EXPERIMENTAL LASER POWDER BED FUSION SYSTEM FOR DIFFICULT TO PROCESS METALLIC MATERIALS

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Dedication

This thesis is dedicated to my parents and my elder brother

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by

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THESIS

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Abstract

The focus of this research was twofold, such as development of defect free fabrication parameters for laser powder bed fusion (LPBF) processing of crack prone or difficult to process metallic materials, and study of the temperature dependence of emissivity for some commonly used metal alloy powders in LPBF process. The later objective extends to the implementation of multiwavelength (MW) pyrometer technology for *in situ* true surface temperature measurement in LPBF process. LPBF is an additive manufacturing (AM) process capable of layer-by-layer manufacturing by successive laser melting of each layer according to CAD data. AM manufacturing has the inherent advantages of fabricating optimally designed geometry with least required material and the shortest lead time that would not be possible all at once by more conventional manufacturing techniques such as machining, casting, welding, etc. Tendency to crack during LPBF fabrication of some of the widely used aluminum alloys with large solidification range, such as AA6061, AA7075, etc. created a bottleneck where AM specific advantages of these materials important for aerospace and automotive industry could not be realized. An open architecture LPBF machine AcontyONE (Aconity3D, Aachen, Germany) enabled with powder bed heating up to 1000 °C was used for fabrication of aluminum 6061 alloy (AA6061) test coupons, such as cubes and cylindrical tensile specimens in the XY plane. Variation of processing parameters such as laser power, scanning speed, hatch spacing, layer thickness, and powder bed heating temperature was carried out to find a combination of parameters that allowed crack free fabrication of AA6061. The following parameters such as 450 W laser power, 1400 mm/s scan speed, 100 μm layer thickness, 80 to 100 μm hatch spacing, and 500 °C powder bed heating resulted in crack free specimens as confirmed by visual inspection, optical microscopy, and tensile testing. In scanning electron microscopy (SEM), coarsening of grains and precipitates

was observed due to high temperature preheating, and a preferential growth in [100] direction was also evident from X-ray diffraction (XRD) analysis. The heat treated, and as-fabricated tensile tested specimens showed equivalent ultimate tensile strength and yield strengths when compared to their wrought counterpart; however, loss in elongation at breakpoint was observed in the LPBF fabricated specimens. This part of the research showcased the potential of high temperature powder bed heating for LPBF processing of crack prone metallic materials without the need for additional preparation of the precursor metal powders.

Unlike the commercial LPBF systems currently in use, the open architecture experimental LPBF system used in this study had the capability of achieving controlled high temperature at the powder bed. Whether this high set temperature that proved to deter visible crack formation in AA6061 fabrication, would be carried throughout the height of a build- required true in situ surface temperature measurement of the powder bed. Therefore, an important aspect of the current research was to evaluate the thermal environment of the build area in LPBF process. Changing emissivity of metallic materials is a major difficulty in evaluation of true temperature during LPBF processes. The existing *in situ* monitoring systems relied on single or dual wavelength pyrometers, raw sensor data, high-speed visual cameras, and infrared (IR) thermography for monitoring and surface temperature measurements; but, without the emissivity information of the target materials, these systems output a qualitative measurement of temperature instead of an accurate surface temperature. The changing emissivity resulting from the non-grey nature of radiation from metallic materials upsets the assumptions of single and dual-wavelength pyrometry, and thereby, renders the measurements inaccurate. On the other hand, Multiwavelength (MW) pyrometer technology would not require any prior information of the target emissivity for accurate temperature measurement and provided a real-time value of emissivity of the target material by

analyzing the IR spectra it would receive from the target. During the LPBF process, on a given layer the precursor powder material in solid state would turn into molten metal tracks after interaction with laser at selected spots, and finally, consolidate to bulk solid state when the rest of the powder on the bed would not go through phase change. At least three different metal states with potentially different emissivity were identified, such as metal powder in solid state, molten metal tracks, and solidified metal tracks. To measure this emissivity for different materials and study their variation with temperature, a Whipmix Pro 200 (Whipmix Inc., Louisville, KY) furnace was modified for optical access to a SpectroPyrometer (FAR Associates, OH, USA) MW pyrometer system. These emissivity measurements could serve as input for IR thermography for extending accurate surface temperature measurements capability from a pointwise measurement using pyrometer to the accurate temperature mapping of an area using the IR thermography. Also, for demonstrating *in situ* temperature measurement in LPBF system using MW pyrometry, processing laser window and the viewing window of the AconityONE system situated on the top and the front side of the machine, respectively were redesigned and fabricated with the facility of quartz and ZnSe viewing ports through which a SpectroPyrometer (FAR Associates, Ohio, USA) MW pyrometer system and a FLIR SC645 IR camera (FLIR Systems, NM, USA) could operate.

Metal powders such as AA6061, AlSi10Mg, Ti-6Al-4V with two different particle size distributions, and Cu were heated in quartz crucibles inside the modified furnace at different temperatures. Argon gas at a pressure of 3 psi and 20 cubic-feet-per-hour were introduced to the heating chamber of the furnace. Despite the use of argon to create inert environment, oxidation of the metallic materials occurred and essentially the measurements made using this setup reflected the properties of the oxidized top layer instead of the intended powder material in its pristine form. However, the effect of powder particle size distribution on emissivity could still be observed as

larger particle size resulted in higher emissivity. Also, two different trends of emissivity changes were identified for the heating and the cooling portion of the furnace operation. Inserting the setup inside a glovebox, use of designed inert gas flow path inside the furnace, and use of better sealing materials for the instrument pass-throughs were recommended for improvement of the experimental setup for future research. On the other occasion of in situ measurements, the data obtained by using the MW pyrometer through the modified AconityONE window was affected by the 1070 nm processing laser since the measuring range of the MW pyrometer was 850 nm to 1650 nm. This problem could be overcome by filtering out the processing laser from the spectra that reaches the MW pyrometer system. Overall, the application of MW pyrometer technology in combination with IR thermography could be a viable option for *in situ* temperature mapping of the powder bed in LPBF systems.

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Chapter 1: Introduction

1.1 Research Motivation

Additive manufacturing (AM) is a freeform fabrication technology where end user parts are manufactured directly from the 3D models created using computer aided design (CAD) software. The requirement for part specific tooling and multiple manufacturing steps involved in the conventional manufacturing processes that account for a long lead time and added costs, could be avoided in AM technologies. For example, the production of a gas turbine blade require four main process steps such as casting, forging, different types or machining, and coating along an array of sub-processing steps [1]. On the other hand, a single step process of manufacturing similar turbine blade directly from CAD was experimentally shown by Fabrizia *et al.* [2]. This is only a single example of cost effectiveness realized by AM processes. Among the different AM technologies, laser powder bed fusion (LPBF) is used for manufacturing of metal parts by selective melting of thin layer of metal powders spread on a solid surface for the first layer and on the previous consolidated surfaces for the subsequent layers.

One of the restricting factors that inhibits the realization of metal AM advantages on an industrial scale is the lack of developed processing parameters for the range of metal alloys used across different industries, such as aerospace, automotive, biomedical, etc. Despite being one of the most widely used aluminum alloys for the automotive and aerospace industries, aluminum 6061 alloy (AA6061) processing parameters have not been developed for fabrication using LPBF AM process due to crack formation [3] [4] [5]. Such a shortcoming deterred the application of LPBF in fabrication of AA6061 and resulting advantages of the process. Also, there are alloys such as AA7075 and AA2024 with cooling characteristics like AA6061 that could not be processed