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Adaptive path planning for wire-feed additive manufacturing using medial axis transformation

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ABSTRACT

Wire-feed additive manufacturing technologies have made it possible to significantly reduce material waste and energy consumption for fabricating large aerospace metal components that feature high buy-to-fly ratios. This paper presents an innovative path planning strategy using medial axis transformation for the wire-feed additive manufacturing process. The proposed path planning strategy is able to improve geometrical accuracy and produce void-free deposition by continuously altering the deposition width of the wire-feed process to accommodate the component geometry, while simultaneously minimising the number of interruptions to the deposition process at the component boundary. As a result, both buy-to-fly ratio and energy consumption are improved through reducing material waste. The algorithm for generating the adaptive path is described and validated through application to various typical geometries. Buy-to-fly ratios are calculated for a number of thin-walled complex structures. Savings of more than 27% in material usage are achieved using adaptive path planning, when compared with non-adaptive methods. The proposed method is tested experimentally through deposition of two metal components. The results demonstrate that the adaptive strategy is capable of generating void-free deposition with improved accuracy at the component boundary using the wire-feed additive manufacturing process.

1. Introduction

Additive manufacturing (AM) technologies have the potential to achieve reduced environmental emissions and energy consumption in comparison to conventional subtractive methods in the metal manufacturing industry (Morrow et al., 2007; Huang et al., in press; Watson and Taminger, in press). An additive process creates a component through the deposition of material layer-by-layer, rather than removing unwanted material from an over dimensioned solid block using conventional machining. By utilizing only the amount of material required for the product, AM technologies have made it possible to reduce the life cycle material mass and energy consumed by significantly reducing scrap. AM is both a cost effective and an environmentally friendly alternative for producing components using materials that have a high monetary or environmental cost. These high costs can be due to scarcity, complex and energy-intensive processing, or the need to use of harmful substances during production. Examples of such engineering materials are titanium and nickel alloys, commonly used in the aerospace industry to produce components with complex geometries that unavoidably suffer an extremely high buy-to-fly ratio (BTF) when manufactured from billet or bar stock (Almeida and Williams, 2010; Ding et al., 2011).

Depending on the form of the supplied additive material, AM technologies can be classified as either powder-based (powder-feed/-bed) or wire-feed (Ding et al., 2015a). Wire-feed AM technologies have attracted research interest for manufacturing metal components of medium to large size due to their combined advantages of high deposition rate, environmental friendliness, and cost-competitiveness (Zhang et al., 2003; Mok et al., 2008; Karunakaran et al., 2010; Xiong et al., 2013).

One of the crucial tasks in AM is path planning, which generates the deposition paths that are used to fill the 2D sliced layers with full density deposits as required by the component design (Ponche et al., 2014). Many types of path patterns have been developed, such as raster, zigzag, contour or spiral (Ding et al., 2014). While these

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are all suitable for powder-based AM, they are not all well suited to wire-feed AM due to certain physical requirements and limitations (Ding et al., 2015a). Firstly, the typical deposition width of powder-based system is around 0.5 mm or less (Milewski et al., 1998), while that for wire-feed process normally ranges from 3 to 11 mm (Ding et al., 2016a, b; Xiong et al., 2013). This limits the ability of wire-feed AM to produce fine features. Secondly, the layer thickness and deposition width of wire-feed AM are strongly related, so the selected layer thickness places limits on the available range of deposition widths that can be produced by the deposition process to create that layer. Thirdly, to produce layers with a smooth upper surface, the distance between adjacent paths is determined by the deposition width (Ding et al., 2015b). Adhering to this condition produces void-free deposits. Fourthly, the continuity of the deposition path should be maintained to avoid frequent start/stop deposition of the wire-feed system. This reduces the number of localised errors in the build direction (i.e. “humps” and “dips”) at the start/stop points. Also, the path direction should not change rapidly (such as sharp corners), as this also tends to produce localised errors in the build direction. Finally, the geometrical accuracy at the component boundaries should be optimised in order to minimize the amount of post process machining. This can be done for wire-feed AM by designing paths that are parallel to the external boundaries of each layer, so there is ideally only one start/stop in each of the paths that form these boundaries.

The type of pattern that is used by the path planning algorithm can be chosen in view of these requirements. Raster path patterns contain a set of discontinuous scan lines, which require the deposition process to start and stop regularly, particularly at the external boundaries of each layer. Therefore, raster patterns are not well suited to wire-feed AM. Zigzag path patterns may involve highly convoluted paths, which result in the accumulation of heat in certain regions, and frequent changes of path travel directions are also not suitable for metal deposition with wire-feed AM (Ding et al., 2014). Contour path patterns which offset parallel to the boundary of the given geometry are often preferred over raster and zigzag path patterns in wire-feed AM. Contour path patterns have been successfully applied to thin-walled structures with constant wall thickness as shown in Fig. 1 (Ribeiro and Norrish, 1996).

However, to fabricate large complex components, geometry-related process parameters, such as deposition width, layer thickness, travel speed, and wire-feed rate, must be carefully designed to achieve the desired geometry (Gibson et al., 2010). If the process intends to maintain geometrical accuracy at the external boundary (Kao and Prinz, 1998; Ding et al., 2015c), using a large deposition width to fabricate complex geometries will inevitably generate voids at the centre of the component as the contour paths are offset starting from the boundary and then move towards the centre (Fig. 2a). These internal gaps (Fig. 2b) are not guaranteed to be filled by subsequent deposits because of the physical difficulty for molten material to fully flow and fuse into the confined corners of an unfilled region.

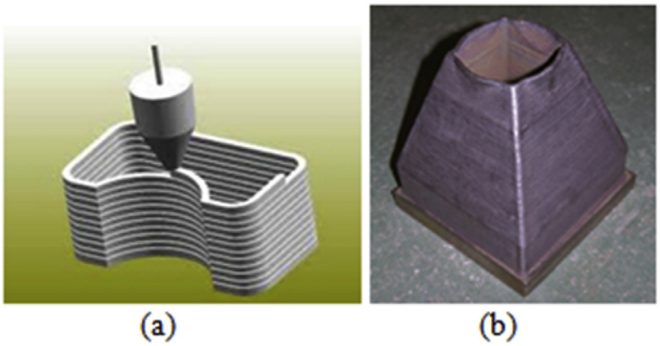

Fig. 1. (a) A schematic deposition process for thin-walled structure with contour path. (b) A “Chimney” shape deposited by contour path in wire-feed AM (Ribeiro and Norrish, 1996).

To avoid such internal voids, the MAT (Medial Axis Transformation) path was introduced (Kao and Prinz, 1998) and its extension for complex geometries has been recently developed (Ding et al., 2015c). MAT path patterns are generated by offsetting the medial axis of the geometry from the centre towards the boundary. Fig. 2c shows an example of MAT path patterns, with the deposition sequence indicated by numbers. Although void-free deposition can be reliably obtained using MAT paths, this is achieved at the cost of creating discontinuities in the paths at the layer boundary (such as path 3, 4, and 5 in Fig. 2c) and excess deposition at the boundary as shown in Fig. 2d. Post-process machining must be used to remove the excess materials and improve the accuracy at the cost of wasted material and energy. The distance between adjacent paths, defined as the step-over distance, is always constant for both contour path patterns (refer to Fig. 2a) and MAT path patterns (refer to Fig. 2c). For certain geometries, it is not possible to achieve both high accuracy (refer to Fig. 2b) and void-free (refer to Fig. 2d) components using paths with constant step-over distance.

These examples show that void-free deposition can be achieved at the expense of excess deposition at the component boundary. There is a clear need to reduce deposition errors at the boundary while maintaining the conditions for void-free deposition at the centre of the component. The wire-feed AM process is capable of producing different deposition widths while maintaining a constant deposit height within a layer, through varying travel speed and wire-feed rate. Therefore, an adaptive path planning strategy is proposed that uses continuously varying step-over distances within any given path. The algorithm automatically selects the process parameters that are needed to produce deposits of constant height, and these are dynamically calculated by using an experimentally-determined model of the deposition process. The variation is step-over distance is constrained by the capabilities of the wire-feed process, and a number of iterations may be needed. The method is implemented several steps. Firstly, the medial axis or “skeleton” of the geometry is computed using MAT. The geometry is then divided into a number of domains according to the skeleton. Each domain is decomposed into a variety of numbered shapes, and the adaptive path pattern is finally generated for each of these shapes. An example of a path pattern for a simple shape is shown in Fig. 2e and f, the developed adaptive MAT path planning algorithm is able to automatically generate path patterns with varying step-over distances through analysing geometry information to achieve better part quality (void-free deposition), accuracy at the boundary, and high material efficiency.

This paper presents an innovative path planning strategy using medial axis transformation for wire-feed additive manufacturing process. The adaptive MAT path planning algorithm, designed to improve path continuity and geometrical accuracy, is described step-by-step. Section 2 details the adaptive MAT path planning algorithm for simple geometries. Section 3 extends the adaptive MAT path for complex geometries with internal features, followed by the experimental results in Section 4. The performance of the proposed path planning strategy is analysed in Section 5.

2. Adaptive MAT path planning for simple geometries

A flowchart of the adaptive MAT path planning algorithm is shown in Fig. 3. CAD models in STL format are commonly used in AM systems. In an STL file, the 3D CAD model is represented by numerous triangular facets with unit normal vectors to indicate the side of the facet. Each layer is obtained through 3D slicing (Choi and