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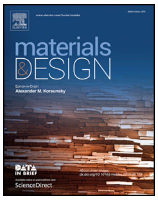

Neutron residual stress measurement and numerical modeling in a curved thin-walled structure by laser powder bed fusion additive manufacturing☆

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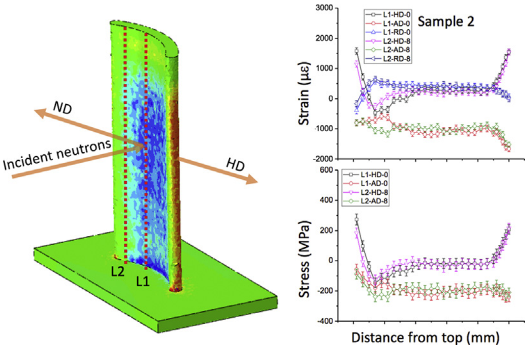
HIGHLIGHTS

- Experimentally solving residual stress of curved structure without stress free lattice measurement
- Accelerated stress simulation for additively manufacturing by simplified methodology
- Validated methodology can be easily adapted to complex parts for guiding part geometry design and process parameter design.

GRAPHICAL ABSTRACT

Neutron is a powerful tool for residual stress determination in AM structures.



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ABSTRACT

Severe residual stresses in metal parts made by laser powder bed fusion additive manufacturing processes (LPBFAM) can cause both distortion and cracking during the fabrication processes. Limited data is currently available for both iterating through process conditions and design, and in particular, for validating numerical models to accelerate process certification. In this work, residual stresses of a curved thin-walled structure, made of Ni-based superalloy Inconel 625™ and fabricated by LPBFAM, were resolved by neutron diffraction without measuring the stress-free lattices along both the build and the transverse directions. The stresses of the entire part during fabrication and after cooling down were predicted by a simplified layer-by-layer finite element based numerical model. The simulated and measured stresses were found in good quantitative agreement. The validated simplified simulation methodology will allow to assess residual stresses in more complex structures and to significantly reduce manufacturing cycle time.

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1. Introduction

Additive manufacturing (AM) has evolved significantly in the last decades. In contrast to traditional subtractive manufacturing, it builds a part through the layer-by-layer deposition of materials to create complex structures directly from a computer model design [1]. In a laser powder bed fusion additive manufacturing process (LPBFAM), such as direct metal laser melting (DMLM) or selective laser melting (SLM), a laser beam of sub-millimeter diameter travels at high speeds, on the order of hundreds of millimeters per second, to melt thin layers of powders; and such powders are rapidly solidified in the wake of the passing laser beam [2]. The high thermal gradients and repetitious local heat transfer cause residual stress build-up in the part [3–5] and local heterogeneous microstructures and textures [6,7], which can have negative effects on structural integrity, geometry tolerances and dimensional stability.

A three dimensional multi-physics numerical simulation in continuum scale provides insightful understanding of the rapid alloy solidification process with non-isothermal phase change [8] and evolution of stresses [9]. While analytical models provide process optimization in simple structure [10], models based on finite element and finite volume methods have been developed to simulate the powder consolidation process using various energy beam scanning approaches and geometries [11–13]. By considering the material properties and process parameters, the actual scanning process can be simulated and variables such as the molten pool geometry can be well predicted. This type of simulation can help optimize the processing parameters to avoid discontinuous tracks, voids, and local stress concentrations. Direct simulation of thermally induced distortion based on the powder consolidation process track by track is computationally expensive [14] and it is impractical for real, complex parts that consists of millions of individual tracks. Therefore, an efficient but simplified approach is required to model the fabrication process rapidly [15] and provide estimates of stress evolution and the resultant distortion.

Quantifying residual stress experimentally will provide essential computational model validation [10,16–18] for predicting the distribution of residual stress, thus helping refining process parameters to improve total structural integrity and advance the adaptation of the advanced manufacturing. Thanks to the deep penetration feature, neutrons are well suited for the additive manufacturing [5,18–24] of metals such as aluminum alloys, stainless steels, and Ni based super alloys for their process variances, voids, textures, deformation behaviors, and residual stress et al. Neutron diffraction (ND) as a non-destructive characterization tool is effective in evaluating macro residual stresses in structures [25–28], where thousands of grains are sampled in a volume of cubic millimeters for their d spacing elastic change due to internal stresses [29]. A thorough 2D or 3D scan could generate the distributions of residual stress/strain in the structure for simulation validation. Here we report a combined neutron experimental and a simplified FEM study of residual stresses in an Inconel superalloy curved thin-walled structure by LPBFAM. A non-destructive stress-free lattice dspacing d_0 determination scheme regardless of the change of chemistry at different locations is adopted and proved to be adequate for the curved thin-walled structure, and the results show that even in an AM thin structure, significant values of residual stress remain. The residual stress is well predicted quantitatively by the simplified FEM simulation and the development of the residual stress is revealed by the simulation.

2. Experiments and modeling

2.1. Sample manufacturing and preparation

The thin-walled parts (Fig. 1) made of IN625 were built using a SLM250 (SLM Solutions NA, Inc.) on a 6.35 mm thick stainless steel (SS304) build plate. The processing parameters, as well as parameters used for simulation including laser absorption and heat transfer coefficients, are listed in Table 1. Three parts, as shown in Fig. 1, with identical dimensions but different orientation, were built on the same build plate, and are named as Sample 1, 2 and 3 for the following discussion. After they were separated along the dashed lines in the figure, Sample 1 was annealed in argon at 1050 °C for 2 h and cooled slowly to room temperature in air. Most of the residual stresses are expected to be relieved by this heat treatment process. All three samples were measured by neutron diffraction to probe the effect of orientation on the stress distribution between Samples 2 and 3 as well as the effect of heat treatment on Sample 1. After the neutron measurement, Sample 2 was sectioned for microstructure analysis using SEM and EBSD.

2.2. Residual stress determination by neutron diffraction

Residual strains can be determined non-destructively by measuring the change of the *d* spacing of certain crystal planes by neutron diffraction [29]. The engineering materials diffractometer, VULCAN, at the Spallation Neutron Source, Oak Ridge National Laboratory [30] was used and the experimental setup is shown in Fig. 2. The specimen is positioned on a sample stage with the curved wall aligned at 45° from the incident beam. The −90° and +90° detector banks record diffraction patterns simultaneously from two sets of orthogonal lattice planes whose normal directions are parallel to Q_1 and Q_2, respectively. The lattice strains in three orthogonal directions, hoop direction (HD), radial direction (RD, normal to the curved surface), and axial direction (AD, which is also the build direction) were measured (Fig. 2). Due to the curvature of the samples, to measure the strain components hoop direction and radial direction to the local surface, the sample is rotated accordingly around the built axial direction to maintain the HD to be 45° from the incident beam (as shown in Fig. 3). To measure the strain along the AD in the −90° detector bank, the sample was rotated by 90° around the RD axis. A 2 × 2 × 2 mm^3 gauge volume is defined by

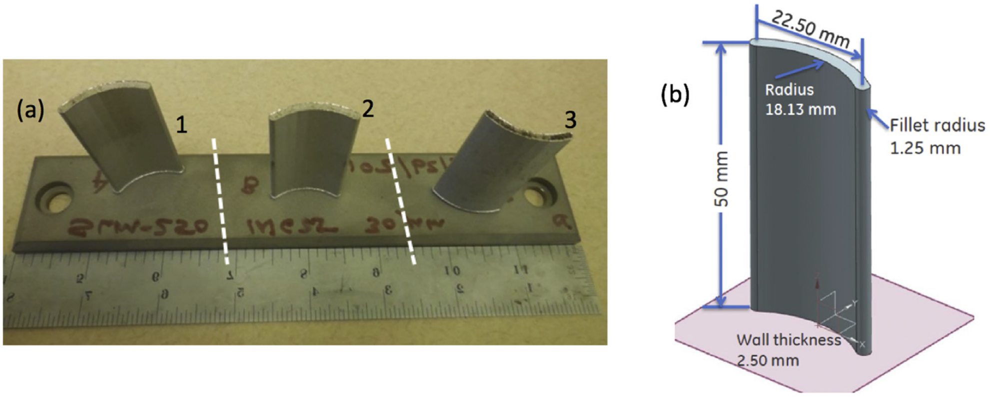

Fig. 1. Three as-built parts, 1, 2 and 3, on the build plate (a) and their design dimensions (b).