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Development of experimental method for in situ distortion and temperature measurements during the laser powder bed fusion additive manufacturing process ☆

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ABSTRACT

Measurements of the temperature and distortion evolution during laser powder bed fusion (LPBF) are taken as a function of time. In situ measurements have proven vital to the development and validation of FE (finite element) models for alternate forms of additive manufacturing. Due to powder obscuring all but the top layer of the part in LPBF, many non-contact measurement techniques used for in situ measurement of additive manufacturing processes are impossible. Therefore, an enclosed instrumented system is designed to allow for the in situ measurement of temperature and distortion in an LPBF machine without the need for altering the machine or the build process. By instrumenting a substrate from underneath, the spread powder does not affect measurements. Default processing parameters for the EOS M280 machine prescribe a rotating scan pattern of 67° for each layer. One test is completed using the default rotating scan pattern and a second is completed using a constant scan pattern. Experimental observations for the build geometry tested showed that for Inconel® 718 and a constant scan pattern produce results in a 37.6% increase in distortion as compared with a rotated scan pattern. The in situ measurements also show that the thermal cycles caused by the processing of a layer can impact the distortion accumulated during the deposition of the previous layers. The amount of distortion built per layer between the rotating and constant scan pattern cases highlights inter-layer effects not previously discovered in LPBF. The demonstrated inter-layer effects in the LPBF process should be considered in the development of thermo-mechanical models of the LPBF process.

1. Introduction

The laser powder bed fusion (LPBF) additive manufacturing (AM) process produces parts from computer-aided-design (CAD) 3D models. First, the CAD model is split into a series of 2D layers where a laser path and power settings can be defined. For the build process, a thin layer of powder is spread evenly across the build area; then a laser selectively melts the material for that layer which in turn cools and solidifies to form a dense geometry. Layers in powder bed systems are built on the scale of 10-100 μm, allowing LPBF to produce net shape parts. While powder bed systems are capable of producing more accurate parts than other AM processes, large thermal gradients are still present, resulting in unacceptable levels of residual stress and distortion which often cause part failure. Typically, these failures are resolved by a trial and error process wherein processing parameters are changed until a successful build is produced. This process can be costly when including the cost of machine time and material. In order to avoid the trial and error approach, a greater understanding of how residual stress and distortion are accumulated through LPBF processing is required. In situ

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measurements will allow for a greater understanding of the LPBF process.

Several different groups have performed experiments on powder-bed machines focusing on varying aspects of the build process including: scan patterns, laser speed, laser power, and melt pool size using a variety of experimental methods. Pohl et al. performed a series of experiments varying laser scan pattern and speed for a single layer of powder [1]. Post-process experimental deflection measurements were then used to inform which parameters reduce distortion. Kruth et al. presented post-process distortion measurements of parts built in a powder-bed machine [2]. Distortion effects from differing scan patterns for both single layer builds and bare plates were compared in order to select proper processing parameters in LPBF. Kempen et al. have demonstrated a technique to provide in situ melt pool characterization during the LPBF process [3]. Several single track tests were completed to determine the ideal processing parameters. The processing parameters were then applied to the manufacture of part scale builds. Post-process tensile and micro-hardness measurements are made of the full build and then compared against high pressure die casting. The experimental results from these studies are useful in understanding the AM powder-bed process, but they also highlight the limited availability of in situ measurements.

Modeling for the powder-bed AM field has become increasingly popular, as shown by Witherell et al., due to the high cost of performing experiments and a desire to avoid the trial and error approach to the successful manufacture of parts [4]. Paul et al. presented a 3D thermo-mechanical FE (finite element) model to estimate the effect of thermal distortion of powder-bed AM [5]. The effects of part orientation in the LPBF process are measured, but no direct experimental validation is completed. An ANSYS model used by Dai and Shaw (2004) is capable of simulating a powder-bed AM process, but the results shown present only two layers and do not provide any validation [6]. Some of the model developers have used experimental results to validate their models. In an earlier paper from Dai and Shaw (2002), an ANSYS model is used to demonstrate how laser scanning patterns can affect distortion [7]. The paper demonstrates that using a spiral laser scan path can reduce distortion in a build. Li applied an ANSYS model to analyze the effects of differing processing parameters on temperature in powder-bed systems and compared the simulation results against post-process experimental measurements [8]. The experimental results used for the validation study are made post-process by measuring track width from single lines of varying scan speeds. Cheng et al. presented a model that matches well with experimental data focused primarily on thermal characteristics of powder-bed electron beam additive manufacturing [9]. King et al. presented several different models of varying scales, ranging from powder and microstructure scale to full scale part modeling in LPBF [10]. Post-process measurements of final distortion are compared against simulation results. Song et al. use an Abaqus FE model of a powder-bed system to simulate strain in a 2D 15 layer build [11]. This model is validated against x-ray diffraction measurements of the horizontal strain component along a horizontal line in the build. The model presented is capable of matching in order of magnitude and trend of the measured strains. Due to the difficulty in implementing measurement equipment in a powder-bed system, validation data comes from either non-contact thermal measurements or post-process distortion or stress measurements. To date, *no LPBF mechanical model has been validated against in situ distortion measurements*.

While it is common to validate a FE model against post-process distortion measurements, this practice does not provide insight into the process physics. The usefulness of in situ measurements for model validation of AM processes has been clearly demonstrated in several previous studies. Denlinger et al. recorded in situ distortion measurements during the laser direct energy deposition (LDED) processing of Ti-6Al-4V [12]. The results showed that due to the solid state phase transformation present in the alloy, distortion does not build up consistently during deposition. Without in situ measurements, this phenomenon would have gone undiscovered. Heigel et al. utilized in situ measurements of the LDED process to demonstrate the significance of convection in FE models [13]. Several convection boundary conditions were compared to experimental measurements to determine which most accurately simulated the LDED AM process. In another paper, Heigel et al. performed a parametric study of the LDED cladding process [14]. The in situ measurements along with the post-process measurements provided by this study increase the understanding of how distortion is built up in LDED processes. Gouge et al. implemented a convection model for FE analysis of the LDED process [15]. Experimental measurements of convection coefficients are used in the development of a convection model which is compared against in situ thermocouple measurements. Peyre et al. used in situ thermocouple measurements to provide a validation of their thermal model of a direct metal deposition experiment [16]. A non-contact digital image correlation (DIC) in situ strain measurement was used by Ocelik et al. to motivate the selection of processing parameters [17]. Lundbäck and Lindgren utilized in situ experimental measurements for both displacement, made using the ARAMIS optical system, and temperature, made using a pyrometer, in the validation of their model [18]. The validation provided by the in situ measurements was integral in the development of the model now used at Volvo Aero. None of these works, demonstrating the importance of in situ measurement, have focused on LPBF processes.

Due to the practicality of the LPBF process no in situ experimental measurements of distortion are currently available. The primary obstacle in capturing these measurements is the powder from each layer which covers the entire part. This makes many in situ measurement techniques, such as a laser displacement sensor (LDS), impossible. Thus far, thorough model validation of the LPBF process has been impossible due to difficulty of in situ measurements. Therefore, an enclosed instrumented system, henceforth referred to as the *vault*, capable of providing in situ measurements of the LPBF process is designed, built and demonstrated. The *vault* is designed to be placed inside of the LPBF machines without requiring machine modification or the changing of the build process. Substrates are attached at the top of the *vault* with minimal contact to reduce measurement interference. Instrumentation equipment inside the *vault* is attached to the underside of the substrate to measure distortion and temperature during the LPBF process without affecting the build process or being obscured by powder. The temperature of the substrate is measured using K-type thermocouples and the distortion is measured with a differential voltage reluctance transducer (DVRT). Using the in situ experimental results, a comparison of constant and rotating scan pattern is completed to show the effect of the scan pattern on the accumulation of distortion during a multi-layer LPBF build process. The time-dependent experimental results produced from these experiments allows for a greater understanding of LPBF processing parameters and the effects that they have on distortion accumulation.

2. Description of experimental procedure

2.1. Experimental setup

Due to the combustibility of the metal powder used in the LPBF process, the build chamber of the LPBF machine must be filled with inert gas to prevent fires and oxidation of the material. To keep the build chamber sealed, no measurement equipment or wires can breach the seal that surrounds the LPBF chamber without