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On the Application of In-situ Process Monitoring to Novel Feedstock Development in Laser Powder Bed Fusion

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Additive manufacturing (AM) affords unprecedented opportunity to mix materials on the fly during a build. This has seen the emergence of in-situ alloying in metal AM, an exciting area of research exploring the potential to develop novel high-performance materials. However, the mixing of constituent elements during melting currently lacks control. Local variations in the elemental distribution can occur across the build area and the exact composition of manufactured parts is unknown. Optimizing process parameters to build defect-free material, an essential task in any alloy development process for AM, is also labour-intensive. Here, we propose the use of in-situ process monitoring to measure and track elemental composition in laser powder bed fusion builds and assess consolidation optimality. In-situ process monitoring methods are briefly reviewed, revealing promising technologies for application. Both fixed and moving frame of reference imaging systems were found to have potential uses. Lastly, potential stages of the novel material development pipeline to which in-situ monitoring could be beneficial were discussed and necessary research objectives for this to be realized were identified.

1. Introduction

Additive Manufacturing (AM) presents unprecedented potential to develop novel, high-performance manufacturing materials. Practically, powder feedstocks can readily be changed between runs or mixed in-situ during the build process. Research interest is growing in developing functionally graded materials [1], high-entropy alloys [2] and new lightweight, printable alloys [3]. Nonetheless, only a relatively narrow palette of materials is widely used for processing today. This owes to the fact that the development and optimization of new materials can be time prohibitive. For example, the printing process parameters to achieve optimum material consolidation and a suitable alloy composition to achieve desired material performance must both be evaluated. When mixing powders in-situ, the distribution of constituent alloying elements can vary, leading to composition changes. Even with premixed, homogenous powder blends, different local compositions of alloying elements can be drawn into each melt pool [4]. In-situ alloying, whether mixing inside the build chamber or blending beforehand, therefore lacks control, validation, and repeatability.

Alongside this, the development of in-situ process monitoring solutions has been an area of intense focus in the field of AM over the last decade [5]. This was initially driven by chronic problems with machine reliability and part quality, which inhibited adoption of the technology. Several roadmap exercises subsequently identified in-situ process monitoring as a solution to these issues [6].

In this paper, we advocate the application of in-situ monitoring methods to accelerate novel feedstock development in AM and explore possible ways in which this might be achieved.

2. In-situ process monitoring

In order to consider potential methods to apply process monitoring to alloy development it is first necessary to examine the different methods that have been developed. A variety of approaches have been explored by both academics and AM machine manufacturers to date. Most commonly, photosensors have been employed and these approaches can be grouped according to their frame of reference, a moving (Lagrangian) frame of reference or fixed (Eulerian) frame of reference.

3.1 Moving frame of reference (melt pool monitoring)

Lagrangian systems are typically mounted coaxially with the laser beam, making use of the existing melting optics and traversing coincident with the laser beam. The position of measurement therefore changes at each time point and the field of view consists of the melt pool and surroundings. Both cameras and photodiodes have widely been implemented in this manner. Owing to the high scanning speeds typically encountered in laser powder bed fusion (LPBF), correspondingly high recording rates are needed to resolve meaningful information at this scale. As a result, photodiodes have widely been employed, particularly by LPBF system manufacturers, due to their low cost. They have shown limited success in detecting defects or process failure in parts, however [7]. High-speed cameras have shown more promise, though they are expensive and generate vast quantities of data which is difficult to process. High-speed camera systems have therefore primarily been developed in an academic setting and have shown limited breakthrough into industry.

3.1 Fixed frame of reference (global monitoring)

The Eulerian frame of reference camera systems are typically mounted towards the ceiling, or outside entirely, of the building chamber. These systems offer a global view of the top surface of the building area, albeit with a trade-off in spatial and temporal resolution relative to the Lagrangian systems. Both visible and infra-red spectrum cameras have been used, with an illumination source typically required to acquire meaningful images when recording in the visible spectrum. Their limited resolution has made it difficult to detect individual defects in parts but some authors have successfully detected global changes in part quality and gross process failure in this manner [8].

3.3 Non-optical methods

Finally, alternative, non-optical, types of monitoring have also been investigated in academia. One method which has shown particular promise is acoustic monitoring, with detection of keyhole porosity through acoustic monitoring being demonstrated [9]. This is noteworthy as keyhole defects have proven difficult to detect via optical means. The build chamber atmospheric gas composition has also been monitored by Pauzon et al. [10]. Whilst this approach is not suitable for individual defect detection, the authors were able to monitor the increase in oxygen content throughout a build and presented an external gas control system to minimize oxygen content further. Such a system has relevance to alloy development in LPBF as certain alloys, for example Ti-6Al-4V, are highly sensitive to oxidation and can suffer from embrittlement and degradation in material properties [10]. A properly controlled chamber atmosphere could therefore be an important prerequisite to the printing of certain feedstocks.

3. Potential application areas

3.1 In-situ alloying

With regards to in-situ alloying, or printing with mixed powders, we can separate this practice into two different methodologies in metal LPBF. The first and most widely exhibited method consists of blending the constituent elemental powders outside of the chamber, prior to the build, then loading the powder mix into the printer [4, 11]. Alternatively, some researchers have mixed the elements inside of the building chamber, using a dual material powder deposition system [12]. In-situ monitoring can offer value in both scenarios.

If powders are mixed inside of the build chamber, this process is highly unlikely to result in a fully homogenous composition of alloying elements across the building area. It is difficult to achieve homogeneity without substantial mixing of powders, greater than that which can be achieved inside an AM build chamber. Dual-material powder dispensers are also in their infancy and have not yet been optimized by printer manufacturers. As a result, regions with a higher or lower concentration of certain elements are likely to exist on the powder bed, leading to differences in alloy composition in the manufactured part. Here both the fixed and moving frame of reference monitoring setups could be of use. For example, a global view camera, with sufficient spatial imaging resolution, could make it possible to detect local variations in powder distribution due to differences in colour, reflectivity or sphericity between powders. Research is necessary to determine whether this can be achieved with contemporary imaging hardware and computer vision software. Lagrangian melt pool imaging or photodiode acquisition could detect local changes in melting behavior due to a change in the alloy composition being melted or even produce a continuous output correlating with the alloy composition processed. This would allow manufacturers to validate that they have produced a component with the desired alloy composition throughout. Potential corrective strategies could also be devised, such as re-melting poorly mixed regions to achieve greater homogeneity [4].

3.2 Alloy development

Developing novel alloy compositions can be a time consuming and experimentally intensive process. Test coupons covering a progressive range of compositional adjustments must be manufactured and examined microstructurally for cracks, porosity and other defects [13]. This forms the basis of a printability assessment for a given composition [14]. In addition, microstructural characterization and mechanical testing are required to ensure the mechanical performance of the new material is in line with its intended application. Several authors have investigated the use of machine learning to short-circuit this development process by predicting the printability and mechanical properties of new alloys based on their thermo-physical properties [15]. In-situ monitoring also has the potential to aid in this process. Whilst it may not be possible to directly predict the mechanical response of a new material based on process monitoring signals, they may be useful in assessing printability. With a moving frame of reference, melt pool imaging system, it may be possible to deduce from the melt pool behaviour whether or not an alloy is consolidating well. This would require experimental efforts to characterize the signals associated with good and poor consolidation and train a predictive model but greatly reduce the overall experimental burden.

3.3 Process parameter optimisation

Finally, process parameter optimisation is another time-consuming task, often carried out empirically, which could be accelerated with in-situ monitoring. Processing parameters, such as laser power, scanning speed etc., require optimisation not just when new alloys are being printed but also when changing to a new LPBF machine or printing a new and challenging part topology with existing alloys. Typically, this is done by systematically varying process parameters across the manufacture of sample test coupons. The coupons are then characterised to assess porosity content and other defects, and potentially microstructure and mechanical properties. The parameter set leading to optimum consolidation maybe then be deduced. Many experimental hours are therefore poured into this development work. In-situ melt pool monitoring has the potential to accelerate this process by identifying defective parameter sets leading to poor consolidation without microstructural characterization. The least optimal parameter combinations should lead to highly adverse melting conditions which could be detected by a melt pool imaging system and potentially a photodiode. This could act as a screening phase, with the most optimal parameters sets as determined by in-situ monitoring still requiring some experimental validation.

4. Conclusions

In this paper, we have advocated for the application of in-situ process monitoring to accelerate novel material development in LPBF. Some of the challenges associated with in-situ alloying in LPBF were highlighted, such as non-uniform mixing of elements and a lack of assurance in the composition of printed parts. Inefficiencies involved in the development of new pre-alloyed powders were also identified. A brief review of different process monitoring systems developed to date identified potential monitoring approaches which could be applied. Both fixed frame of reference and moving frame of reference imaging systems were found to have potential for application. Different stages of the novel material development process to which in-situ monitoring might add value were discussed, including multi-material processing, in-situ alloying and process parameter development. Some of the research challenges associated with each area were also identified.

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