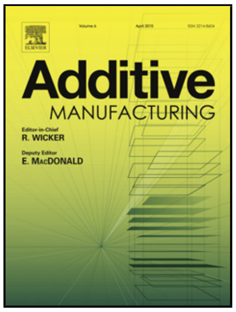

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Utility of Superposition-Based Finite Element Approach for Part-Scale Thermal Simulation in Additive Manufacturing

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Abstract: The utility of a superposition-based finite element approach is explored for part-scale thermal simulation in additive manufacturing. The approach consists of summing a nearly analytic solution for a moving source in a semi-infinite medium with a correcting finite domain field computed with finite element analysis. The accuracy and computational expense of the approach are tested against a fully converged traditional finite element approach. Through efficient implementation of the nearly analytic solution and the use of a coarse finite element mesh away from surfaces, part-scale thermal modeling appears possible without sacrifices in accuracy, at least in the context of the linear heat equation.

Keywords: Additive Manufacturing, Thermal Modeling, Finite Element, Superposition, Part-Scale

1. Introduction

Additive manufacturing (AM) is a rapidly emerging technology with a potential to significantly impact many application areas [1–3]. AM techniques offer the capability to economically fabricate customized parts with complex geometries in a rapid design-to-manufacture cycle. The lack of tooling allows for a distributed manufacturing model, and the geometric freedom allows for improved design and functionality not possible with traditional techniques. Here we focus on AM processes that utilize thermal energy to fuse materials, where the intensity of the thermal energy can be rapidly modulated, e.g. directed energy deposition and powder bed fusion.

When parts are additively manufactured by thermal energy (via energy sources such as lasers, electron beams, and electric arcs), the applied power is a critical parameter [4–9]. If the power is too low, lack of fusion and/or balling defects will be ubiquitous. If the power is too high, other defects may dominate, e.g. keyhole defects [7, 8, 10]. The presence of such defects can be highly detrimental to the mechanical performance of an AM part, particularly with respect to fatigue and ductility [11]. A key challenge to producing mechanically reliable AM parts is that the appropriate power density is not constant during the build. Instead, it is a field that varies spatially throughout the part. The fluctuation arises from the accumulation of previously supplied heat and the variation in the rate that heat is conducted away from each point.

As demonstrated long ago by Rosenthal [12] and Christensen et al. [13] for welding applications, a useful estimate of the appropriate power density can be obtained from the temperature field that solves the linear heat equation,

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T + \frac{Q_v}{\rho c_p} \tag{1}$$

where T is the temperature, ∇^2 is the Laplace operator, α is the thermal diffusivity, Q_v is the volumetric heating rate, ρ is the density and c_p is the specific heat.

With that said, closed form solutions to the linear heat equation only exist for a small set of possible geometries and time histories [14], with typical AM applications being outside of this set. Numerical approaches, such as the finite element method, can easily address geometric and temporal complexities, but are overwhelmed by the disparity of scales that exists in a typical AM problem. In other words, the local temperature field near the heat source is crucial to AM part quality; yet, sufficiently resolving this field requires a level of discretization that makes part-scale calculations computationally infeasible. As a result, most thermal modeling of the AM process has (1) focused on local details of the material - heat source interaction far below the part scale [15–26], (2) coarsened the action of the heat source over time and space, e.g. deposition of multiple layers (or tracks) at one time [27–33], (3) reduced the order of the thermal model [34, 35], and/or (4) required adaptive remeshing [34–38]. As such, there is a dearth of models capable of guiding the selection of an optimum power density schedule over the domain of the component to minimize build defects.