and valley in the graph correspond to topographical height variations on the actual surface: High peaks (grayscale values ~150-180) correspond to elevated features on the surface; Low valleys (grayscale values ~30-50) correspond to depressions or recessed areas.

Oscillation periodicity: The graph exhibits a relatively regular repeating pattern, with approximately 14-15 major oscillation cycles across the entire analysis range, demonstrating that this is a surface with a repeating structure - most likely the surface of a 3D printed specimen with a sinusoidal zigzag pattern as suggested by the sample designation.

Oscillation amplitude: The oscillation amplitude is considerable (ranging from approximately 30 to 180 grayscale units), indicating significant surface roughness with distinct differentiation between peaks and valleys.

Homogeneity assessment: Despite having a repeating structure, the cycles are not perfectly identical, showing variations in amplitude and peak morphology, which demonstrates a certain degree of non-uniformity across the specimen surface.

To ensure accuracy, three different positions on each specimen were selected for analysis, and the average values were calculated.

5.2. Detailed characteristic analysis

Dimensional accuracy

- Sharp-angled zigzag exhibits superior dimensional accuracy with a deviation of -0.25mm (narrower than design specifications), potentially attributable to the acute angles minimizing material accumulation at directional transition points.

- Sinusoidal zigzag demonstrates moderate dimensional deviation (+0.30mm), indicating an effective balance between smooth transitions and dimensional control.

- Square-angled zigzag presents the largest dimensional deviation (+0.85mm), consistent with material accumulation phenomena at square corners resulting from abrupt directional changes.

Surface characteristics

- Sinusoidal zigzag produces the smoothest surface topography, characterized by minimal oscillation amplitude and gradual transitions, making it suitable for applications requiring smooth surfaces.

- Sharp-angled zigzag generates surfaces with the highest roughness, featuring extremely high oscillation frequency and numerous sharp peaks, resulting in the richest surface texture.

- Square-angled zigzag creates surfaces with moderate roughness but high regional heterogeneity, characterized by flat regions interspersed with steep transitions.

Homogeneity

- Sinusoidal zigzag exhibits the highest homogeneity with consistent oscillations across the entire surface, indicating stable deposition processes.

- Sharp-angled zigzag demonstrates moderate homogeneity with some regions showing denser oscillation patterns.

- Square-angled zigzag presents the lowest homogeneity with significant variations in oscillation amplitude and morphology between regions.

Microstructural features

- Sharp-angled zigzag produces surfaces with the richest microstructural features, characterized by numerous small oscillations interspersed between primary oscillations.

- Square-angled zigzag creates moderate microstructural complexity, with some small oscillations in transitional regions.

- Sinusoidal zigzag generates minimal microstructural features, with predominantly smooth oscillations and few fine details.

Table 2. *Advantages and limitations of each zigzag toolpath type*

Zigzag Type	Advantages	Limitations
Sinusoidal zigzag	• Produces the smoothest surface topography • High homogeneity across the entire surface • Minimal material accumulation points • Moderate dimensional accuracy • Greatest achieved height (16.70mm)	• Limited microstructural features • Low oscillation frequency resulting in fewer surface details • Width exceeds design specifications (+0.30mm)
Sharp-angled zigzag	• Superior dimensional accuracy (width closest to design specifications) • Richest surface texture with abundant microstructural features • High oscillation frequency, increasing effective surface area • Efficient material distribution	• Highest surface roughness, potentially unsuitable for applications requiring smooth surfaces • Numerous sharp directional transitions may create localized structural weaknesses • Height below design specifications (-0.35mm)
Square-angled zigzag	• Readily programmable and implementable in CAM software • Interspersed flat regions potentially enhancing structural rigidity • Distinct transitions facilitating layer identification	• Poorest dimensional accuracy (width exceeding design specifications by +0.85mm) • High regional heterogeneity • Numerous material accumulation points at square corners • Lowest achieved height (15.30mm)

6. Conclusions and perspective

This research has demonstrated a new Grasshopper-based approach for generating parametric zigzag toolpaths for thin-walled structures in WLAM (Wire Laser Additive Manufacturing). The key contributions and findings include:

1. Development of three customizable zigzag pattern types (sinusoidal, sharp-angle, and square-angle) with parametric control over key characteristics.

2. Methodology for applying these patterns to arbitrary path geometries, enabling toolpath generation for complex structures.

3. Experimental validation showing that different zigzag patterns result in distinct dimensional and surface quality characteristics:

- Sharp-angled patterns provide the best width accuracy;

- Sinusoidal patterns produce the smoothest surfaces and greatest height;

- Square-angled patterns result in wider walls with more surface irregularities.

The Grasshopper-based approach offers significant advantages for WLAM toolpath generation, including:

- Visual and intuitive pattern creation and modification;

- Parametric control allowing for rapid iteration and optimization;

- Seamless integration with 3D modeling workflows;

- Flexible application to diverse geometric features.

Several directions for future research emerge from this work:

1. Application to complex thin-walled components: Extending the methodology to more complex thin-walled structures with varying wall thickness and intersections.

2. Material and mechanical property assessment: Evaluating the mechanical properties, porosity, and microstructure of structures produced with different zigzag patterns.

3. Toolpath automation: Developing more sophisticated algorithms for automatically selecting and optimizing zigzag patterns based on local geometric features.

4. Multi-material deposition: Exploring the application of parametric zigzag patterns for functionally graded or multi-material thin-walled structures.

5. Process parameter optimization: Investigating the relationship between zigzag pattern characteristics and optimal process parameters to further enhance dimensional accuracy and surface quality.

The parametric toolpath generation approach presented in this paper provides a valuable framework for advancing WLAM capabilities, particularly for thin-walled structures with complex geometries.

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REFERENCES

[1] A. Zhang, Y. Liu, B. Ma, H. Chen, and C. Zhang, "Advancements in Laser Wire-Feed Metal Additive Manufacturing: A Brief Review", *Materials*, vol. 16, no. 5, p. 2030, 2023.

[2] M. Rauch, J.-Y. Hascoët, and V. Quérard, "A multiaxis tool path generation approach for thin wall structures made with WAAM", *Journal of Manufacturing and Materials Processing*, vol. 5, no. 4, p.128, 2021.

[3] F. Xie, Y. Liu, and J. Zhang, "Hybrid path generation method for multi-axis laser metal deposition of overhanging thin-walled structures", *Micromachines*, vol. 15, no. 6, p. 704, 2024.

[4] F. Michel, H. Lockett, J. Ding, F. Martina, S. Williams, and P. Kazanas, "A modular path planning solution for Wire + Arc Additive Manufacturing", *Robotics and Computer-Integrated Manufacturing*, vol. 60, pp. 1-11, 2019.

[5] S. Maissen, S. Zürcher, and M. Wüthrich, "Adaptation of Conventional Toolpath-Generation Software for Use in Curved-Layer Fused Deposition Modeling", *Journal of Manufacturing and Materials Processing*, vol. 8, no. 6, p. 270, 2024.

[6] C. Wade, D. Beck, and R. MacCurdy, "Implicit Toolpath Generation for Functionally Graded Additive Manufacturing via Gradient-Aware Slicing", *arXiv preprint arXiv:2505.08093*, 2025.

[7] J. Wang, Y. Liu, and H. Zhang, "Parallel Tool-Path Generation for Additive Manufacturing: A GPU-Based Zigzag Filling", *Advances in Industrial and Manufacturing Engineering*, vol. 6, pp. 100-107, 2023.

[8] J. Park and D. W. Rosen, "Quantifying effects of material extrusion additive manufacturing process on mechanical properties of lattice structures using as-fabricated voxel modeling", *Additive Manufacturing*, vol. 12, pp. 265-273, 2016.

[9] Y.Jin, Y. He, J. Fu, W. Gan, and Z. Lin, "Optimization of tool-path generation for material extrusion-based additive manufacturing technology", *Additive Manufacturing*, vol. 1, pp. 32-47, 2014.

[10] N. Itohara and T. Tateno, "Toolpath Generation Algorithm Using Route Model for Non-Planar Layering in Additive Manufacturing", *Proceedings of the International Conference on Design and Concurrent Engineering*, 30, 2023.

[11] D. Ding, Z. Pan, D. Cuiuri, H. Li, N. Larkin, and S. Van Duin, "Automatic multi-direction slicing algorithms for wire based additive manufacturing", *Robotics and Computer-Integrated Manufacturing*, vol. 37, pp. 139-150, 2016.

[12] N. Ashrafi, S. Nazarian, and N. Meisel, "A grammar-based algorithm for toolpath generation: Compensating for material deformation in the additive manufacturing of concrete", *Additive Manufacturing*, vol 55, p.102803, 2022.