Title:
Virtual Quality Assessment Tools for Material Extrusion Processes

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Introduction:
The material extrusion additive manufacturing (AM) process family includes the well-established fused deposition modeling (FDM) process [7], and processes presently under development such as the 'Big Area Additive Manufacturing' (BAAM) [2], large scale additive manufacturing, (LSAM) [4], and Medium Area Additive Manufacturing (MAAM) [5] processes. Layers are built from molten thermoplastic filaments or fibre-reinforced filaments. The general material extrusion process characteristics are similar, as material is fed through a temperature-controlled head and extruded when it is in a semi-viscous state. However, the size and shape vary for these processes, as the beads may vary from 0.25 mm in width to 12 mm, and some processes apply a force onto the extruded bead to facilitate inter-layer bonding. The anisotropic properties associated with the layered manufacturing process are well known [1, 3, 6]; however, when exploring mechanical properties for tensile and compressive samples with 'lightweighting' internal voids, unexpected failure results occurred [8]. The original research goal was to reduce material costs without compromising the product performance characteristics. Parametric spherical void lattice patterns based on atomic crystal structures were developed (primitive, body centered cubic and face centered cubic) and experimental samples fabricated for selected void radii and spacing. The failure points did not initiate where expected, and the inconsistent results were observed. It was found that unexpected voids and discontinuities where embedded in the interior (Fig. 1) of the specimens, and are due to the tool paths. Although the build volume of material may be close to the CAD model volume, this was no indicator with respect to the 'quality' of the interior fill.

With large, thick walled components fabricated with a thin slice height (0.13 mm) and small bead width (0.25 mm), the probably of voids existing and creating a performance issue is reduced. However, one of the benefits of AM is the ability to produce complex thin walled components without tooling. Standard strength optimization solutions include applying 'thin wall' gussets and ribs strategically to provide strength or damping characteristics where required on a product. In these scenarios, voids and discontinuities are problematic. The tool paths/voids for two layers are shown for a casting pattern (pink) gusset (Fig. 2(a)), and an insulator / cable tray (Fig. 2(b)). These are the 'best' case results when exploring the component orientation and bead geometry options using the Insight® software. In this software, there is a selection of slice heights and bead width input options, the individual layers can be visualized, and the tool paths can be edited. However, for components consisting of 100's of layers, a manual review is time consuming. There are no void and discontinuity quality checks available in the Insight® software. However, there are optimization strategies focus on build time and support material usage. For the newer processes that have larger beads, the problems related to voids and discontinuities are amplified. Consequently, tool path quality assessment tools, which provide insights into voids and discontinuities, need to be developed which complement the material extrusion tool path generation and visualization tools.

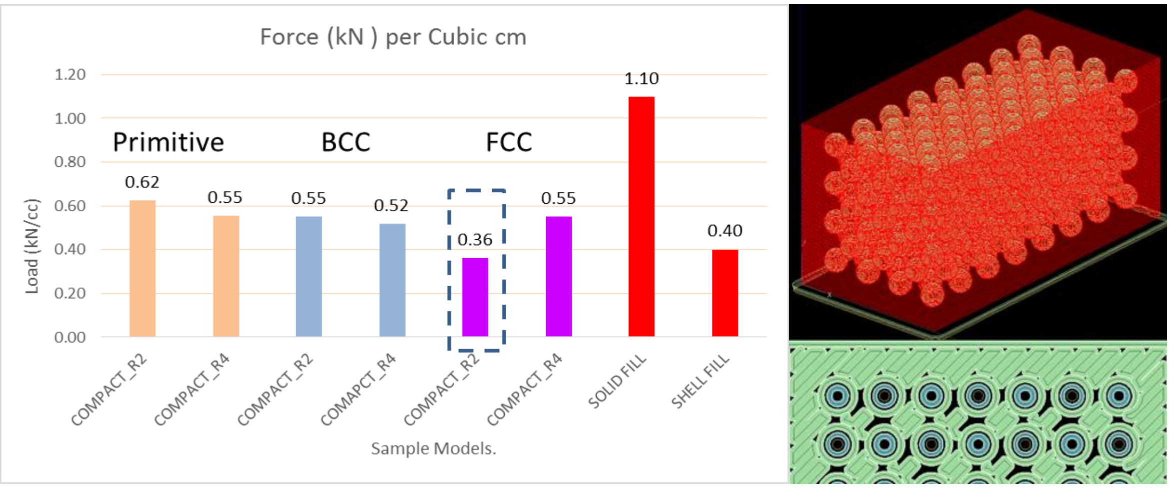

Fig. 1: (a) Compressive forces for samples with primitive, body centered cubic and face centered cubic void patterns, (b) a face centered cubic specimen, (c) unexpected voids (layer 28), adapted from [8]

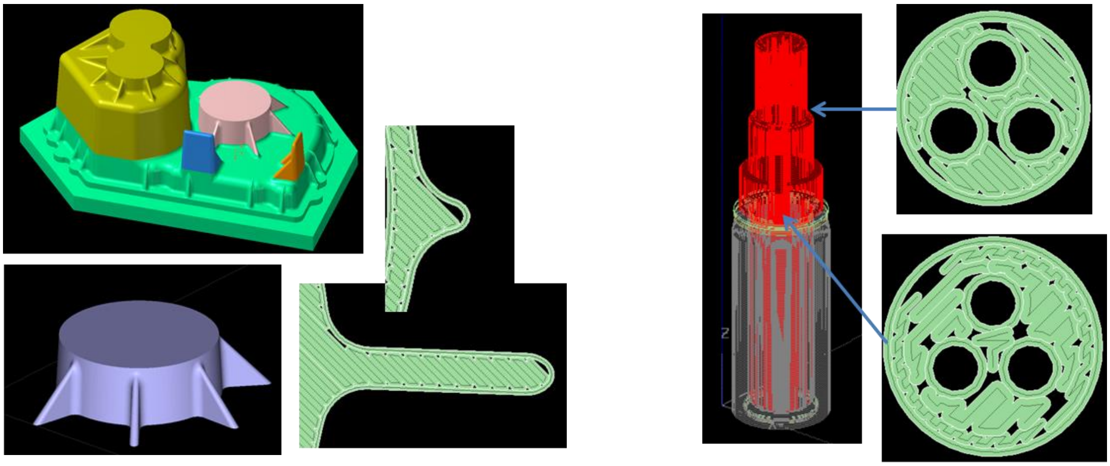

Fig. 2: (a) Casting pattern segment, and fill patterns, (b) insulator and fill patterns.

<u>Research Methodology:</u>
The research methodology consists of: (i) developing a set of case studies, (ii) developing a standard tool path process input set to be employed to test different operation settings (using a commercial AM bead extrusion based process planning software), (iii) determining the void centroids, calculating total travel length, the void area, and enumerating the tool path segments, and (iv) comparing process planning solutions via normalization to determine optimal process planning settings for a component.
The standard bead deposition fill strategy for each layer consists of boundary contouring and zig-zag tool paths. The input parameters for this research are:

- Boundary bead width & height
- Number of boundary beads
- Boundary pass overlap (for multiple contours) as a % of the bead width
- Maximum pass overlap as a % of the bead width
- Stop / start overlap as a % of the bead width
- Fill type (zig-zag or one way)

- Fill pass overlap (for multiple contours) as a % of the bead width
- Maximum pass overlap as a % of the bead width
- Boundary to fill overlap as a % of the bead width
- Starting fill angle
- Change in angle per layer

The operation order, 5 axis motion, contour offsets and other related process parameters are not considered, as they are related to the motion control. The travel path related for rapid motion is not included in the analysis.

The shapes employed for this work are a set of n-gons (4, 7, 11 sides), a plate with holes which was compared to the Insight® solutions, and three complex shapes: a timing mechanism, and a Celtic knot. The standard bead width is 1 mm.

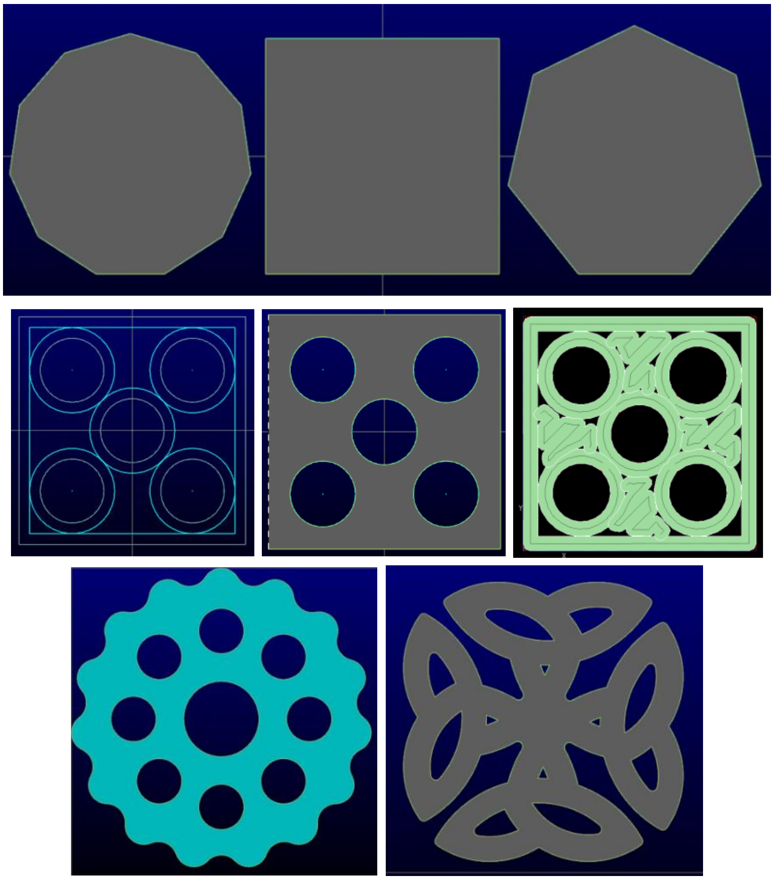

Fig. 3: (a) a heptagon, square, and 11-sided polygon, (b) a plate with five holes, showing the width of a boundary bead, (c) the solid model, (d) the Insight® tool path solution, (e) the timing mechanism, and (f) the Celtic knot.

The bead width is constant for the tool path testing, and the allowable boundary pass overlap range is 15-50%. The stop/start overlap is 50%. One, two, and three contour beads (with fill) and 100% boundary fill options are explored. The fill overlap range is 10 – 15%, and boundary to fill overlap is 25%.The starting raster angle is 0˚, and the increment angle is 1˚. The slice height is segmented into 91 layers to create a solution for all raster increments between 0 – 90˚. A sample set of solutions for the 5 hole block and the 11-sided polygon is presented in Fig. 4.

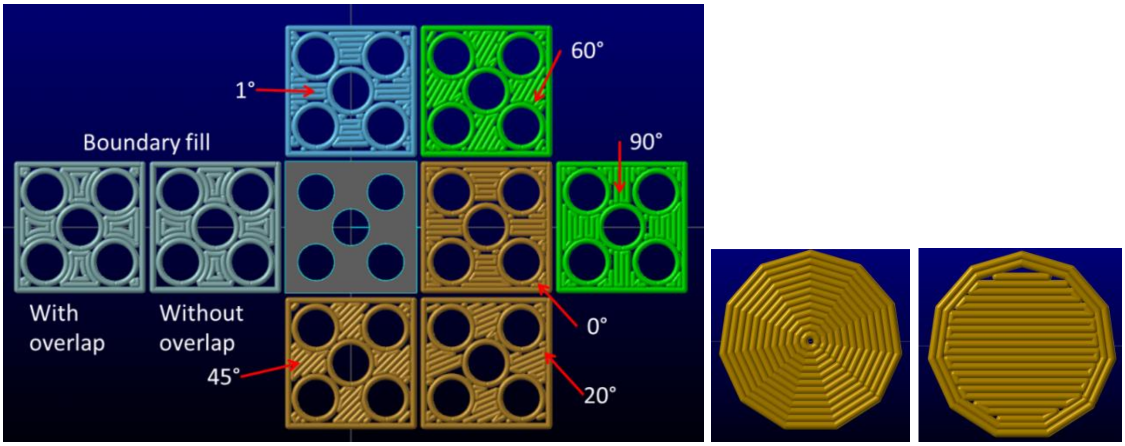

Fig. 4: One boundary curve with various raster angle fill strategies & 100% boundary fill for the block with holes, and the 11-sided polygon with 100% boundary fill and a two bead contour-0˚ raster fill.

The total travel path length (when material is deposited, no rapid moves), the void area, and the number of tool path segments are calculated for each raster angle-layer set. The data is output into a CSV file. The tool path travel length and void data are normalized to the 1 boundary bead-0˚ fill raster solutions. A comparison of the normalized tool paths for the n-gons is presented in Fig. 5. The best fill angles are between 34-56˚ degrees for the square with 34˚ and 56˚ being optimal, 57˚ and 71˚ degrees for the heptagon, and 0˚ and 49˚ for the 11-sided n-gon.

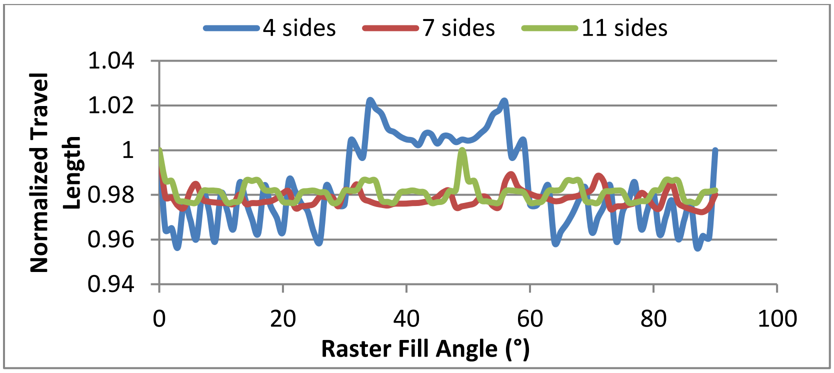

Fig. 5: Normalized n-gon tool path strategies for one boundary contour and a raster fill.

For the Celtic cross, having 3 boundary beads with a raster fill of 57˚ and 45˚ provides the best travel path length (max. volume), and the poorest condition exists for a one boundary contour, with a 3˚ or 78˚ raster fill angle (Fig. 6). The discontinuities may be an issue. For the 11-sided polygon with the cut out of the Celtic knot, there are several raster angles (16, 17 35, 36, 44, 56, 59, 60, 61, 84, 88, 89, 90), which have the minimum number of segments: 26. The raster angles with the minimum void area or the maximum travel path length would provide the optimal fill strategy. Multiple scenarios using various weights for considering the effect of void area, discontinuities, etc. in a basic optimization function are explored in the paper.

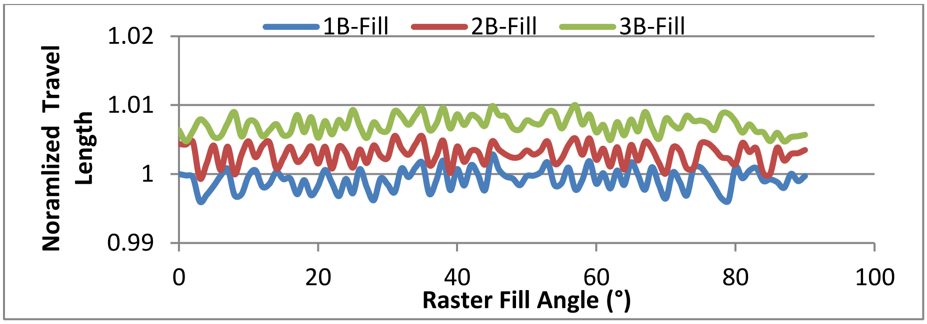

Fig. 6: Celtic cross travel length for various tool path strategies.

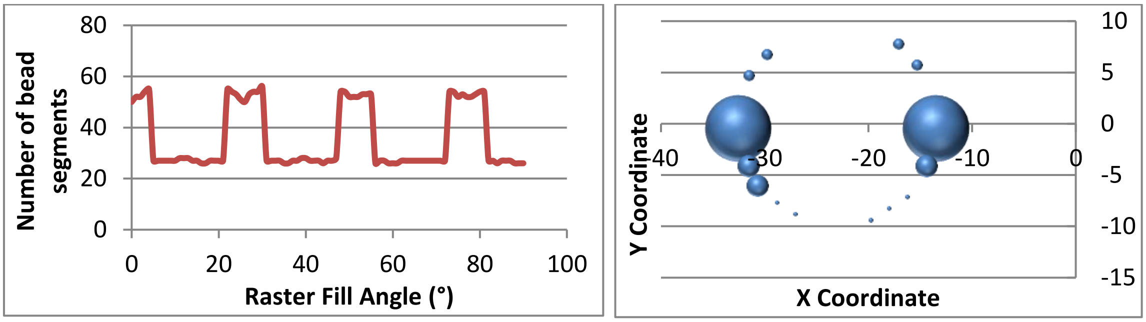

Fig. 7: 11-sided n-gon with the Celtic cross removed bead segments per raster fill angle, and a bubble chart showing the x-y coordinate and area of each void for the 90° raster angle.

Conclusion:

AM tool paths introduce unique quality issues related to voids and discontinuities, and presently there are no tool path quality assessment tools. A multi-perspective set of visualization tools are being developed so that process designers can visualize the void distribution, void area, the total travel path length, and the number of beads. This will provide some insight with respect to potential issues. However, this research needs to continue, along with continuing void reduction validation with industrial partners. A 3D void map and statistical tools need to be developed to virtually determine leak paths or chimneys, and predict problematic regions.

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