A Multiscale Modeling Suite for Part Qualification in Metal Additive Manufacturing

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ABSTRACT

Metal Additive Manufacturing (AM) shows great potential for producing light-weight structures, reducing development cost and lead time in critical industies such as aerospace and medical device. However, a major barrier that remains is rapid qualification of additively manufactured components. Sentient Science Corporation (Sentient) has been enhancing its DigitalClone® software to include an ICME (integrated computational materials engineering) modeling framework for part qualification in metal additive manufacturing (AM). This physics-based multiscale model can be used to qualify material and process parameters with minimal calibration. Specifically, the DigitalClone model can take key AM process parameters (e.g. laser power, scan speed, hatch strategy, layer thickness) as inputs, and simulate part-level distortion and residual stress.It can also simulate the microstructure (e.g. grain structure, porosity) of as-built parts, and fatigue performance when the part is used in the field. This paper will present a series of case studies to demonstrate Sentient's simulation suite. Sentient expects this to be one of the most comprehensive software solutions for part qualification in metal AM.

Keywords: metal additive manufacturing, part qualification, ICME, computational modeling

1 INTRODUCTION

Additive manufacturing as defined by ISO/ASTM 52900-15 [1] is the "process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to conventional manufacturing including subtractive manufacturing technologies and formative manufacturing methodologies" (ISO/ASTM 52900-15). Metal AM has been increasingly popular due to the significant advantages and capabilities, including rapid prototyping, fabrication of complex geometries, reduction of product development cycles, and high utilization of material. Aerospace original equipment manufacturers (OEMs) and the defense industry needs the AM technique to build light-weight structures with innovative designs. However, a major barrier that remains is rapid qualification of additively manufactured components.

The current qualification approach for AM components relies heavily on empirical testing. Fully qualifying a material often requires thousands of individual tests, which cost millions of dollars and many years to complete. A minor change of any variable would require complete re-qualification. The high qualification cost and time is encouraging companies to keep the resulting data proprietary, which in turn makes qualification even more costly. As such, a software-based qualifcation procedure is higly desirable.

Considering the complex mechnaism of layer-by-layer manufacuring process, a multi-scale and multi-physics model is needed to account for different stages of building an AM component. This includes qualification of material and machine parameters, qualification of component design and support structure, qualification of resulting microstructure and properties, and qualification of dynamic performance when component is used in the field. Current software on the market are typically limited to thermo-mechanical analysis to predict part-level distortion. That software can reduce the development cost and time to a certain level, but they are not able to assess resulting microstructure, mechanical and dynamic properties which will also consume large amount of qualification effort. Therefore, a more comprehensive software is highly needed to truly minimize qualfication process and accelearate AM productilization.

2 SENTIENT'S MODELING FRAMEWORK

Sentient has been enhancing its DigitalClone software to include a multiphysics and multiscal ICME modeling framework for part qualification in metal AM. This physics-based model can simulate several aspects of a metal AM component, including part-level distortion and residual stress, grain structure and porosity, and fatigue performance when the part is used in the field. Fig. 1 lists the schematic of Sentient's modeling framework. The model will take a variety of physical parameters as inputs, including AM machine parameters (e.g. laser power, scan speed, layer thickness, hatch space), part geometry, support structure, material property, and mechanical loading. The first step is to simulate the AM process, detailing the evolution of temperature, stress, and distortion. This simulation will identify any potential distortion and over-heating before actual printing. The second step is to simulate the microstructure of as-build AM components. This includes the grain structure and porosity which are of high interest in metal AM process. The simulation in this step will inherent the temperature evolution from previous step, and the simulation result will identify any potential porosity and grain structure with respect to process parameters. Once the qualification at microstructure level is completed, the next step is to qualify the performance of the AM component. Sentient's unique simulation tool for life prediction will simulate the mechanical performance at system level by considering microstructure, dynamic loading, part geometry, and material properties. This simulation will inherent the microstructure from the previous step, and provide fatigue peformance. This will qualify the feasibiilty of AM components to be used in the field. As such, Sentient's ICME framework will provide a quality assessment of AM comopnent at a wide range of scopes, including qualification before printing, durng printing, and post printing. The following sections will present a series of case studies that demonstrate each simulation step and relevant validation against physical testing.

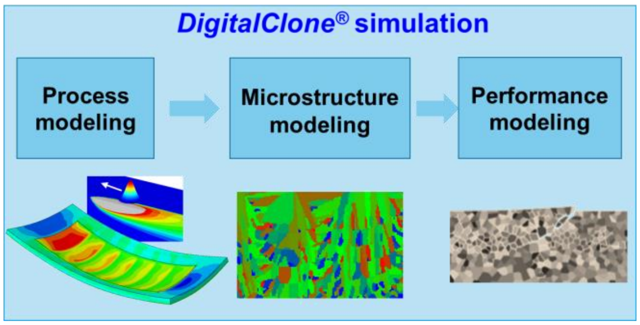

Fig. 1 DigitalClone simulation framework for qualifying the AM process and component.

3 PROCESS MODELING

Process modeling is the first step in Sentient's simulation framework. It involves a physics-based multiscale model that considers different time and length scales. Specically, the model will take several key inputs, including process parameters (e.g. power, scan speed, layer thickness, hatch space) and material geometry, and simulate the temperature evolution at a microscale level which invovles a few scans and layers. Fig. 2 shows the representative results of thermal modeling. The energy source was represented by a physics-based heat flux which considers power, scan speed and hatch space. Also, temperature-dependent and material state-dependent properties are incorproated in the simulation, so the heat transfer phemonenon in the AM process can be accurately capatured. Temperature history at each location can be obtained as shown in Fig. 2d. This simulation result can be used to qualify process parameteres for different materials. As we know, a good heat dissipation is critical in metal AM. Overheating or lack of fusoin both result in part defects, and thermal modeling can be a good tool for better thermal management.

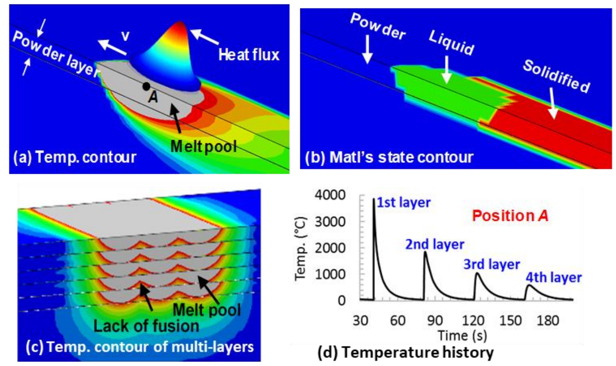

Fig. 2 Thermal modeling at microscale: (a) temperature distribution in single scan; (b) material state transition (powder-liquid-solid), (c) temperature distribution in multi-layers and multi-scans; (d) temperature history at representative location.

In addition to thermal modeling at microscale, there is also a macroscale thermal-mechanical model that can predict the distortion and residual stress of an as-build AM component. As known, thermal-stress is the primary reason that causes printing failure such as part distortion, cracking or recoater jam. As a result, industrial OEMs currently invest heavily in design and process optimization in order to prevent such defects. However, experimental trial-and-error iterations are very expensive in terms of time and money, so a computational tool is highly needed to predict distortion and residual stress. Simulation of part-level distortion is very challenging using traditional fintite element analysis (FEA), because the inherent layer-by-layer process requires the simulation of hundreds of thousands scans which is not realistic [2]. Sentient has implemented a unique algorithm in a FEA solver that simulates part-level distortion at very high accuracy and efficiency. Fig. 3 shows distoriton modeling of a bridge coupon, whose geometry was created by NIST in an AM benchmark test [3]. Part distortion occurs when a section of the part was seperated from the substrate. Sentient's thermal-mechanical model was validated against testing data of such bridge coupons on three different materials (IN625, 15-5 Stainless steel, and IN718). IN625 and 15-5 stainless steel coupons were built on an EOS M270 laser powder bed fuson (LPBF) machine located at NIST, and IN718 bridge coupon was build on Matsuura Lumex Avance-25 laser powder bed fusion machine located at University of Nebraska-Lincohn. As seen in Fig. 3, Sentient's model captured the distortion very well both qualitatively and quantitatively. This demonstrated that the model can account for the material difference. In addition, Fig. 4 shows the residual stress coutours and profiles of the cross section of the 7th leg in the IN625 bridge coupon. Thepredicted results correlate well with experimental data. This thermal-mechanical model has also been validated by several actual AM components made by other materials such as Ti64, 17-4 PH stainless steel.

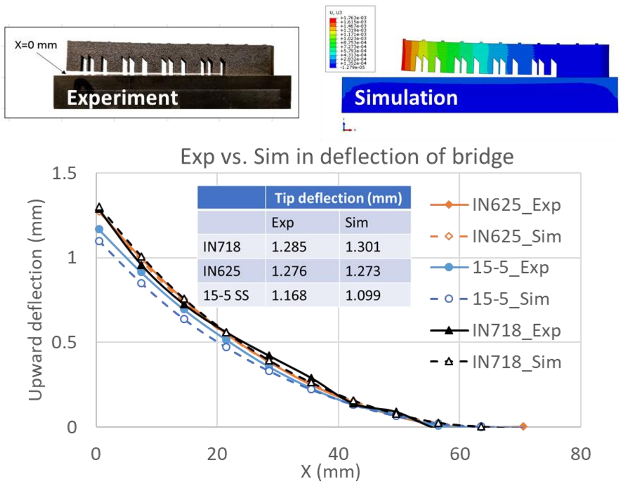

Fig. 3 Part-level distortion prediction: experiemnt vs. simulation. (note: bridge image and distortion data of IN625 and 15-5 stainless steel bridges are from NIST website. [3])

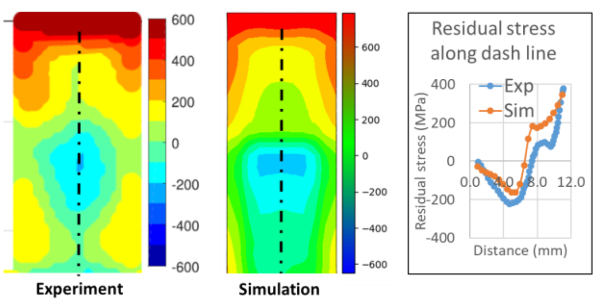

Fig. 4 Part-level residual stress prediction: experiemnt vs. simulation of cross section of IN625 bridge in Fig. 3. Contour area is 5 mm × 12 mm. (note: experimental data is from NIST website. [3])

4 MICROSTRUCTURE MODELING

Microstructural inhomogeneities and defects have significant impacts on resulting properties such as mechancial strength and dynamic properties. AM-built parts typically have different microstructural features from conventionally manufactured components, and the AM microstructure needs to be fully understand in order to confidently deploy AM components to the field. As explored widely [4], AM microstructure is largely dependent of process parameters and materials. As such, industrial OEMs need large amount of trial tests and material characterization to qualify AM parameters for each material and AM machine. Sentient has developed a physics-based microstructure model that can predict grain structure and porosity with respect to process parameter and materials in the metal AM process. The model expects to reduce trial-and-error iterations for AM users and allow them to print with designated microstructure. The general flow of microstructure simulation starts with importing temperature data from process modeling, map the data into a refined grid, and then simulate the grain structure. The microstructure model has been validated by several materials and processes. Fig. 5 shows predicted grain structure of AlSi10Mg by LPBF in comparison with experimental data. Predicted grain structure correlates with expermental results in terms of morphology, pattern, and size. Fig. 6 shows predicted micorstructure at different orientations, as compared to experimental data. It shows the microstructure model can account for grain structure at different orientations. Fig. 7 shows the porosity prediction at different laser powers, and compares it with experimental data. The predicted porosity aligned with experiental data in both low energy density and high energy density. This demonstrates that the model can account for both lack-of-fusion porosity and boling/keyhole porosity.

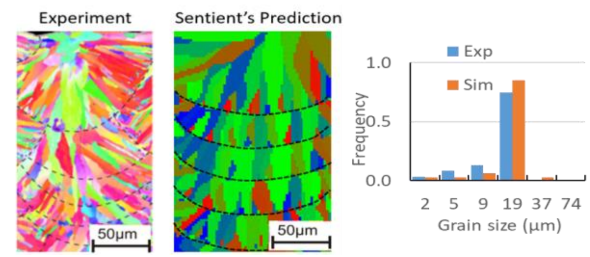

Fig. 5 Grain structure of AlSi10Mg by LPBF process. Experimental data is from [5].

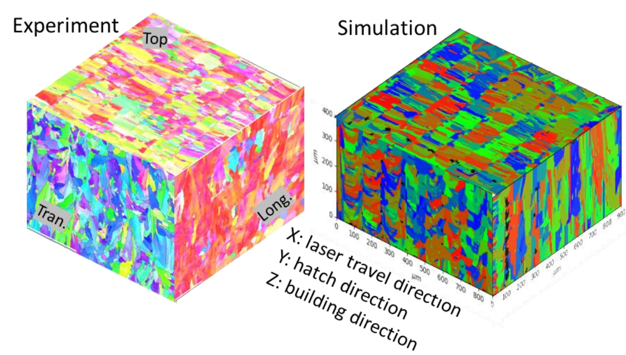

Fig. 6 Grain strcuture of IN718 by LPBF process in three different orientations.

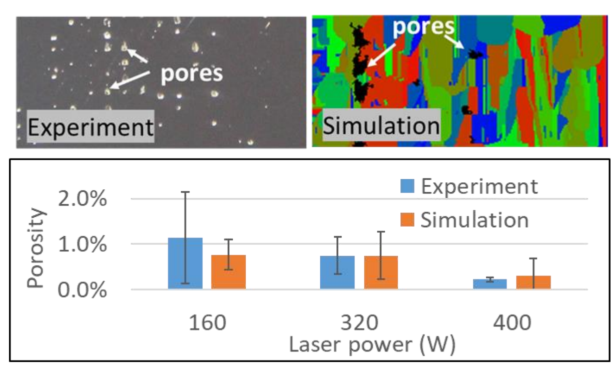

Fig. 7 Porosity of IN718 by LPFB at different laser powers. (Note: exp. and sim. images are not in the same scale.)

5 PERFORMANCE MODELING

After microstructural features have been verified, AM comopnents need to be tested with mechanical property and dynamic property. Conventional destructive testing methods provide limited data at high cost. Sentient's core technology, DigitalClone, is a physics-based modeling tool that simulates the microstructure of different components and their behavior, calculates internal stresses caused by different applied loading conditions, accumulates internal damages resulting in crack nucleation and propagation, and investigates the performance and life prediction. DigitalClone technology has been extensively validated to successfully predict fatigue performance of several conventional materials from wind, aerospace, and rail industries. Through a further development, the innovative AM microstructure model has been seamlessly integrated in our DigitalClone life prediction module. As a result, DigitalClone can predict the fatigue performance of metal AM components made by several different materials and cornrospoding unique microstructural features. Fig. 8 shows the simulation of axial fatigue of 17-4 Ph stainless steel coupons made by LPBF process. A macro-level mechanical analysis was performed first using conventional finite element method. This obtains the mechanical boundary conditions for the representative volume element (RVE) that is unique to specific faitgue loading. Then, the boundary condition of RVE is applied to the AM microstructure domain to simulate the crack initiaion and propogation. Sentient's microstructure model incorporates stochastic features, which generate certain variations in each microstructure. As such, crack initiation and propagration in one simulation is different from a repeated simulation, resulting in the uncertainty of fatigue testing. Fig. 8 shows different crack patterns from two microstructure domains that were generated from the same AM process parameters.

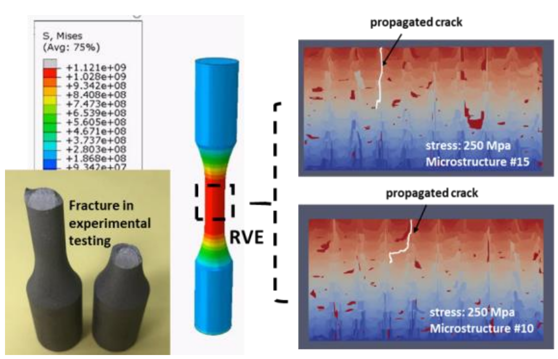

Fig. 8 Fatigue modeling demonstration. Simulated crack patterns vary with microtructure.

By applying different dynamic loading conditions, and repeating each condition with various microstructures, a S-N dataset can be constructed using simulation results. Fig. 9 shows comparison of simulation and experiment of fatigue data at different loads. As seen, simulation results align with the experiment very well. Also, modeling provides more data points at much higher efficiency. The fatigue module has been validated with different fatigue modes (including bending fatigue, axial loading fatigue) for different AM compoents made by various materials.

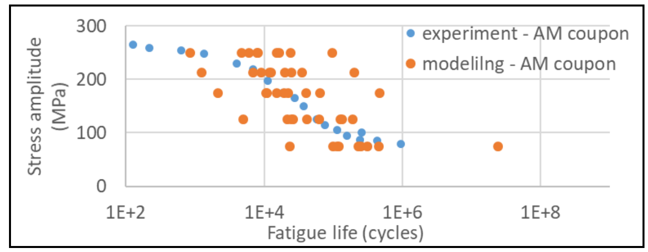

Fig. 9 Fatigue modeling of 17-4 PH stainless steel by LPBF process. Comparison of simulation and experiment.

6 SUMMARY

This paper demonstrates Sentient's modeling capability for part qualification in metal additive manufacturing. Sentient's physics-based model can consider effects at process level, microstructure level, and performance level. This software tool will help AM users to largely reduce the trial-and-error iterations, and make qualified components at significantly reduced time and cost.

Sentient is currenlty deploying this techniology to industrial applications. Please email contact@sentientscience.com for more information.

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