AVision toward Layer-wise Intelligent Monitoring and Control of Scan Strategy in Powder-bed Fusion Process

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ABSTRACT

Despite significant developments in metal powder-bed fusion (PBF) additive manufacturing (AM) process, some frequent thermal anomalies hinder the repeatability and uniformity in microstructure, mechanical properties, and dimensionl accuracy of printed parts. Controlling the thermal evolution of the fabrication process is the key toward producing parts with better ultimate qualities. The temperature distribution of printing layers has been well recognized as a significant proxy to control the thermal evolution of the fabrication process. Scanning strategy, namely, scanning pattern and process parameters are the main factors for controlling the temperature distribution. In this paper, we depict a framework that shows an online thermography and intelligent hybrid control methodology to modify scan strategy layer-by-layer. Detection of the thermal distribution and specification of a layer under fabrication will help to modify the scanning strategy for printing the subsequent layer with a more uniform temperature distribution and within a specified range of temperature. This helps to diminish the frequent thermal anomalies such as warpage, distortion, and delamination during the fabrication process and produce parts with higher performance and accuracy.

Keywords: laser metal printing, powder-bed fusion, online monitoring and control, temperature distribution, scan strategy

1 INTRODUCTION

Our literature review [1] shows that a significant portion of the defects depicted in Fig. 1 [2] are rooted in the thermal characteristics of the process. Study the effects of process parameters on thermal characteristics of the fabrication process is crucial since these parameters induce defects, affect the ultimate mechanical properties, repeatability, and geometry precision in all the inherently thermal AM processes [1, 3]. The study of these effects are crucial especially in the fabricatioin of customized parts with complicated geometry in stringent industries such as airospace and automobile indsutry [4]. Respect to the complex and dynamic nature of the PBF process, scholars recommend online monitoring and control (OMC) to deminish or avoid the defects.

According to the study by Everton et al. in 2016, currently, some AM machine manufacturers offer additional modules for online monitoring (OM) of the PBF process, which can be added to the basic AM machine. However, in many cases, the data generated is stored without being analyzed real-time for closed-loop feedback. In these cases, the thermal data merely was employed to study different inherent thermal AM processes. For instance, Chivel and Smurov in 2010 measured the important thermal parameters in the PBF process such as maximum surface temperature, temperature distribution in the processing area, and temperature value versus laser power [5]. In another work, Price et al. used electron beam AM (EBAM) machine with a FLIR A320 IR camera to determine the repeatability of temperature measurements, build height effect on temperature profiles, transmission losses due to metallization of sacrificial glass, molten pool emissivity, molten pool dimensions, and overhanging structure thermal effects [6]. Rodriguez et al. incorporated an IR camera into an ArcamA2 EBAM machine in order to analyses surface temperature profiles for each build layer [7]. Other studies predominantly concentrated on monitoring the effects of melt pool characteristics on the ultimate quality of a fabricated part such as microstructure, mechanical properties, etc. in the SLM process [8-10]. Laser power is the only process parameter altered in all the previous works. However, sensitive analysis (SA) in our recent study [11] shows that with considering a constant layer thickness, scan speed is the most effective parameters on the energy density (ED) exerted by laser on the layer under print.

We recommand an intelligent approach to adjust the scan speed layer-by-layer throughout the entire layer. This adjustment will help to control the temperture value and avoid heat affected zones (HAZ). Furthermore, controlling the temperature distribution is crucial for removing/minimizing some frequently thermal anomalies such as distortion and warpage.

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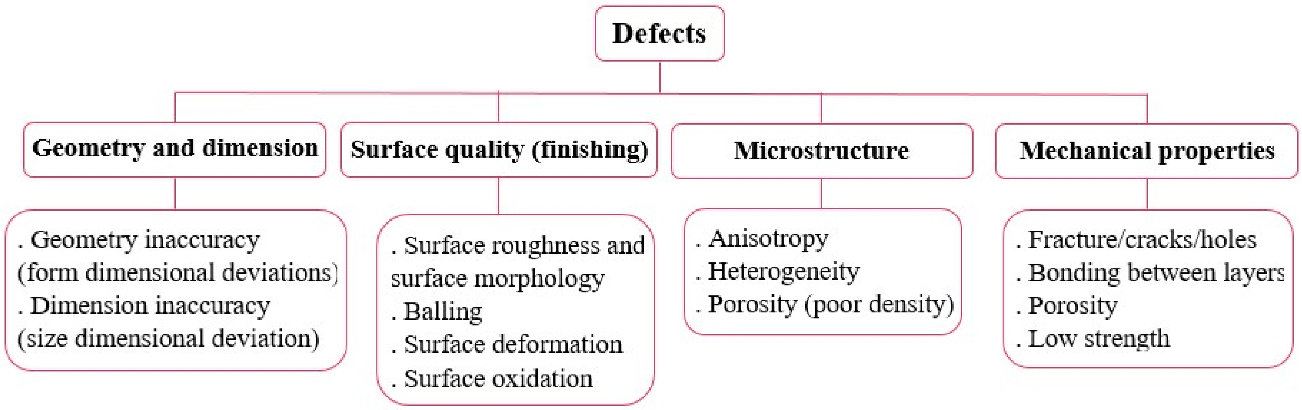

Figure 1: Common defects in the PBF process [2]

2 ONLINE MONITORING VS. FEA: STRENGTHS AND CHALLNAGES

To resolve critical frequent quality issues in PBF process, two fundamental research questions need to be answered. (1) What are the critical thermal abnormalities, their contributing parameters, and the correlation between these parameters and the defects? Moreover, (2) what is the thermal evolution during the fabrication process and how can we optimize it through the modification of the scan strategy and process parameters. Precise answers to these questions help to understand the thermal behavior/nature of the process better and remove/diminish the thermal abnormalities through controlling the process. Our review [1] demostrates that there are few controllable process parameters, namely, laser specifications and some manufacturing specifications. Altering these parmaeters can significanly affect the ultimate quality of fabricated parts. However, the correlation between the parameters and the defects or the ultimate part quality is still under study.

Scan pattern and ED are amongst two most effective process parameters on the temperature distribution of a printed layer. According to the literature, scholars currently follow two main approaches, namely, finite element (FE) simulation of the process and OMC to study the effects of scan pattern and process parameters. FE is limitted on size, very expensive in computational time, and it is not validated in most cases. However, OM can capture thermal data from a bigger area, it is a much faster approach, and it shows the exact temeperatrue generated throughout the field of view (FoV). For an instance, we employed IR termography in fused deposition modeling (FDM) process to study the thermal evolution of the process since it is an inherently thermal AM process [12]. The same methodology can be employed to study the thermal evolution and behavior in the PBF process.

Intelligent monitoring and control can ultimately be used to control the thermal evolution of the process and overcome some most frequent thermal abnormalities in the fabrication process such as distortion, warpage, heterogeneous microstructure, etc. However, high memory consumption of image processing and some communication delays, poor spatial resulution or limitted field of view, the lack of real-time closed loop control system to adjust the process parameters, and lack of an open-source software to implement the desighed control system hindered OMC techniques to be implemented practically in the PBF process. As the future tasks, we are trying to solve the aforementioned issues by employment of IR thermography to monitor the entire printing layer. Next section provides the framework, which shows different tasks of this project.

3 OBJECTIVES AND FRAMEWORK

Literature demonstrated that generating a uniform temperature distribution within a specific range during the fabrication process would avoid/diminish significantly the fabrication thermal abnormalities [1, 13]. This is achievable either by fabrication of proper support structure, specially in overhanging zones [14] or by controlling the scanning pattern and exerted energy density. This project aims to pursue the latter approach by employment of an IR thermography methodology that capture thermal data real-time from the entire fabrication bed area (Task 1 in Fig. 3). The monitoring system will send feedback to a closed-loop control system, which will be able to analyze the acquired thermal data real-time (Task 2 in Fig. 3) and adjust the objective process parameters subsequently.

This methodology integrates and/or develops the existing monitoring and control techniques in order to generate the most possible uniform temperature distribution within a specific range as the ultimate objective of this project. Fig. 3 shows the schematic abstract of the project, which presents different tasks of this project.

4 MAIN COMPLEMENTARY TASKS

4.1 Task 1: Real-time thermogrphy

Monitoring the thermal evolution of the fabrication process is the prerequisite step to avoid/diminish/remove thermal abnormalities. The temperature distribution is recognized as a significant proxy to control the thermal evolution of the process and as a result, the ultimate quality of the part under fabrication [1, 13]. Generation of uniform temperature distribution is vital to avoiding/minimizing heat residual stresses, improving microstructure, and mechanical properties [1, 2, 11, 14]. Monitoring of thermal distribution throughout the layer under fabrication helps to optimize the scan pattern and process parameters for printing of the next layer to generate more uniform temperature distribution and reduce the thermal residual stresses. It also helps to study the effects of support structure fabricated to diminish the distortion and facilitate the conduction between the overhangs and the printed layers beneath [14, 15].

4.2 Task 2: Modification of scan pattern and process parameters

Modification of scan pattern and optimization of the required process parameter, namely, ED will generate uniform temperature distribution through a layer under fabrication, reduce temperature gradient between the layers, and keeps the sintering temperature within a desired range thus, avoid overheating areas. Furthermore, it hinders balling phenomena, heterogeneous microstructure, and assists in stabilizing the microstructure in order to obtain an isotropic grain size [16]. Our study [11] demonstrated that it also makes a more uniform microstructure (Fig. 2.A) while minimizing the porosity (Fig. 2.B). We obtained the primary optimum range of ED for SS 316L (Fig. 2.B) [11]. This range will be narrowed down more in future.

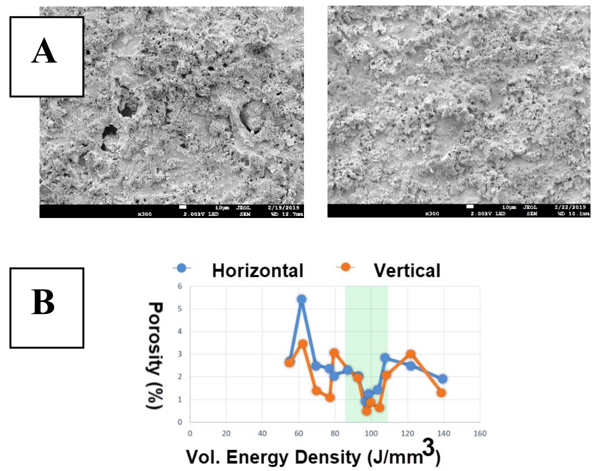

Figure 2: A. Microstructure of two samples fabricated by an not-optimized (left) and optimized (right) ED; B. Porosity vs. ED and primary optimized range of ED (green area)

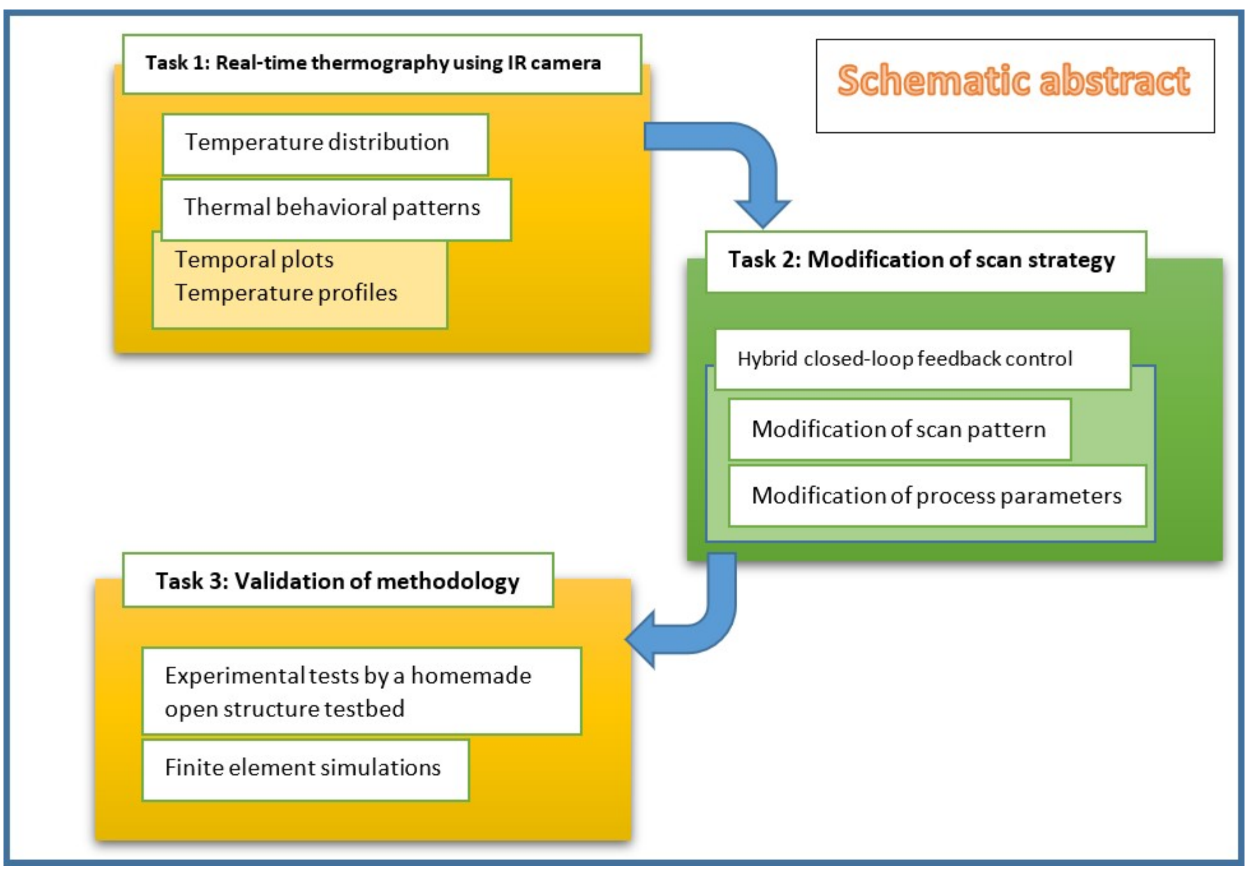

Figure 3: Schematic abstract of different tasks and subtasks to develop an intelligent OMC system

4.3 Task 3: Validation of methodology

Performing practical experiments is crucial to validate and troubleshoot the under development online monitoring and control strategy. Fig. 4 shows a homemade test-bed, designed and manufactured at the Quad City Manufacturing Lab (QCML) to enable experimental validation of designed scan strategies. Moreover, the system will enable to acquire adequate data by using the OM system, which will be mounted on it to provide feedback for the control system.

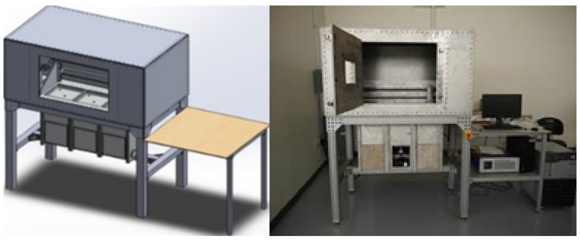

Figure 4: The homemade test-bed for carrying out experiments and validating the resaults

5 CONCLUSION

This paper presents the advantages and challenges for employment of OMC system. Then, it provides a framework how we can develop such system to overcome the challenges. It recommends to monitor the temperature distribution of the entire layer under fabrication, layer-by-layer, to control the thermal evolution of the process. This will be achievable through controlling the scan strategy and energy density.

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