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Simulations and Experimental Validation of Residual Stresses in Additively-Manufactured Components

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ABSTRACT
Deployment of additively manufactured components into high consequence engineering environments requires a comprehensive understanding of factors such as residual stresses, mechanical properties, and distortions. Sharp and quickly evolving thermal gradients during additive manufacturing lead to residual stresses with highly varying spatial gradients and magnitudes near room temperature material yield stress. Finite element modeling was selected as a method of predicting and improving performance outcomes for additively manufactured components. To model the additive manufacturing process, a coupled thermal-mechanical Lagrangian finite element process model workflow was implemented in the SIERRA software package. Several different 316L stainless steel geometries were designed such that residual stresses and microstructures could be measured experimentally, and the specimens could be simulated in a reasonable time. Validation of the modeling results through comparison to experimental residual stress, hardness, and microstructure measurements was performed. Through the integration of experimental measurements, baseline modeling results are validated and can be extended to elucidate the full-field residual stress and mechanical properties in additively manufactured components.

Keywords: Additive Manufacturing, Residual Stress, Finite Element Analysis

INTRODUCTION

Emerging manufacturing capabilities collectively referred to as additive manufacturing (AM) are enabling the repair, prototyping, and manufacturing of components not possible through conventional manufacturing [1]. Of particular interest to engineers is the additive manufacturing of structural alloys, and in particular austenitic stainless steels. AM in structural stainless steels is primarily carried out in either powder bed fusion (PBF), or laser engineered net shaping (LENS) processes. This work focuses on the experimental validation of a previously developed thermal mechanical finite element modeling workflow [2] using experimental data from residual stress measurements for 316L stainless steel structures built using the LENS process. In the LENS process, a continuous spray of metal powder is deployed to the focal point of a laser creating a melt pool, and the deposition of material. Through movement of the baseplate, the melt pool is also moved, and progressively cooled to build up forming the final desired geometry. Inherent to the LENS process with stainless steel are high cooling rates as the molten pool cools, that produce residual stresses on the order of material yield strength (~400 MPa) [3] as well as spatially varying material properties [4]. The quantification, prediction. and understanding of residual stresses, material properties, and the resulting structural performance remains a barrier to the deployment of LENS parts in critical engineering applications.

Model results are of particular relevance to the AM community because they are capable of capturing the spatially varying material properties and residual stresses present in AM builds without destructive, or time consuming characterization. However, calibration and validation of model predictions is absolutely essential in order to develop confidence in model results. Thus, the aim of this work is to compare the residual stress predictions from this model have which have yet to be validated against precise measurements of residual stress in order to develop confidence in model predictions.

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BACKGROUND

Experimental assessments of residual stress presented herein were obtained through the contour residual stress method. The contour method is able to measure residual stresses normal to a cutting plane through destructive measurement of a structure. In this work an electron discharge cutting machine was used to cut a cylinder AM built part into two equal pieces. The surface deformations caused by residual stresses on the freed surface are measured and an inverse finite element problem is solved to determine the stresses that caused the measured deformations [5]. Thus, an experimental assessment of the stress component normal to the cut surface throughout the cut surface is available for comparison to model results.

To generate modeling results, a previously established thermal mechanical finite element modeling workflow [2] was used to simulate the complete cylinder AM build process. A primary barrier to quick production of model predictions is the computational time required to accurately resolve the time and length scales present in an AM build. Accurately capturing the thermal mechanical history at both part (~m) and melt pool (~mm) length scales throughout the build process remains a computational challenge. Thus, for this study experimental build samples were designed such that they would be computationally tractable, yet still able to be evaluated experimentally. The experimental design strategy focused on maintaining a build volume that was as small as possible while modifying the build geometry, raster pattern, and build plate size to demonstrate different variations in the resulting residual stress profiles that may appear in LENS builds. Additionally, to decrease the computational time required to simulate the cylinder builds, a lumped laser method where the laser was simulated using a computational laser heat source model twice the size of the actual laser was applied. The power density for the enlarged laser beam was kept the same as the experimental build process, and the raster path was approximated accounting for the larger simulated beam. Following the process modeling simulation and cooling to within 70 K of room temperature, an additional simulation was completed to capture the effects of unclamping, or releasing of baseplate constraints following the build. Model results following unclamping are then compared to contour method measurements of residual stress. After the completion of a more comprehensive set of experiments and simulations, model parameters (e.g. constitutive parameters and laser source models) will be calibrated to experimental measurements, and a more robust code will be deployed to enable critical predictions for LENS parts.

ANALYSIS

Model predictions for a cylinder built using a ‘spiral in’ raster pattern were compared to residual stress measurements made using the contour method. Contour plots showing both model results and contour method residual stresses are shown in Figure 1.

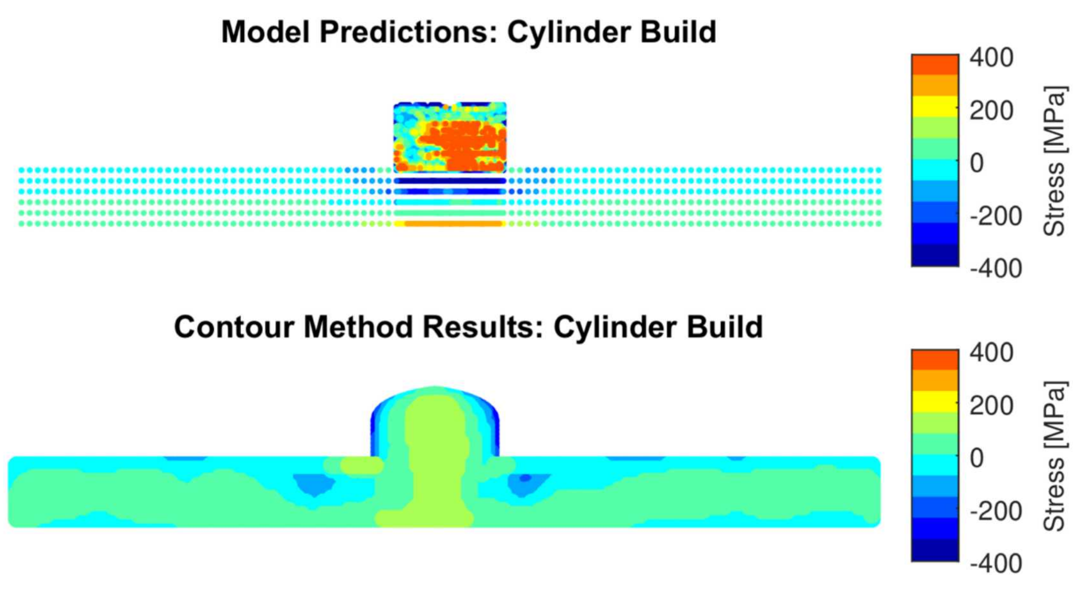

Figure 1: Residual stress from (top) model and (bottom) contour measure for cylindrical build.

In general, model results predicted higher tensile stresses in the center of the build, and near the baseplate/part interface. Similarly, slightly higher residual stress magnitudes were predicted to occur in the baseplate compared to the contour method measurements. Modeling results also show oscillations in stress on the length scale of each build layer that are not observed in the contour method measurements. Line plots for several locations in the build for both model predictions and experimental contour method measurements are shown below in Figure 2.

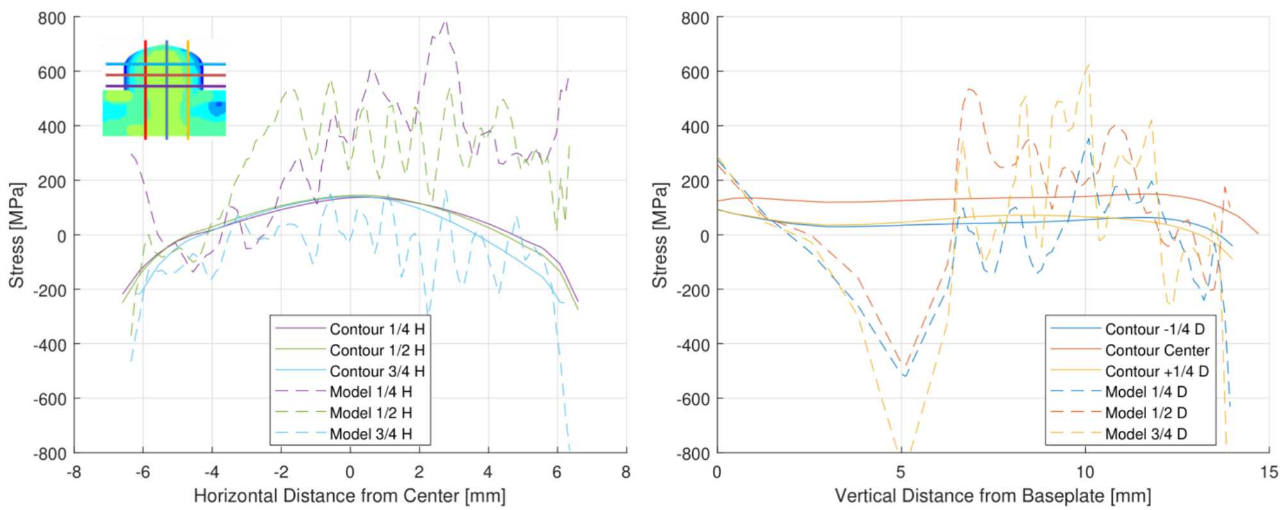

Figure 2: Line plots of model and contour measurements for cylinder build at (left) various radial positions and (right) various axial positions. The cylinder height is designated by, "H" and cylinder diameter is designated by, "D."

CONCLUSION

The integration of experimental measurements for the purpose of validation of computational model is essential prior to deploying a predictive computational capability. In this case, residual stress predictions from a thermal mechanical finite element process model are compared to experimental residual stress assessments from the contour method. Results from both model and experiment show similar residual stress patterns for the example build and baseplate structure. Model predictions resolve stresses at a finer length scale compared to the contour method, and generally showed higher stress magnitudes compared to the contour method measurements. These results demonstrate general agreement, and suggest that calibration of the model is required in order to more closely match experimental measurements. Future work will expand these methods to incorporate several different geometries and LENS build strategies. In addition, additional residual stress measurement techniques including neutron diffraction and slitting methods will be included to provide additional means of assessing residual stress in additive manufacturing build. This complete set of model predictions and experimental measurements will be integrated to improve confidence and enable high quality predictions for the as manufactured properties and performance of LENS parts.

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