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A level-set based continuous scanning path optimization method for reducing residual stress and deformation in metal additive manufacturing

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Abstract

Thermal residual stress and distortion inherent in metal melting and solidification process is the main cause of build failure in metal additive manufacturing (AM) techniques such as laser powder bed fusion and directed energy deposition. To ensure build quality against residual stress/distortion, it is desirable to tailor the scanning path for a given geometry that needs to be built. Since the local deformation introduced by the moving heat source is anisotropic due to non-uniform heat transfer and mechanical constraints, the scanning path can affect residual stress within a part significantly. Aiming at thermal residual stress/distortion mitigation, this paper presents a novel level set-based scanning path optimization method. The method is developed to enable layer-wise continuous scanning path optimization for geometrically well-defined parts. To make the optimization efficient, a fast process simulation method called the inherent strain method is employed to simulate the thermal residual strain. Full sensitivity analysis for the formulated compliance- and stress-minimization problems is provided, where a novel strategy called the adaptive level set adjustment (ALSA) is proposed to remedy the deficiency of ignoring the non-implementable sensitivity terms. The effectiveness of the proposed continuous scanning path optimization method and ALSA strategy has been proved by a few numerical examples. Finally, the concurrent design scenario for simultaneous scanning path and structural optimization is investigated to demonstrate the further residual stress reduction.

Keywords: Continuous scanning path; Level set method; Residual stress mitigation; Adaptive level set adjustment; Concurrent design

1. Introduction

Metal additive manufacturing (AM) approaches, such as powder bed fusion (PBF), wire-feed additive manufacturing and directed energy deposition (DED) have emerged as the mainstream AM processes for metallic part fabrication. Among these approaches, the PBF process, including selective laser melting (SLM), electron beam melting (EBM) and directed metal laser sintering (DMLS), has the highest manufacturing accuracy and best surface finish. With this technique, metal powders are spread to form a thin material layer of tens of microns, and laser beam selectively melts the powders based on the geometric input. Once the layer-wise scanning is finished, the build tray moves downwards to process the next layer. In directed energy deposition (DED) and wire-feed additive

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manufacturing, metal powder or wire is fed into the melt pool created by the heat source such as a laser, arc or electron beam. Compared with PBF, these approaches could build metal parts in much larger scale efficiently. These layer-by-layer fabrication processes can easily be utilized to fabricate complex geometries so that the potential to design higher performing structures for AM can be fully exploited. On the other hand, residual stress is inherent in these AM processes due to sharp thermal gradient and rapid cooling rate, which may lead to severe part distortion, cracking, and delamination from the build plate. This type of thermal stress-induced failure will cause a build to stop abruptly and thus will increase manufacturing time and cost.

To address this issue, the effect of scanning strategy on residual stress has been extensively investigated. Scanning strategy can be divided into two parts, namely the scanning parameters (heat source power and velocity, hatching space and layer thickness) and scanning path. Studies on scanning parameters in SLM have been performed to improve fabrication quality of parts with horizontal structures [1] and downfacing structures [2]. Studies on scanning path were mainly focused on the so-called island-type scanning pattern, in which the layer is divided into blocks and scanning is conducted in a block-by-block sequence. Different scanning orientations and island sizes have been explored to examine the influence on thermal residual stress [3–9]. Rather than focusing on the island scanning strategy effects, we will explore free-form continuous scanning path optimization on residual stress mitigation for metal parts. The continuous scanning strategy is a scanning pattern with high efficiency widely used for different metal AM processes, including PBF, wire-feed additive manufacturing [10] and DED process [11]. Ding et al. [12,13] proposed a continuous path planning method based on medial axis transformation algorithm to produce void- and gap-free part in wire + arc additive manufacturing (WAAM). To the best of the authors' knowledge, optimizing continuous scanning path for residual stress reduction has not been studied yet. The main obstacles include complexity of the optimization problem and computational expense of full scale AM process simulation.

Even though continuous scanning path optimization for metal additive manufacturing has never been tackled, there are extensive numerical studies on optimal path planning on fiber reinforcement design or polymer AM, wherein material properties are greatly affected by build path orientation. Ponche [14] proposed a global design for AM (DfAM) framework to consecutively design the build direction, structural shape, and deposition paths. Hoglund [15] performed compliance minimization topology optimization with fiber angles as additional design variables for fiber-reinforced polymer printing. A limitation of this method is that fiber angles are treated as discrete variables without considering the overall printing path smoothness and continuity. To address this issue, filters [16–18] are introduced to project the discrete angle variables for smoothness improvement. Other than that, a level set-based continuous fiber path optimization method was proposed by Brampton et al. [19]. Fiber paths were defined by iso-value level set contours, so that continuity is always guaranteed. Beyond that, smoothness of the paths can be addressed by adding curvature constraints, and signed distance property of the level set field makes it trivial to derive a ready-to-print deposition path. However, there are also limitations of this method that the solution is heavily dependent on the initial guess and convergence is reported to be slow. Another level set-based continuous path optimization method was developed by Liu et al. [20], wherein the structural topology was concurrently optimized rather than fixing the structural geometry. With that method, deposition path planning is performed by offsetting the structural boundary, and hence it cannot handle deposition path optimization for fixed geometry. In addition to fiber deposition and polymer printing, the level set method has been applied to contour-offset path generation for traditional machining [21,22] as well.

Among the aforementioned methods, the approach developed in [19] will be referred in this work since similar continuous path optimization problem for well-defined geometry is the subject of interest here. Improvements will be made to this approach to enhance the robustness and convergence speed. More importantly, 3D stress minimization problem will be solved in addition to compliance minimization. Beyond that, part of the sensitivity (in domain integration form) was ignored in their implementation [19]. That may be fine for compliance-type problems, but may cause severe convergence fluctuations or divergence for stress minimization problem. Therefore, we have proposed the adaptive level set adjustment (ALSA) strategy to remedy the negative impact of ignoring part of the sensitivity result. Another major difference is that the underlying physics are different. Unlike polymer printing in which the process-induced material anisotropy is inevitable, material anisotropy of metals is much less significant [23], which often times can just be ignored. Therefore, the effect of scanning path on material constitutive model is ignored in the proposed optimization model, while the thermal residual strain is assumed to be dependent on the scanning path [24]. More details about these physics will be illustrated in Section 2.

As discussed earlier, the high computational expense of full scale process simulation is another obstacle toward implementing scanning path optimization. In general, full-scale process simulation for metal AM takes hours or days for a typical part. Therefore, it is impractical to implement detailed full-scale simulation based scanning path optimization, since it may require hundreds of iterations to converge. This challenge has drawn quite some attention, and many fast simulation models have been proposed recently. In this research, the recently proposed modified inherent strain method [24,25] is adopted for its fast speed and acceptable prediction accuracy. Details about the modified inherent strain method will be discussed in Section 2, and briefly speaking, the inherent strain-based fast prediction can shorten the simulation time to minutes with good accuracy, e.g., usually less than 10% error for residual deformation.

In summary, existing optimization methods have partially addressed the deposition path planning in terms of 2D compliance cases and discontinuous elemental angle optimization but it still deserves more exploration to advance the state-of-the-art. This paper is organized as follows: In Section 2, the modified inherent strain method, a novel method for part-scale stress and distortion simulation of the metal AM process, is presented. Section 3 presents the level set based formulation of compliance and stress minimization. Section 4 details the adaptive level set adjustment and, the numerical strategy developed for effective contour update and convergence. The effectiveness of this continuous deposition optimization framework is demonstrated by several 3D numerical examples in Section 5. Section 6 presents the extension of the proposed method to concurrent design to optimize the structure and scanning path simultaneously. In Section 7, discussions and conclusions are given.

2. Modified inherent strain method

Although the mechanism of residual stress and distortion in laser powder AM process has been extensively studied through numerical simulations in micro-scale [5,26–28], there is still a large gap between these finite element models and part scale AM part prediction. For example, a full-scale thermomechanical simulation for a large EBM part consisting of 107 layers takes 15 h to complete by running the Pan Computing software [29], which is one of the fastest commercial software packages with well-developed numerical techniques. Because of the high computational expense, full-scale simulation for metal AM part residual distortion and stress prediction is impractical, particularly for gradient-based iterative optimization.

To address this issue, the inherent strain method is adopted as an alternative solution. The inherent strain method was originally introduced by Ueda to simulate conventional welding decades ago [30]. The basic theory of this method is that residual distortion and stress are the result of incompatible internal strains, such as plastic, elastic and phase transformation strains. After the welding is completed, elastic strain is fully relaxed and thus the inherent strain equals the plastic strain generated in the welding process [31–34].

Unlike welding problems that only have single or a few welds, a metal part produced by AM utilizing a high energy source consists of thousands of layers and also thousands of hatch lines in each layer. Boundary conditions in the process simulation dynamically evolve in a thermomechanical analysis. Hence, elastic strains due to thermal expansion mismatch cannot be fully released as in welding problems. Considering the uniqueness in metal additive manufacturing, Liang et al. [24,35] proposed a modified inherent strain model to predict residual stress and distortion at the part scale. The proposed model allows for extraction of accurate inherent strains directly from results of high-fidelity microscale detailed process simulation by solving the transient thermomechanical problem. As shown in these previous works, the inherent strains are anisotropic with respect to the scanning direction due to the non-uniform heat transfer caused by the moving heat source. In general, the inherent strain along the scan direction is compressive with the largest amplitude among the three normal strain components. The inherent strain transverse to the scan direction is also compressive but with a smaller amplitude, while that in the build direction is tensile due to the Poisson effect. This scanning orientation dependency in the inherent strains is the reason why changing the scanning path in the AM process has a significant effect on the residual stress and strain distribution.

After the scanning orientation-dependent inherent strains are computed from the elastic and plastic strain histories obtained, they are being treated as thermal strains applied to the AM part in a series of layer-by-layer static equilibrium analysis. To carry out the inherent strain based analysis in commercial finite element software, the scanning orientation-dependent thermal strains are inputted as the thermal expansion coefficients, and a unit temperature rise is applied to carry out the analysis. Due to its high efficiency, inherent strain based AM process simulation has drawn increasing attention from academia [36–38] and industry. Most of the commercial AM process simulation packages, such as Simufact (MSC), Amphyon, Pan Computing (AutoDesk) and 3DSim (ANSYS), have