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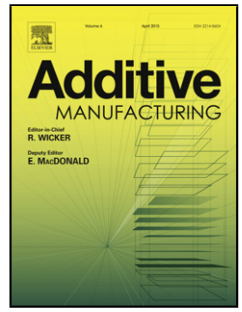

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Simulation Modeling for Optimal Control of Additive Manufacturing Processes

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Abstract

Simulation models of direct energy deposition and powder bed fusion processes have been developed to investigate dynamic control at the process level. A meta-model, developed from computational experiments with an existing numerical model, is used to characterize the physics at the hot spot beneath a laser beam. The meta-model describes model the process dynamics at the millisecond scale using closed-form analytic equations to which we add un-modeled dynamics in physical processes. An auxiliary finite difference model of heat transfer simulates heating of regions adjacent to the laser track. Temperatures predicted with the auxiliary model are incorporated as initial conditions for meta-model predictions of future laser scans. The synergy of the meta-model and the finite difference model creates a higher-fidelity model, which is used to generate input data for a model-free optimal controller. Simulation results prove the capability of proposed optimal controller to vary scan speed accordingly when accounting for track-to-track interaction.

Keywords: additive manufacturing, simulation model, optimal control, laser powder bed fusion

1. Introduction

Advanced manufacturing has rapidly become an active research area in the United States since the President's Council of Advisors on Science and Technology (PCAST) report in June 2011 [1]. Additive Manufacturing (AM) has attracted attention due to its advantages in cost reduction, adaptive design and development, and diversity in product design, as compared to traditional manufacturing. Still, to achieve global competitiveness, AM needs to meet additional demands from contemporary issues such as energy and process level intelligence. Handling such issues requires advanced process control from the integration of high performance computing for modeling, simulation, and analysis. In particular, optimal control may address the energy issue by searching for the most energy efficient process control trajectory. More importantly, if a model-free control technique automatically finds an optimal process from sensor-collected data without a priori process dynamic models, the manufacturing process could be regarded as having an intelligence to self-adjust for optimality.

In this paper, a recently developed single input single output (SISO) model-free optimal control technique is utilized [2]. The merit of this technique is its capability to find optimal solution of a black-box dynamic system such as AM process with only observation data. That means, this model-free technique is expected to work with any type of numerical model as long as it produces an observational data set. The ultimate goal of this technique is to obtain automatic optimal control trajectories of AM processes through iterative optimization without needing to identify the explicit dynamics. Technically, this model-free approach needs only time series observation data sequences of control and state variables.

The selection of control and state variables is determined by their proper relationship as an input and an output of the system. In many AM processes, it is still not clear how much influence each factor has on the build quality of AM product. For example, Hu [3] set laser power as a control variable for feedback control while other parameter values such as scan speed and powder feed rate are fixed in order to maintain a uniform melt-pool size, which lead to a uniform build shape. Simch [4] studied a relation between build density and laser energy input power which includes several control variables such as laser power, scan rate, scan line spacing, and layer thickness.

A recent NIST report [5] shows correlation between control variables and product qualities through a number of process signature parameters. Some investigations have given hints to identify the convoluted relations between them. Gong [6] tried to show the relationships between beam speed, temperature profile, and microscopic build quality through experimental data of four different beam speeds. Even though the explicit relationship was not modeled quantitatively, the result showed that two specific beam speeds with similar temperature profile peak values resulted in best quality. This implies that the build quality may be achieved by controlling the peak value of temperature profile, which is again controlled by beam speed. Therefore, a laser scan speed and peak temperature beneath the laser beam have been selected as control and state variables respectively in this study.

The observational data for the development of process models is obtained from either numerical process simulation or real experiment. Recent empirical research has been reporting both the opportunity and challenge of a thermographic measurement

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