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A practical path planning methodology for wire and arc additive manufacturing of thin-walled structures

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ABSTRACT

This paper presents a novel methodology to generate deposition paths for wire and arc additive manufacturing (WAAM). The medial axis transformation (MAT), which represents the skeleton of a given geometry, is firstly extracted to understand the geometry. Then a deposition path that is based on the MAT is efficiently generated. The resulting MAT-based path is able to entirely fill any given cross-sectional geometry without gaps. With the variation of step-over distance, material efficiency alters accordingly for both solid and thin-walled structures. It is found that thin-walled structures are more sensitive to step-over distance in terms of material efficiency. The optimal step-over distance corresponding to the maximum material efficiency can be achieved for various geometries, allowing the optimization of the deposition parameters. Five case studies of complex models including solid and thin-walled structures are used to test the developed methodology. Experimental comparison between the proposed MAT-based path patterns and the traditional contour path patterns demonstrate significant improved performance in terms of gap-free cross-sections. The proposed path planning strategy is shown to be particularly beneficial for WAAM of thin-walled structures.

1. Introduction

Additive manufacturing (AM) or 3D printing, which is based on layer-by-layer manufacturing approach instead of conventional material removal methods, has gained worldwide popularity over the past thirty years [1]. The original techniques include stereolithography apparatus [2], laminated object manufacturing [3], fused deposition modelling [4], 3D printing [5] and selective laser sintering [6]. These AM processes are typically applied to fabricate polymer parts which are usually used for prototyping or illustrative purposes. The current development focus of AM has shifted to producing functional metal components of complex shape that can meet the demanding requirements of the aerospace, defence, and automotive industries [7]. Wire and arc additive manufacturing (WAAM) is by definition an arc-based process that uses either the gas tungsten arc welding (GTAW) or the gas metal arc welding (GMAW) process has drawn the interest of the research community in recent years due to its high deposition rate [8–10]. This technique has been presented to the aerospace manufacturing industry as a unique low cost solution for manufacturing large thin-walled structures through significantly reducing both product development time and “buy-to-fly” ratios [11,12].

One of the crucial tasks in WAAM is the generation of paths which guide the motion of the deposition head to fill the 2D layers representing the cross-sectional geometry of an object. Many types of path patterns have been developed for AM, as summarized in Table 1 [13–26]. It is found that the essential step to generate paths is offsetting. Commonly used patterns are raster patterns which offset parallel to a given direction, and contour patterns which offset parallel to the boundary of geometry. Other path patterns are either variations or combinations from these general strategies.

Contour path patterns are often preferred over raster path patterns for producing thin-walled metal structures due to certain practical concerns. Raster path patterns build the whole component along the same direction, which means the deposition head is required to be turned frequently, leading to a poor building quality [26]. In addition, the fabricated component will have warpage and anisotropic problems. By following the boundary trend of the geometry, the contour path method overcomes the warpage as well as anisotropic issues by changing path direction constantly along the boundary curves of the sliced layer [26].

However, the contour path patterns pose a severe quality problem of potentially leaving gaps within the deposited layers. This is because the contour paths, which are generated by offsetting the boundary curves recursively toward its interior, do not

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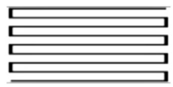
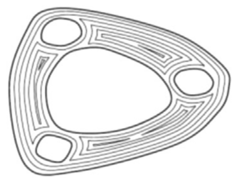
0736-5845/

Table 1
A brief summary of AM tool-path generation methods.

References	Tool-path pattern	Examples
[13]	Raster	
[14,15]	Zigzag	
[16–18]	Contour	
[19,20]	Spiral	
[21–24]	Continuous	
[25,26]	Hybrid	

guarantee to completely fill a desired 2D geometry. As shown in Fig. 1, a cross-section of a simple thin-walled geometry is described by the boundary (Fig. 1a). The contour paths (green lines shown in Fig. 1b) are generated by offsetting the boundary towards its interior with the ith contour path offset at distance $(i-(1/2)d)$ from the boundary, where d is the step-over distance. The step-over distance is defined as the distance between the next deposition track and the previous one. For WAAM, the overlapping of weld beads is necessary to achieve smooth surface. As shown in Fig. 2, weld beads are overlapped with the certain step-over distance (centre distance d). According to different weld bead overlapping model, the optimal step-over distance d is the function of weld bead width w, which $d=0.667w$ or $d=0.738w$ [27]. The deposition process can be considered as a constant-radius disk with the diameter of d being swept along the computed path. It is found that contour path patterns leave narrow gaps since there is not enough space for offsetting the next path as the middle white area

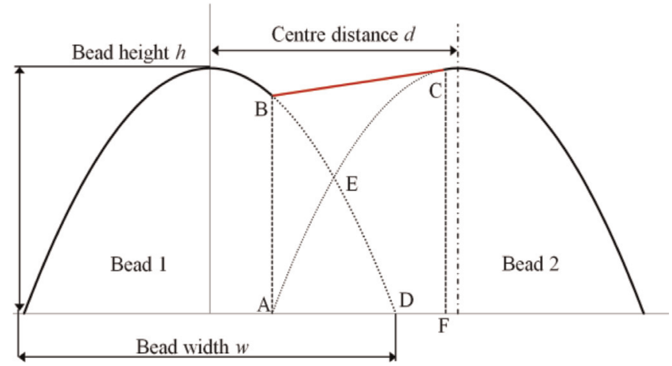


Fig. 2. Illustrations of step-over distance (or centre distance d) [27].

shown in Fig. 1c. The area of the produced gaps is highly dependent on the step-over distance d, which varies for different AM system. For powder-based AM, d could be generally small within the range of 0.01–1 mm. The negative effects of gaps with small area on the quality of the produced components could be neglected for many applications. However, for WAAM d typically varies from 2 mm to 12 mm depending on the diameter of the feed wire, the travel speed of deposition head, and the wire feed rate. Gaps resulting from poorly planned paths in WAAM could be a severe problem, especially for thin-walled structures. The unavoidable gaps may potentially lead to structural failure of highly loaded components.

Possible solutions to the gap problem can be reducing the step-over distances or revisiting the gaps through overlapping the deposition path. However, as has been mentioned, the step-over distance is limited by the deposition system, and will affect the deposition rate. Moreover, the work pieces may have a complex structure where wall thickness varies along its boundary, making it impossible to fill the entirely region using contour path patterns. On the other hand, the strategy of revisiting requires the deposition head to move into a small unfilled region that is surrounded by deposited material. Voids or gaps are often produced during such "infilling" due to the difficulty for material to fully reach into the confined corners of an unfilled region.

Kao [28] has proposed an alternative methodology of using the Medial Axis Transformation (MAT) of the geometry to generate the offset curves by starting at the inside and working towards the outside, instead of starting from the boundary and filling towards the inside. This approach is able to compute paths which can entirely fill the interior region of geometry as the paths are generated from interior to the boundary. This strategy avoids producing gaps by depositing excess material outside the boundary, as illustrated in Fig. 3. The extra material can subsequently be removed by post-processing. Therefore, the traditional contour path patterns from

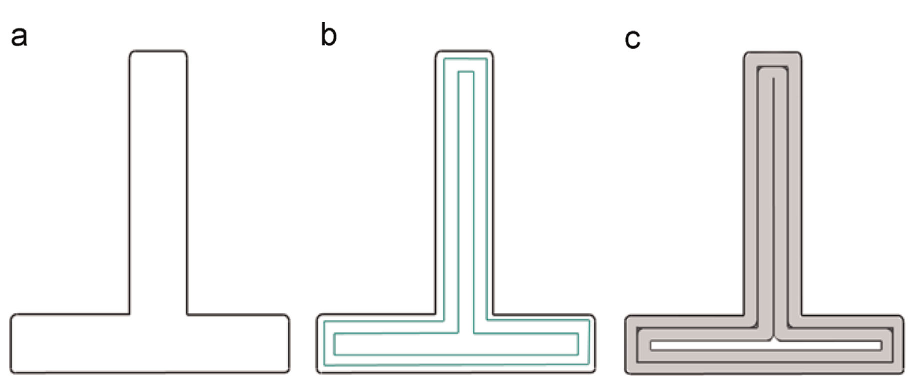


Fig. 1. (a) A cross-section of a simple thin-walled structure. (b) Contour path patterns generated by offsetting the boundary curves towards its interior. (c) Deposition of materials along the generated path. Narrow gap (middle white area) is left which cannot be filled by the path.