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Design of a multi-sensor measurement system for in-situ defect identification in metal additive manufacturing

Afaf Remani[1], Richard Williams[2], Adam Thompson[1], John Dardis[3], Nick Jones[3], Paul Hooper[2], Richard Leach[1]

[1]*Manufacturing Metrology Team, Faculty of Engineering, University of Nottingham, Nottingham, NG8 1BB, UK*
[2]*Department of Mechanical Engineering, Imperial College London, SW7 2AZ, UK*
[3]*Renishaw Plc, New Mills, Kingswood, Wotton-under-Edge, GL12 8JR, UK*

Afaf.Remani@nottingham.ac.uk

Abstract

The lack of quality assurance in additive manufacturing, and specifically in metal laser powder bed fusion (MLPBF), is a major barrier to the adoption of these technologies in high-value industrial applications. Despite its potential for producing complex components, MLPBF is afflicted by the occurrence of in-process defects that affect the integrity of finished parts and impact their dimensional accuracy. However, while defects are generally undesirable, not all of them are necessarily detrimental to the functionality of the part, and a suitable approach is required to discriminate harmful defects from neutral faults. Such knowledge is vital to understand the manufacturing process, and without it, it is not possible to determine whether a part is functional or scrap. We call this the 'Hard Problem' and propose addressing it through a series of in-process and post-process measurements. Several measurement techniques have been developed to detect the occurrence of defects; however, very few have attempted to tackle the Hard Problem. In this work, we present a multi-sensor approach to correlate the layer-by-layer development of the part with its post-process mechanical properties. First, the MLPBF build will be monitored in-process using a multi-view fringe projection system, a high-speed thermal camera and other systems, to capture defects as they form during the process. Next, the finished part will be scanned using X-ray computed tomography, to examine the defects that exist within the finished part. Finally, the part will be mechanically tested to failure to locate critical defects. The aim of this experiment is to establish meaningful connections between in-process phenomena and defects and develop methods of distinguishing between neutral anomalies and critical defects. Here, the methodology and experimental plan of this approach will be discussed, and the integration of the multi-sensor system inside a commercial MLPBF system will be described, alongside its anticipated measurement capabilities.

Keywords: Metrology, multi-sensing, metal laser powder bed fusion (MLPBF), defect detection, effect of defect

1. Introduction

Metal laser powder bed fusion (MLPBF) is, at present, the most widely employed AM technique for the manufacturing of metal parts [1,2]. While this growing interest has been encouraged by its ability to manufacture complex and optimised designs, the process is still held back by a lack of confidence in the quality of as-built parts, namely their structural integrity and mechanical properties. These barriers are due to the complex thermo-mechanics inherent to MLPBF that govern interactions between deposited materials and substrates [3]. As a result, defects are always present to some degree in MLPBF parts and are unavoidable even with the most optimal processing parameters. Part acceptance or rejection, however, cannot be conducted on the mere basis of defect occurrence, but on their effects on part functionality. On this basis, the 'Hard Problem' is defined as follows: Can in-process phenomena be correlated with function-critical defects to discriminate them confidently and reliably from neutral faults?

In most publications, focus is generally put on the monitoring of the MLPBF process or the inspection of finished parts for defect detection. Several techniques have been proposed for in-process inspection, such as off-axis optical systems [4,5], co-axial pyrometry [6,7] or a combination of these methods with machine learning [8,9]. Other methods, particularly fringe projection [10,11], have also been presented. Through layer-by-layer image acquisition, these techniques have allowed for the identification of geometrical deviations and various powder bed defects, as detailed in our recent review [12]. Post-process techniques have, on the other hand, permitted the inspection of the volume of the part to reveal the defects therein. However, in-process and post-process techniques alike are insufficient to tackle the Hard Problem if not combined with appropriate mechanical assessment. In this work, we present a multi-sensor approach that combines a variety of in-process and post-process techniques, through a methodology that correlates in-situ continuous topographic and thermal measurements with the final volume and integrity of the part. The layer-by-layer development and final states of defects will be matched with their impact on mechanical properties, and appropriate conclusions will be drawn to discriminate critical defects from harmless flaws and provide insight into the Hard Problem.

2. Methodology

A measurement pipeline is currently being developed to tackle the Hard Problem in metal AM parts built inside a Renishaw AM250 MLPBF machine. The system will consist of three sensing systems integrated within the commercial machine to perform in-situ measurements on a (250 $\times$ 250) mm powder bed. The system combines multi-view fringe projection, IR thermography and high-speed thermal imaging technologies to perform a series of in-process measurements, following the layerwise paradigm. Each layer of the build will be individually imaged by the different sensors right after laser melting is completed. This approach will not disrupt the normal flow of the MLPBF process, as a suitable external trigger has been implemented to initiate imaging immediately after laser scanning and before the deposition of the next layer. Naturally, the total build time will not increase as the build process does not need to be paused for measurements to take place. Upon build completion, the multi-sensing approach extends to performing post-process measurements on as-built parts using X-ray computed tomography and mechanical testing, to inspect the final volume of the part and test its mechanical properties.

There are numerous measurable quantities that can provide relevant information about the interacting physical phenomena and thermal stability of the MLPBF process, as well as the onset of defects that can occur [12]. In the context of in-situ sensing, these quantities were first referred to by Mani et al. [13] as 'process signatures' and can be classified into 'observable' or 'derived'. The in-process sensing phase of this study focuses on the measurement of observable process signatures, as information that can be directly acquired in-situ. We will investigate these signatures on two levels, starting from the most easily visible signature and scaling down to a higher level of detail. The first process signature is the powder bed, particularly the printed layer and the surrounding unprocessed powder, and will be investigated using two techniques: a multi-view fringe projection system to obtain topographic information of the bed and an IR thermography system to monitor temperature changes across build layers. The acquisition of such topographic and thermal surface data can provide information about the occurrence of defects. Critical defects, such as hotspots, were previously revealed using these techniques [14]. The second process signature that this study looks at is the melt pool, by means of a high-speed thermal imaging system. This signature provides insight into the phenomena that occur within the laser melting zone and their influence on the formation of defects. Moreover, most common defects in MLPBF are on the same size scale as the melt pool [15], which makes melt pool monitoring critical to solving the Hard Problem.

The general methodology of this study consists of conducting said in-process measurements and comparing the detected defects with those present in the finished part. In practice, it is not guaranteed that the 2D layer defects identified in-situ will remain in the bulk in the same size, shape or population when 3D volume faults are examined. MLPBF process dynamics dictate that, due to the inherent sequence of the build process, some defects might 'self-heal' while others could amass at layer level or even form inter-layer clusters [16]. This is why subsequent post-process measurement is vital to understanding the types of defects that have persisted in the part and their impact on mechanical properties (sometimes referred to as "effect of defect" [16]).

2.1. In-process measurements

2.1.1. Multi-view fringe projection

The multi-view fringe projection system proposed in this study is an enhanced version of the prototype described elsewhere [17,18], where a (250 × 250) mm powder bed is monitored from four different perspectives. Major adjustments were made to the assembly to allow for operation within the environment of a Renishaw AM250 build chamber and to overcome spatial constraints. The system hardware consists of four Basler ace acA5472-17uc camera sensors (pixel array: 5472 × 3648, maximum frame rate: 17 frames/s, sensor size: 13.1 mm × 8.8 mm), each equipped with a Basler C10-1214-2MS 12.5 mm focal length lens, and a DLP4710 0.47 projector (pixel array: 1920 × 1080, maximum binary pattern rate: 1440 Hz, brightness: 1000 lumens). The cameras are tilted at 47° from the vertical to view the powder bed and are shielded from metal condensate using additively manufactured enclosures, capped with replaceable UV filters. The camera assembly is fixed onto the circular lens cover of the chamber and suitably positioned such that the laser optics are not obstructed. Due to spatial constraints limiting camera working distances, the resolution capabilities of the system are optically limited rather than sensor limited. A resolution of 57.62 μm/pixel is anticipated to be achieved in both lateral directions, which is sufficient to view a wide range of common defects in MLPBF, such as some keyhole pores (10 μm to 125 μm [6]) and lack of fusion flaws (40 μm to 340 μm [19]). The projector is placed on top of the build chamber ceiling and positioned at 24.6° downwards from the vertical. An optical mirror (flatness: 4-6 λ, wavelength range: 400 nm to 700 nm, coating: protected aluminium) is installed such that it receives the projector beam and reflects it onto the powder bed. The dimensions of the projected fringes are (250.38 × 140.84) mm and thus achieve a satisfactory coverage of the powder bed. A CAD model of the multi-view fringe projection system is shown in figure 1. The data collected from each camera during the build process will be aligned and fused to reconstruct the surface. The final output of the multi-view fringe projection system consists of a height map that can indicate surface irregularities and geometrical distortions in the printed layer.

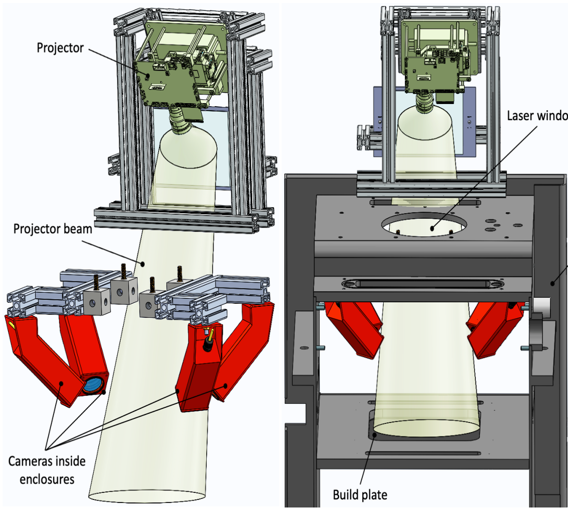

Figure 1. CAD models of the multi-view fringe projection system (left) and the open uninstalled model (right) Integrated into the AM250 build chamber.

2.1.2. Full-field IR thermography

To measure temperature changes across powder layers, a new in-situ wide-field IR thermography system [1] is proposed for thermal sensing. A forward looking infrared (FLIR) A35 IR camera is housed inside a vacuum-tight enclosure to shield the optics from dust and condensate, and views the powder bed through a germanium window, as shown in figure 2. The camera is tilted downwards at 66° from the horizontal and captures a full view of the build area at a resolution of 1 mm/pixel in both directions (image size = 320 × 256 pixels). Simultaneously, a recording of the build process is taken at 60 Hz. Given these spatial and temporal resolutions, the camera is only capable of acquiring temperatures at large scales and the melt pool cannot be viewed [1]. However, the most prevalent temperature changes across layer surfaces, such as overall temperature drops, can be resolved. The IR thermography system outputs raw IR images that can visibly show the areas currently being scanned by the laser, the zones previously scanned emitting residual heat, and spatter. The camera is calibrated using a simple empirical method described elsewhere [1].

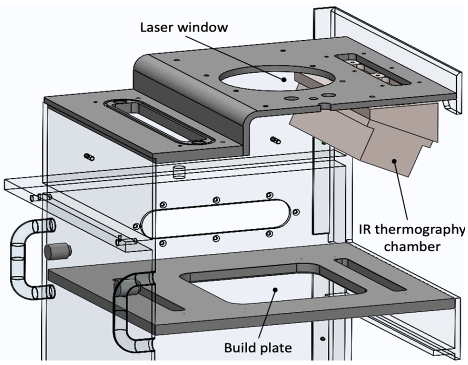

Figure 2. CAD model of the IR thermography system installed inside the AM250 build chamber.

2.1.3. Melt pool monitoring

On the same Renishaw MLPBF machine, a high-speed thermography imaging setup, detailed elsewhere [20], is installed to capture thermal variations in the melt pool. The laser beam path was modified to allow for coaxial imaging. The optical train follows two paths: one to obtain melt pool emissions and another to ensure that they reach the imaging enclosure. In the first path, a dichroic beamsplitter is placed before the scan head to reflect laser wavelengths and pass shorter ones through. The resultant light is then passed via a low-pass filter to further filter out laser specular reflections. Inside the imaging enclosure, the light is focused towards a long-pass dichroic beamsplitter and bandpass filters to transmit the bands of interest to the imaging sensors. The setup includes two Photron FASTCAM SA5 high-speed cameras imaging at two wavelengths, 700 nm and 950 nm, to ensure maximal transmission and account for emissivity changes [20]. A recording speed of up to 500 000 frames/s can be reached and images are captured with a resolution of 20 μm/pixel (image size = 128 × 128 pixels) [1]. The system renders video recordings of the melt pool at a predetermined (*x*,*y*) location and during a specified timeframe. Recordings can be broken up into a sequence of still frames that display a colour-coded thermal map of the melt pool at different instances in time. Such data enables the analysis of melt pool metrics (length and width), area, thermal stability and cooling rates, from which qualitative and quantitative inferences could be made. However, despite its merits, the minimum detectable temperature range of the proposed high-speed thermography system is restricted by the saturation of the imaging sensors.

2.2. Post-process measurements

2.2.1. X-ray computed tomography

We propose the use of X-ray computed tomography (XCT) to visualise imperfections in finished parts. This is a critical step in tackling the Hard Problem, given the non-destructive insight it provides on the volumetric integrity of the part and its dimensions. Following their manufacture, as-built parts will be measured using an XCT system to assess their porosity levels, pore distributions and resultant defects (populations, sizes and locations). The resultant data, in the form of 3D volumetric information, will assist to coordinate between data collected in-process and eventual destructive mechanical testing. First, XCT voxel data will be compared with layer topographic and thermal data to flag the defects that appear in both datasets and those that do not. Final defects will then be characterised in terms of size, distribution and population and categorised as either pores, spatter or lack of fusion. Second, these defects will serve as focal points of interest and as a guiding tool for mechanical testing to reveal their impact on microstructural properties. As shown in various studies [21,22], XCT is capable of detecting micrometre-sized and sub-micrometre-sized defects and provides high-quality 3D data. However, its accuracy is affected by internal structures and complex shapes, and the smallest pores are often missed due to resolution limitations [22]. The final resolution is also restricted by sample size, such that in some cases, the best attainable voxel resolution is 2000 times smaller than the width of the measured part [23].

2.2.2. Mechanical testing

Numerous correlations can be made between the sizes and distributions of flaws and their impact on part mechanical properties. However, such associations remain speculative until the part has been tested to failure to reveal the actual effects of defects. With the help of the acquired in-process and XCT data, we aim to direct mechanical assessment towards the regions where the defects, thought to be harmful, have occurred, to reveal their real impact. There are several mechanical properties of interest (tensile strength, ductility, toughness, etc.) and various methods of testing them. However, the most relevant property in this study is tensile strength as its assessment allows for the identification of cases of premature failure. As such, we will use tensile testing on finished specimens to evaluate their resistance to failure and locate failure points. These locations will be matched with XCT volume data to pinpoint the cause of failure and determine life-limiting defects. However, it is worth noting that minimum prescribed values for tensile testing parameters (elongation and yield strength) are material specific, and that, although most of these values have not yet been determined for all powder materials in AM, some dynamic loading standards for cast materials can be applicable to MLPBF built components [16,24]. In addition to tensile testing, part microstructure will be thoroughly examined using sectioning and electron backscatter diffraction to evaluate the grain size, orientation, and morphology of the sectioned parts. Regions where large pores and defect clusters have occurred will be specifically investigated to assess changes in the surrounding microstructure. With the obtained data, a set of correlations can be established to discriminate harmful defects from neutral faults and provide meaningful insight into the Hard Problem.

3. Discussion and future work

Several challenges have been encountered thus far during the design and integration phase of the multi-sensor system inside the Renishaw MLPBF machine. In addition to the instrument limitations already mentioned, other obstacles can be classified into two categories: challenges due to the in-process nature of MLPBF and challenges due to the spatial and environmental constraints imposed by chamber design. Starting with the former, the in-process nature of MLPBF dictates that the flow of process events (powder deposition, laser melting, etc.) happens both sequentially and rapidly. This poses a challenge to the implementation of a monitoring system that can carry out measurements at a high temporal resolution and exactly when required. In other words, the ability of the multi-sensor system to cope with the MLPBF process is dependent on its data acquisition rates and on the instances at which measurements are triggered in every layer. The machine vision cameras installed in the fringe projection system have an acquisition rate of up to 17 frames/s. Although a higher rate is always desirable, this rate is sufficient to carry out layerwise measurements. Additionally, the fringe projection system has been fitted with an external trigger that continuously acquires signals from machine modules (the recoating mechanism, platform and laser) and triggers imaging when the bed is clear. The IR and high-speed thermography systems are not concerned with these changes as they acquire continuous data. Other challenges faced during the design phase were mainly related to the environment and space within the build chamber. These included limited space availability, restricted installation locations and risks of laser obstruction and contamination of the optics. Cameras were shielded inside enclosures while the projector was installed on top of the chamber ceiling between the machine wall and the laser galvanometer. However, an issue that persists is that, due to the current placement of the IR camera housing, the IR camera cannot be operated concurrently with the fringe projection system. At present, it is required to uninstall the IR camera while the fringe projection system is imaging. This issue will be addressed in the future, but in the meantime, the IR system can still be used by itself for result validation or for the acquisition of additional in-situ thermal data.

Presently, the multi-view fringe projection system is being assembled and installed on a workbench for testing. While that happens, it is crucial to trace a roadmap to establish data correlations and address the Hard Problem. We will interpret the data acquired from all in-process sensing systems and interrelate powder bed defects with melt pool data for individual layers of the build. When comparing in-situ findings with XCT volume scans, we will classify defects by type, size and distribution. Such qualitative and numerical data will serve to determine thresholds above which defects appear to yield a detrimental effect when the part is mechanically tested. Predictions that pores smaller than a critical size have no effects on mechanical properties and that irregular lack of fusion pores often act as stress concentrators [16], can be verified. In cases where the cause of mechanical failure is not apparent, thresholds indicating the smallest defects that can go undetected by the multi-sensing system will be deduced. To establish meaningful correlations from the entirety of monitoring information and destructive testing, we will address the following questions: at what level does pore formation become a problem? What types/sizes of defects induce failure in a certain geometry? How are failure mechanisms driven by defect populations and distributions? Which defects are less likely to impact yield strength? How does part microstructure change around killer/detrimental defects?

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