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International Journal of Production Research

ISSN: 0020-7543 (Print) 1366-588X (Online) Journal homepage: http://www.tandfonline.com/loi/tprs20

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*International Journal of Production Research*, 2016
http://dx.doi.org/10.1080/00207543.2016.1223378

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# A review on measurement science needs for real-time control of additive manufacturing metal powder bed fusion processes

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(*Received 24 August 2015; accepted 8 August 2016*)

Additive manufacturing technologies are increasingly used in the development of new products. However, variations in part quality in terms of material properties, dimensional tolerances, surface roughness and defects limit its broader acceptance. Process control today based on heuristics and experimental data yields limited improvement in part quality. In an effort to identify the needed measurement science for real-time closed-loop control of additive manufacturing (AM) processes, this paper presents a literature review on the current AM control schemes, process measurements and modelling and simulation methods as it applies to the powder bed fusion process, though results from other processes are reviewed where applicable. We present our research findings to identify the correlations between process parameters, process signatures and product quality. We also present research recommendations on the key control issues to serve as a technical basis for standards development in this area. Complimentary details to this paper with summary tables, range of values, preliminary correlations and correlation figures can be accessed from a National Institute of Standards and Technology Report (http://nvlpubs.nist.gov/nistpubs/ir/2015/NIST.IR.8036.pdf). This paper is developed based on the report.

**Keywords:** additive manufacturing; powder bed fusion; real-time control; measurement science; correlations; process parameters; process signatures; product qualities

## Introduction

The widespread adoption of Additive Manufacturing (AM) (ASTM Standard 2792 2012) is challenged by part quality issues, such as dimensional and form errors, undesired porosity, delamination of layers, as well as poor or undefined material properties. Part quality issues can be attributed to the AM process parameter setting, typically done today by a trial-and-error method for each material. This is time consuming, inaccurate and expensive. According to a road map workshop on the measurement science needs for metal-based AM (Bourell, Leu, and Rosen 2009; Energetics Inc. for National Institute of Standards and Technology 2013) hosted by the National Institute of Standards and Technology (NIST), closed-loop control systems for AM were identified as an important technology and measurement challenge vital for: monitoring of process and equipment performance, assurance of part adherence to specifications and the ability to qualify and certify parts and processes. Variability in AM part quality can be reduced through robust process control. However, it is important to first establish relationships between the AM process parameters and the process/part characteristics. Once the correlations are established, in-process sensing and real-time control of AM process parameters can be done to minimise variations in AM processes to ensure desirable part quality.

Powder Bed Fusion (PBF) one of the seven categories of AM processes defined in ASTM F2792 (2012) uses thermal energy to selectively fuse areas of a layer of powder using laser or an electron beam as the energy source (ASTM Standard 2792 2012; Wohlers 2013). There are several different types of PBF processes that can produce either polymer or metal parts. Some PBF processes use low-power lasers to bind powder particles by only melting the surface of the powder particles (called selective laser sintering or SLS). These processes produce green parts that require further post-processing to infiltrate and sinter the parts to make them fully dense. Another class of PBF processes uses high-power energy beams to fully melt the powder particles, which then fuse together to the previous layer(s) when the molten material cools, e.g. selective laser melting (SLM), direct metal laser sintering or electron-beam melting (EBM) to produce fully dense parts. These processes are of primary interest to this study.

Based on a literature review, this paper identifies the measurement science needs for real-time monitoring and control of PBF processes.

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## Literature review

There have been efforts in the past to summarise specific research efforts on real-time control for AM (Boddu, Landers, and Liou 2001; Rosen 2004; Zeng, Pal, and Stucker 2012; Guo and Leu 2013). More recently, Tapia and Elwany (2014) provided a high-level overview of monitoring metal-based AM and the tasks that need further research. Our review strategy is focused on identifying the correlations between process parameters, process signatures and product qualities to exploit these relationships in the monitoring and control solutions. AM *process parameters* are the 'inputs' and primarily determine the rate of energy delivered to the surface of the powder and how that energy interacts with material. We categorise process parameters into either controllable (i.e. possible to continuously modify), such as laser power and scan speed, or predefined (i.e. set at the beginning of each build) material properties, such as powder size and distribution. The *process signatures* are dynamic characteristics of the powder heating, melting and solidification processes as they occur during the build. These are categorised into either observable (i.e. can be seen or measured), such as melt-pool shape and temperature, or derived (i.e. determined through analytical modelling or simulation), such as melt-pool depth, and residual stress. Process signatures significantly influence the final product qualities. Those *product qualities* are categorised into geometrical, mechanical and physical qualities. Identifying the correlations between process parameters, process signatures and product qualities, as shown in Figure 1, should facilitate the development of the in-process sensing and real-time control of AM process parameters to characterise and control the AM PBF process.

We present our literature review in three categories: *control schemes*, *process measurements* and *modelling and simulation* efforts as applicable to real-time process control.

### *Control schemes in AM*

In the reported studies relevant to a closed-loop adaptive control system, the melt-pool temperature and size are often assumed to be the critical control factors influencing the outcome of the process.

#### *PBF-related*

Craeghs et al. (2010) reported a control system for a laser-based PBF system based on real-time monitoring of the melt-pool. Camera-based images were used to determine the melt-pool geometry which in turn was used as an area-based signature feedback to control the laser power resulting in an improved surface roughness. The work extended to explore an online control methodology using two complementary measurement systems: (1) visual inspection of powder layer deposition, (2) real-time monitoring of melt-pool, i.e. both melt-pool geometry and infrared (IR) radiation intensity signal (Craeghs et al. 2011). The optical system was further developed to detect process failures in each build layer by mapping the melt-pool temperature signatures as a function of the X–Y laser beam position on each layer (Craeghs et al. 2012). Using such maps in real-time, deformations due to thermal stresses and overheating zones due to overhangs were detected. Mumtaz and Hopkinson (2010) studied the effect of heat delivered to the melt-pool, to determine the roughness of the surface generated by the solidified melt-pool. Using a pulsed laser system, they experimented with various pulse shapes to distribute energy within a single laser pulse. It was proposed that the use of pulse shaping would offer precise and tailored control over the heat input and would allow improvement over the use of standard rectangular pulses. The added degree of control through pulse shaping resulted in a combined lower surface roughness on the part. Ning et al. (2006) studied the accuracy of a PBF system by investigating the percentage shrinkage due to different geometric shapes. They experimentally studied the effect of 2-D geometric shapes on dimensional accuracy and later used

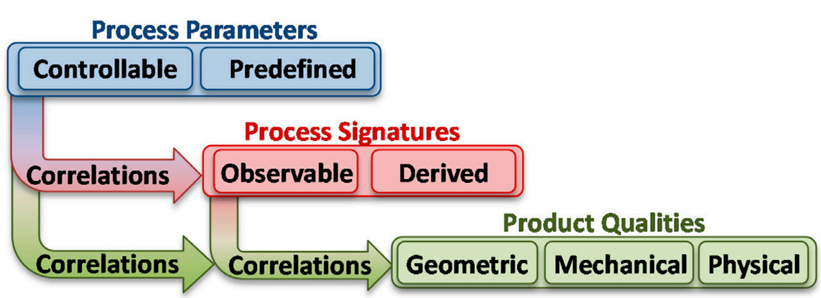


Figure 1. Correlations between process parameters, process signature and product qualities.

that information to analyse the effect of different geometric shapes on the dimensional accuracy of the part. Simchi, Petzoldt and Pohl reported on improving accuracy of sintered parts using an integrated beam compensation technique, where the laser beam diameter is offset to compensate for the observed dimensional error as a result of the shrinkage. The process was strongly affected by shape, size and distribution of the particles, and the chemical constituents of the powder (Simchi, Petzoldt, and Pohl 2003). Similar works based on laser beam offset were also reported in Wang (1999) and Mahesh et al. (2006).

*Non-PBF related*

Non-PBF-related research on closed-loop control, notably in directed energy deposition (DED) processes has been reported in the last two decades. DED processes use thermal energy to fuse materials by melting as they are being deposited (ASTM Standard 2792 2012). Doumanidis and Kwak described a control scheme based on measuring bead profile geometry using a laser optical scanner and IR pyrometry for a DED process. The control involves modulating process input parameters, such as thermal source power, source velocity, material transfer rate and direction of material transfer with respect to source velocity. A simplified proportional-integral-derivative (PID) control system was implemented using the cross-sectional area of the bead as the scalar error (actual vs. expected area) and the thermal source velocity as the input parameter. The control of melt-pool size under steady-state conditions over the full range of process variables was reported (Doumanidis and Kwak 2001). The control was later extended to consider melt-pool size under transient conditions and as a function of process size scale (e.g. 500 W laser application vs. 3 kW) (Aggarangsi, Beuth, and Griffith 2003; Birnbaum, Aggarangsi, and Beuth 2003; Aggarangsi, Beuth, and Gill 2004; Birnbaum, Beuth, and Sears 2004). Numerically determined melt-pool temperature response times were used to establish a lower bound on the response times for thermal feedback control systems. Similar works have been reported in Boddu, Landers, and Liou (2001). Cohen (2010) developed a control system for droplet-based DED processes using the part geometry to determine the locations of subsequent droplets to compensate for geometric inaccuracies. Using geometric measurements and a model of the target object, the system chooses appropriate locations for subsequent droplets such that the fabricated part ultimately matches the target geometry. Bi et al. (2006) investigated a closed-loop control of a DED process, based on the IR-temperature signal, for deposition of thin walls. A PID controller was built between a photodiode and laser in the control system. The IR-radiation from the melt-pool was detected by the photodiode and converted to a temperature signal. The actual value of the temperature signal was compared with a set-value. The PID-controller created a control variable out of the deviation to regulate the laser power, so that the melt-pool temperature was controlled. Hu and Kovacevic 2003studied real-time sensing and control to achieve a controllable powder delivery for the fabrication of functionally graded material using DED processes. An optoelectronic sensor was developed for sensing the powder delivery rate in real-time at a high sampling frequency. To achieve consistent processing quality, a closed-loop control system was developed for heat input control in the DED process based on the observed IR image of the heat-affected zone (HAZ). The experimental results of closed-loop controlled DED showed improvement in the geometrical accuracy of the part being built (Hu and Kovacevic 2003; Hu, Mei, and Kovacevic 2002).

Process maps have often been used as a method to optimise AM processes. For the DED processes, Birnbaum et al. considered the transient behaviour of melt-pool size, due to a step change in laser power or velocity, for dynamic feedback control of melt-pool size using IR imaging techniques. They modelled the relationship between the process variables (laser power and velocity) and the desired melt-pool size (Birnbaum, Aggarangsi, and Beuth 2003). Bontha and Klingbeil (2003) addressed the ability of thermal process maps for predicting and controlling the microstructure in DED materials. The focus of the work was the development of thermal process maps relating solidification cooling rate and thermal gradient (key parameters controlling microstructure) to DED process variables. A closed-loop DED system with image feedback control was patented in 2002 (Griffith et al. 2002). The feedback controls material deposition using real-time analysis of IR radiation images. From the imaging, data intrinsic parameters such as temperature distribution, size and shape of the molten pool, maximum degree of pool superheating, the trailing thermal gradient and thickness of the deposition are extracted. A feedback-based control system then compares the current intrinsic parameters with the target intrinsic parameters to generate new control values based on the feedback-driven adjustments and the predetermined operating schedule. The issue of residual stress control for laser-based AM processes has also been addressed using the process map approach (Vasinonta, Beuth, and Griffith 2000; Vasinonta, Griffith, and Beuth 2007). The thermal gradient behind the melt-pool was used to predict changes in residual stress based on thermal simulation results. A method of stress reduction by localised part preheating via a dual-beam laser or electron beam system was also proposed (Aggarangsi and Beuth 2006).

### ***Process measurements***

This section focuses on pre-process, in-process and post-process measurements described in the literature to identify potential correlations between the key process parameters, process signatures and product qualities.

#### *Pre-process measurements*

Pre-process measurements often relate to material properties (density, thermal conductivity, etc.) and intrinsic properties of the system (laser power, powder absorptivity, etc.). Pre-process measurements although not directly applicable to *in situ* feedback control can influence appropriate system input parameters, or supplement a process model for use in feed-forward control. They are crucial to establishing relationships between input process parameters and process and part characteristics. Kruth et al. (2007) reviewed a list of material-related properties that significantly affect melt-pool signatures: surface tension, viscosity, wetting, thermo-capillary effects, evaporation and oxidation. Cooke and Slotwinski summarised metal powder characterisation methods that measure and describe powder size and distribution (Cooke and Slotwinski 2012). Slotwinski et al. (2014) studied size distribution, particle morphology, chemistry and density of powders and compared sample-to-sample consistency and variability from recycling used metal powders. Amado et al. (2011) reviewed and demonstrated multiple methods of flowability characterisation for polymer PBF powders for SLS applications. While these works focused on powder characterisation techniques, they did not investigate the relationships between variations in these characteristics and resulting process signatures or final part quality.

The role of powder size and distribution in sintering kinetics is well understood, i.e. it affects the relative density of the powder, which in turn affects the activation energy required for heated particles to coalesce (Su and Johnson 1996; Robertson and Schaffer 2009). Smaller powder sizes with higher relative powder densities require less energy to sinter. It is known that a wider distribution of particles sizes can allow for higher powder density, since smaller particles can fit in the gaps between larger particles. McGeary (1961) demonstrated that specific ratios of bi-modally distributed powder sizes can achieve an optimal packing density. Multimodal distributions could achieve even higher densities. Higher relative density in powders improves the process by reducing internal stresses, part distortion and final part porosity (Kruth et al. 2007). High relative densities increase the relative thermal conductivity of the powder bed (Cervera and Lombera 1999; Gusarov et al. 2003). However, this decreases the absorptivity of the laser energy in AM systems, counteracting the benefits of a lowered energy barrier (Gusarov and Kruth 2005). In some instances, these effects may negate each other (Karlsson et al. 2013). Liu et al. (2011) also tested two powder distributions (narrow and wide with similar mean values) in the PBF process under varying scan speeds and laser power levels. They found that the wider particle size distribution i.e. with a higher relative powder density, resulted in higher part density requiring less laser energy intensity. Spierings et al. showed that unless a certain relative powder density is achieved, a lower scan speed (e.g. higher energy density) is required to produce fully dense parts (Spierings and Levy 2009; Spierings, Herres, and Levy 2011). Differences in the relation of the powders to the densities, layer thicknesses and laser scan speeds indicate that powder grain size distribution should be taken into account for optimal results.

Thermal conductivity has an effect on melt-pool signatures and thus part quality. Although metal powder thermal conductivity has been measured in multiple instances (Tsotsas and Martin 1987), conductivity of the fully dense material is generally better known and easier to measure. This measurement can be supplemented to models to derive the effective powder conductivity. Gusarov et al. demonstrated a method to calculate effective thermal conductivity of powders in which the relative density, the sphere packing coordination number (i.e. the mean number of the nearest neighbours to each particle) and the inter-particle contact size were shown to have the greatest effect (Gusarov et al. 2003).

#### *In-process measurements*

The primary research focus on in-process monitoring has been associated with determining the geometry and the temperature profile of the HAZ. IR thermography and pyrometry are two well-developed non-intrusive techniques for the measurement of surface temperatures. There are also some reported works on in-process monitoring of the dimensional accuracy, errors and defects during the build process. A few reports also discuss the in-process measurement of strain–stress.

Thermographic imaging of AM processes can be grouped based on the optical path used by the imaging system. In co-axial systems, the imager field of view aligns with the laser beam through the beam scanning optics (Berumen et al. 2010; Chivel and Smurov 2010; Craeghs et al. 2010, 2012; Lott et al. 2011; Yadroitsev, Krakhmalev, and Yadroitsava 2014). In these systems, the field of view follows the laser beam, thus the melt-pool, throughout its scan trajectory. Alternatively, the imager may be set externally to the build chamber to view the build through an observation window

(Wegner and Witt 2011; Price, Cooper, and Chou 2012; Rodriguez et al. 2012; Dinwiddie et al. 2013; Price et al. 2013, 2014). An improvised method was developed by Craeghs et al. (2012). Using the co-axial system, they mapped the charged-coupled-device (CCD) camera and photodetector signals corresponding to the observed melt-pool temperatures in the build plane using the XY laser scan coordinates. This created mapped images of the entire build area, with more local and detailed signatures of the melt-pool. Through this method, they could detect part deformation and overheating near overhanging structures through measured changes in the photodetector signal. A lower signal resulted from the laser defocusing on distorted surfaces. A higher signal resulted on overhang surfaces that had less heat sinking support structure, and thereby poorer surface quality.

There are several known difficulties with thermography of additive processes. First and foremost, the imaged object's emissivity must be known in order to determine a true thermodynamic temperature from radiation-based measurements. Emissivity is likely different for the melt-pool, unconsolidated powder and solidified surface, so a thermal image composed of all three components could give deceptive temperature predictions. For example, Rodriguez et al. (2012) noted that the powder areas surrounding the solidified part surfaces glowed brighter than the part in thermal images even though the powder was likely lower temperature. This was attributed to the lower emissivity of the part surface, which reduced the imaged radiant intensity in these areas. Several techniques have been used to determine emissivity of different build components in AM systems: (1) assume a certain imaged area is at the liquidus or solidus temperature of the melt and use this as a reference emissivity (Hofmeister and Griffith 2001; Price et al. 2013, 2014), (2) create an emissivity reference by building and imaging a blackbody cavity (Rodriguez et al. 2012; Dinwiddie et al. 2014) or (3) only provide temperature without correction for emissivity (e.g. apparent or brightness temperature) or provide raw sensor signal values (Krauss, Eschey, and Zaeh 2012). Second difficulty, in particular with co-axial systems, is that f-theta lenses used in scanning systems induce chromatic or spectral aberrations. This requires that only radiation sensor systems with narrow bandwidth near that designed for the f-theta lens may be used accurately (Chivel and Smurov 2010; Craeghs et al. 2012; Kruth et al. 2007). Third difficulty is that metallic debris from the HAZ can coat a window or viewport used in a AM imaging system, and disturb temperature measurements by changing the radiation transmission through the window (Bi et al. 2007; Dinwiddie et al. 2013; Price et al. 2014). This is particularly troublesome in EBM systems, and prompted Dinwiddie et al. to create a system to continuously roll new kapton film over the viewport in order to provide new, unsullied transmission (Dinwiddie et al. 2013).

Several studies using thermography are of particular interest in relating process signatures to either input parameters or product qualities. Krauss, Eschey, and Zaeh (2012) described the radiance (not temperature) images of the HAZ, captured by a microbolometer, in terms of area, circularity and aspect ratio. They compared these measurands vs. scan speed, laser power, hatch distance, scan vector length, layer thickness and changes when the melt-pool passes over an artificial flaw. Despite the relatively slow exposure time and limited resolution, they showed that the size of the HAZ area was the most suitable measurand to detect deviations in scan velocity or laser power. Santospirito et al. (2013) described a thermography-based system to record heat movement through the laser track to detect defects (cracks, porosity, etc.) that result in lower conductivity regions that affect heat flow. Pavlov, Doubenskaia, and Smurov (2010) described pyrometric measurements taken co-axial with the laser to monitor the temperature of the laser impact zone to detect deviations of process signatures that correlate to deviations of process parameters from their set values.

There is not much work that focuses on the in-process geometric measurements. Cooke and Moylan showed that process intermittent measurements can be viable for both process improvement and characterisation of internal part geometries. Process intermittent measurements were compared to contact and non-contact measurements of the finished parts to characterise deviations in printed layer positions and changes in part dimensions resulting from post-process treatments (Roberts 2012). Pedersen, De Chiffre, and Hansen (2013) discussed a vision system for enhancing build-quality and as a means of geometrical verification. A generic geometry reconstruction method was suggested, where each layer is inspected prior to addition of the successive layers. The hypothesis was that, although most AM processes have a tendency to accumulate stresses, and suffer from elastic deformations, the non-deformed layers characterised by such system will yield sufficient data to assess whether defects of internal geometries are present. This includes visually present defects from the inspected layers. Kleszczynski et al. (2012) used a high-resolution CCD camera with a tilt and shift lens to correct the image obtained through the observation window of a commercial PBF machine. They categorised potential error sources during the build process and collected images representing these errors.

There are a number of techniques to measure strains and residual stresses in metal components. However, the relative part sizes and other physical attributes associated with the scanned region make it extremely difficult to apply direct methods of measurement. There are a number of reported indirect measurement techniques applicable. These indirect methods monitor physical attributes which are representative of the strains and residual stresses. Indirect techniques are based on strain or displacement measurement relating to the rebalancing of internal stresses that are released when material is removed or allowed to deform (Masubuchi 1980; Ekmekçi et al. 2004). Several researchers have reported on surface distortion measurement methods while investigating residual stresses (Klingbeil et al. 2002; Gan, Ng, and Devasenapathi 2004; Branner, Zaeh, and Groth 2008). Robert used scanning confocal microscopy to measure the topography of the top surface and to derive the platform's surface distortion by comparing the surface positions before and after the DLD process (Roberts 2012). Shiomi (2004) discussed the use of strain gauges mounted to the build platform to measure residual stress *in situ*. They were able to measure the strain changes in a build platform when SLS-induced layers were successively milled off. They found that the residual stresses decreased (i.e. stress relief) as more layers were removed from the built part. More recently, Van Belle, Vansteenkiste, and Boyer (2013) used a strain gauge rosette mounted under a support platform. By monitoring the variation of the strain gauge data during a PBF process, residual stress corresponding to elastic bending was calculated in the support and the part, using force balance principles.

### *Post-process measurements*

The post-process measurements have in general focused on the part quality and are based on the following categories: dimensional accuracy, surface roughness, porosity, mechanical properties, residual stress and fatigue strength.

*Dimensional accuracy.* Several papers discuss dimensional accuracy with examples. Yasa et al. (2009) used contact surface profilometer and optical microscope to investigate the elevated edges of parts, built using different laser power levels, speeds and scan strategies. The paper identified that certain process parameters and scanning strategies could improve flatness of surfaces by reducing the elevated edges. Using a three-dimensional (3D) scanner, Abd-Elghany evaluated PBF processed parts and observed deviations in dimensions before and after finishing by shot-peening process. It was also noted that the tolerances were not uniform and varied in the $z$-direction (Abd-Elghany and Bourell 2012). Mahesh et al. (2004, 2006) identified correlations between the controllable PBF process parameters such as scanning speed, laser power and scanning direction on the geometrical profiles of the geometric benchmark part. They reported the preferred settings of control parameters based on the analysis of the mean dimensional errors for the specific geometric features on the benchmark part. Paul and Anand developed a mathematical analysis of the laser energy required for manufacturing a simple part based on laser energy expenditure (minimum total area for sintering) of SLS process and its correlation to the geometry (Paul and Anand 2012). Khaing, Fuh, and Lu (2001) used A CMM to measure the dimensional accuracy of the parts fabricated by PBF. They concluded that the optimisation of the process parameters and the accuracy of the laser scanning units were crucial to improve the dimensional accuracy. Similarly, Krol, Seidel, and Zaeh (2013) stated that the scanning speed, the support geometry, the preheating temperature of the substrate and the scanning pattern were the most influential parameters for dimensional accuracy. The accuracy and repeatability of medical models based on different materials and AM technologies have also been reported (Salmi et al. 2013).

*Surface quality.* Abd-Elghany and Bourell (2012) evaluated the surface finish of the PBF processed part with varying layer thickness. The roughness of the top and side surfaces was measured using a scanning electron microscope. The results indicated that large particles inside thick layers could increase surface roughness because of the volume of particles have a tendency to form voids when they are removed in finishing processes. It was also noted that the side surface was smoother at the bottom than at the top. Mumtaz and Hopkinson (2010) investigated the effects of the laser pulse shape on the plasma plume height, and the width and roughness of thin walls built by PBF, using a digital video camera, digital callipers and profilometer. The results indicated that the wall width varied with the pulse shape which in turn influenced the melt-pool width. A suppressed pulse shape that consisted of a high peak power, low energy and short time duration proved to be the most effective pulse shape for PBF. Pulse shaping was also shown to reduce spatter and improve the top surface roughness of parts. Meier and Haberland (2008) investigated various process parameters to evaluate their influence on part density and surface quality for parts fabricated by PBF. Approaches to improve density, surface quality and mechanical properties were also presented.

*Mechanical properties.* Meier and Haberland (2008) carried out tensile tests of stainless steel and cobalt-chromium parts. They showed that the density measurements do not identify deficient connections of consecutive layers, specimens have lower tensile strengths and elongations in vertical fabrication direction. Abd-Elghany and Bourell also characterised hardness and strength of parts made by SLM process as a function of layer thickness and scan speed. The findings conclude that hardness is not much affected within the range of process parameters studied; however, variations in hardness due to surface porosity were observed. Strength was good at low scanning speeds and thin layers. The parts became brittle with higher layer thickness due to porosity and micro-cracking. Sehrt investigated a dynamic strength and fracture toughness on a cylindrical beam and disc by the rotating bending fatigue tests. Specimens were investigated at defined oscillating stresses and the resulting number of cycles that led to the failure of the specimen was determined.

The findings showed that fatigue strength was comparable to conventionally manufactured parts (Sehrt and Witt 2010). Storch et al. (2003) analysed material properties of sintered metals to qualify metal-based powder systems in comparison to conventional materials used in automotive engines and power trains. Key observations included material properties being sensitive to the build direction and that material strength increases with the chamber atmospheric temperature. By studying the material properties and the process parameters, Gibson concluded that the powder properties directly affect the process, which in turn affect the mechanical properties of the resultant component (Gibson and Shi 1997). Wegner and Witt (2012) developed a statistical analysis to correlate part properties with main influencing factors. According to their study, PBF shows non-linear correlations among multiple parameter interactions. The four main influences on mechanical properties (i.e. tensile strength, young's modulus, elongation) were scan spacing, scan speed, layer thickness and interaction of scan spacing and layer thickness. Manfredi et al. (2013) reported on the characterisation of aluminium alloy in terms of size, morphology and chemical composition, through the measurement and evaluation of mechanical and microstructural properties of specimens built along different orientations parallel and perpendicular to the powder deposition plane. Yadroitsev and Smurov (2010) studied the effects of the processing parameters such as scanning speed, laser power and layer thickness on single laser-melted track formation. Instabilities appear at low scanning speed in the form of distortions and irregularities, and, on the contrary, excessively high speed gives rise to the balling effect. From the specimens fabricated, they also found that the mechanical properties were approximately identical and did not depend on the scanning strategy.

*Residual stress.* With rapid heating and cooling inherent in any metal PBF process, thermal stress and residual stress certainly affect the resulting parts by warping of the part, features or build platform. As such, residual stress has been widely studied by AM researchers (Shiomi 2004; Mercelis and Kruth 2006; Casavola, Campanelli, and Pappalettere 2008; Sercombe et al. 2008; Casavola, Campanelli, and Pappalettere 2009; Zaeh and Branner 2010; Dadbakhsh, Hao, and Sewell 2012; Kruth et al. 2012; Roberts 2012; Buchbinder et al. 2013; Leuders et al. 2013; Van Belle, Vansteenkiste, and Boyer 2013; Vrancken et al. 2013). Mercelis and Kruth (2006) described the two mechanisms causing the residual stress: the large thermal gradients that result around the laser spot and the restricted contraction during the cooling that occurs when the laser spot leaves the area. Withers and Bhadeshia (2001) discussed the various post-process destructive techniques used to measure residual stress. The methods include measuring mechanical distortion (e.g. hole drilling), X-ray and neutron diffraction (atomic strain gauge), light scattering (Raman spectroscopy), changes in elastic wave speeds (ultrasonics) and changes in magnetic field due to stress relaxation or rise. Many researchers linked process parameters to the residual stress in the resulting parts and investigated strategies to reduce the residual stresses. The most commonly discussed method of reducing residual stress was through post process heat treatment, not relevant to process control (Shiomi 2004; Mercelis and Kruth 2006; Sercombe et al. 2008; Leuders et al. 2013). Residual stresses were also significantly reduced by heating the build platform (Shiomi 2004; Mercelis and Kruth 2006). The scan strategy and the thickness of each layer have also been shown to influence the residual stress (Mercelis and Kruth 2006; Casavola, Campanelli, and Pappalettere 2008; Van Belle, Vansteenkiste, and Boyer 2013).

*Porosity/density.* Porosity/density has a direct effect on the mechanical properties of components fabricated by PBF (Kruth et al. 2010). Internal and external pores, voids and micro-cracks introduced during fabrication act as stress concentrators that cause premature failure and thus compromising part quality. Fully dense AM parts have shown to have mechanical properties equal to or better than the properties of wrought materials. The effects of various process parameters, such as laser power, scan speed, scan spacing and layer thickness, on part density for many materials have been investigated. (Morgan, Sutcliffe, and O'Neill 2004; Meier and Haberland 2008; Spierings and Levy 2009; Yasa, Deckers, and Kruth 2011; Spierings, Wegener, and Levy 2012), which suggest a correlation between the energy density and the part density. Parthasarathy et al. (2010) evaluated the effects of powder particle size, shape and distribution on the porosity of a stainless steel. Morgan, Sutcliffe, and O'Neill (2004) concluded that the density increased with decreasing scan speed, but not significantly affected by scan spacing, while the plasma recoil compression forces could modify melt-pool shape and affect density. Gu et al. (2013) showed that coupons fabricated using the same energy density level using different laser powers and scan speeds (195 W/800 mm/s, 95 W/389 mm/s and 70 W/287 mm/s) showed significantly different levels of porosity. Two types of porosity formation mechanisms were identified and discussed. Balling phenomena and high thermal stress cracking were mainly responsible for the porosity that occurs at very high laser power and scan speed, while insufficient melting was the primary reason for crevices filled with many un-melted powders at very low laser power and scan speed. Also, pores in coupons manufactured using both high laser power and scan speed exhibited smaller size and more circular shape in comparison with pores in coupons manufactured using both low laser power and scan speed. Chartterjee et al. (2003) observed that the increasing layer thickness and hatching distance result in an increase in porosity that reduces the hardness and density of the sintered parts.

*Fatigue.* Fatigue performance is crucial if AM parts are to be used as functional components employed in dynamic environments, e.g. aircraft engines. Under dynamic conditions, AM parts have shown to have a high sensitivity to surface quality and internal pores that act as stress concentrators. Researchers have recently reported on studies to characterise fatigue performance, endurance limit and fracture behaviour of AM components for various materials using Woehler fatigue tests (i.e. rotating bending test) and compact tension tests (ASTM 1997), as well as high cycle fatigue (HCF) tests (Sehrt and Witt 2010; Spierings, Herres, and Levy 2011; Brandl et al. 2012; Khalid et al. 2012; Gu et al. 2013; Leuders et al. 2013; Lipinski, Barbas, and Bonnet 2013; Spierings, Starr, and Wegener 2013; Wycisk et al. 2013).

### ***Modelling and simulation***

Physics-based predictive models are crucial to predict the outcome of AM processes that accounts for the changes in material properties. Understanding of material transformations during melting (microstructure, phase) would enable optimisation and control of the processes improving overall product quality. Many models have been developed for simulating highly dynamic and complex heating, melting and solidification of materials during PBF processes. Dynamics imply heating, melting, wetting, shrinking, balling, solidification, cracking, warping, etc. in a very short period of time. Complexity implies highly coupled heat and metallurgical interactions in the AM process. This section reviews available modelling and simulation research works with the following objectives: (1) review currently available physics-based, numerical models that describe the PBF processes, or DED if reasonable comparison of results may be inferred; and (2) identify observable and derived process signatures that are necessary for closed-loop control. Zeng, Pal, and Stucker (2012) thoroughly reviewed the methodology development in modelling and simulation research for PBF processes. Though much focus of AM modelling papers is on development and model verification, many offer insight into process parameter relationships.

#### *Methods*

Nearly all models of the laser-based PBF and DED processes include the following input parameters in one form or another: (1) a heat source representing the laser with associated power and profile shape and (2) solid metal and/or powder domains, boundary conditions (typically radiation and convective on the heated surface with either adiabatic or isothermal far-field conditions) and thermo-mechanical material properties. These are modelled either numerically (e.g. through multi-physics finite element (FE) analysis) or analytically with varying degrees of dimension, geometry, scale, and with varying modelled phenomena or subprocesses. In 3D FE models, laser heat sources are typically modelled as a Gaussian-shaped surface flux with variable power or radius, or as an internal heat generation (Patil and Yadava 2007). Many use a laser ‘absorptance’ factor relating the fraction of laser energy converted to thermal energy, and/or an ‘extinction coefficient’ or ‘penetration depth’ of the laser energy into the powder. Gusarov et al., developed an analytical model for absorptance, extinction coefficient and reflected radiation based on multiple laser reflections and scattering through the open pores of a powder bed (Gusarov and Kruth 2005; Gusarov 2008). Various other empirical or analytical submodels are also used for temperature, phase or powder density-dependent thermal conductivity and specific heat or enthalpy (Williams and Deckard 1998; Kolossov et al. 2004; Patil and Yadava 2007; Wang and Felicelli 2007; Wang et al. (2008); Roberts et al. 2009).

Analytical models mostly use the 3D ‘Rosenthal’ solution for a moving point heat source (Rosenthal 1946). However, its limited complexity allows it only to verify more complex results from numerical methods (e.g. FE results from Wang and Felicelli 2006). Other, more complicated models typically use numerical methods such as finite difference to solve for laser radiation interactions (Gusarov and Smurov 2010). Some analytical models use non-dimensional parameters, which aid in comparison of models and experiments across varying scales and conditions. Vasinonta et al. developed non-dimensional parameters that relate input parameters and results of DED process simulations to material parameters based on the Rosenthal solution (Vasinonta, Griffith, and Beuth 2000; Vasinonta, Beuth, and Griffith 2000). Others who develop non-dimensional parameters include Chen and Zhang (2004, 2006) for the SLS process, and Gusarov et al. (2007) described results using traditional heat-transfer non-dimensional parameters such as Peclet number using the laser beam width as a characteristic length. A thorough analysis of potential non-dimensionalised parameters for the PBF process has been reported (Van Elsen, Al-Bender, and Kruth 2008).

A relatively new method for modelling hydrodynamic effects in the melt-pool is the lattice Boltzmann method (LBM). This method uses particle collision instead of Navier–Stokes equations in fluid dynamics problems. The LBM can model physical phenomena that challenge continuum methods, e.g. influence of the relative powder density, the stochastic effect of a randomly packed powder bed, capillary and wetting phenomena and other hydrodynamic phenomena (Körner, Attar, and Heinl 2011). For example, Korner et al. demonstrated multiple melt-pool morphologies could result from the stochastically varying local powder density near the scanned region, or effect of changing the bulk powder density. They also developed a process map for scan morphology as a function of laser speed and power for one specified powder packing density. LBM is very computationally intensive, since multiple simulations are needed (by varying input parameters) to extract parameter–signature relationships (Attar 2011; Körner, Attar, and Heinl 2011; Ammer et al. 2012; Zhou et al. 2013).

*Parameter–signature–quality relationships*

In general, for single scan tracks in PBF processes, the melt-pool and high-temperature zone form a comet-like shape, with a high-temperature gradient in the leading edge of the melt-pool, and lower temperature gradient on the trailing edge (Cervera and Lombera 1999; Hussein et al. 2013; Roberts et al. 2009).

As mentioned earlier, melt-pool size and temperature are already being used as feedback parameters in closed-loop control schemes. Melt-pool size as a single-valued measurand is not always defined explicitly in reported simulation results. However, length (in the scan direction), depth, width and area values are sometimes used to relate to process parameters. Often in the literature, a plot of the melt-pool temperature vs. some cross-section distance is given (Patil and Yadava 2007; Dong et al. 2009; Yin et al. 2012; Hussein et al. 2013). Melt-pool size may be inferred and related to input parameters, though it is not often expressed as a single-value measurand (e.g. the melt-pool is x mm). Soylemez et al., mentioned that while melt-pool cross-sectional area is a key descriptor, melt-pool length was known to affect deposited bead shape, so they proposed using length-to-depth ratio (L/d) as a descriptor in their process mapping efforts (Soylemez, Beuth, and Taminger 2010). Childs, Hauser, and Badrossamay (2005) also mentioned L/d ratio determined the boundary between continuous and balled tracks when scanning on powder beds without a solid substrate.

Typically, the melt-pool size and temperature increase with laser power; however, the relationship with scan speed is more complicated. For stationary-pulsed laser tests (e.g. Shiomi et al. 1999), the effects of longer pulse durations are related to lower scan speeds and resulting in higher temperature. Multiple studies have addressed the trends in temperature and size of the melt-pool with process parameters. It was shown in Hussein et al. (2013) that the width and depth decreased slightly with scan speed (from to 300 mm/s), while the length of the melt-pool in the scan direction increased, contributing more to the overall melt-pool size. This was for the single-layer model geometry. Chen and Zhang (2004) also showed depth decreasing with speed, but change in length was less pronounced. Chen and Zhang also created simulations where melt-pool depth was kept constant, which required more input power at the higher speeds. The thin-wall geometry modelled in the DED process in Vasinonta, Beuth, and Griffith (2000) and Vasinonta, Griffith, and Beuth (2007) showed that melt-pool length decreased with increasing scan speed, though at much lower speeds. One interesting approach by Birnbaum et al., used an FE model to look at transient changes to melt-pool geometry given a step change in laser power with the specified intent to apply in thermal imaging feedback control (Birnbaum, Aggarangsi, and Beuth 2003).

Modelling offers a comprehensive analysis of the melt-pool, to deduce the irregular shape and temperature contours in the interior and not just the surface. Surface level measurements of melt-pool signatures are leading efforts in *in situ* process control. Modelling and simulation can relate these melt-pool signatures to the complex and dynamic process characteristics, powder bed or the solid part itself such as residual stresses, porosity or metallic phase structure.

One promising application of AM simulation to closed-loop control is the ability to study the effect of varying thermal conductivity on melt-pool signatures, and thus the part quality. The fully solidified part exhibits higher thermal conductivity than the surrounding powder, thereby conducting more heat from the laser source, reducing the melt-pool temperature but increasing its size. Multiple AM models have shown this phenomenon or studied it in detail (Chen and Zhang 2004; Childs, Hauser, and Badrossamay 2005; Hussein et al. 2013). Hussein et al. (2013) showed how the melt-pool and trailing hot zone changed temperature and shape depending on whether the laser scanned over powder bed (low thermal conductivity) or solid substrate (high conductivity). Scanning over the powder bed produced lower peak temperatures in the melt-pool but higher temperatures in the trailing region for the first scan. However, this trend changed such that subsequent scans over the solid substrate always resulted in lower temperatures. Chen and Zhang (2004) simulated multiple layers while keeping melt-pool depth constant. They showed that more power was necessary as build layers increased to maintain the processing depth, indicating that more heat was conducting into the solid layers. Wang came to the same conclusion, but for multiple layers in a thin-wall geometry Wang et al. (2008). The relationships between melt-pool signatures and changes in thermal conductivity have guided the use of feedback controlled melt-pool size. However, there are other critical phenomena that are less understood, but may be addressed through intelligent melt-pool monitoring guided by results from modelling and simulations.

The time-history of temperature plays a crucial role in residual stresses and build-direction variability in density and material phase structure. While extremely important to final part quality, these phenomena are difficult to measure *in situ* during a build. In the future, successful models may be able to predict these phenomena to be exploited in feed-forward control schemes. In a series of papers, Wang et al. (2008) and Wang and Felicelli (2007) looked at time history of temperature in each layer as the build progresses in a DED system. Subsequent scans on new layers re-heated the base layers, which turned originally hard martensitic layers to softer, tempered martensite while new layers stayed consistently hard. By increasing scan speed and laser power (keeping melt-pool size constant), the number and consistency of hard, martensitic layers could be increased since the lower layers were subjected to shorter heating from upper layer builds. Others have also studied this lower layer reheating phenomena (Dong et al. 2009; Roberts et al. 2009) and its effect on residual stresses (Matsumoto et al. 2002; Labudovic, Hu, and Kovacevic 2003; Van Belle, Vansteenkiste, and Boyer 2012; Hussein et al. 2013).

Others (Li et al. 2009; Yin et al. 2012; Hussein et al. 2013) also studied pre-heating and post-heating of a surface point before and after the laser scan had passed on one layer (rather than subsequent layers). Under certain conditions, locations on previously scanned tracks were re-melted. This number of re-melting cycles increases for narrower hatch spacing. For constant hatch spacing, Yin et al. (2012) showed that lower scan speeds promoted re-melting primarily due to the resulting higher temperatures. However, one can assume that under different conditions, a slower scan speed would allow points on adjacent tracks to cool enough not to be re-melted. This re-melting effect has been shown experimentally to relate to part quality (e.g. surface roughness, mechanical properties, porosity) (Guan et al. 2013).

Hussein et al. (2013) also studied thermal stresses in PBF process for multiple layers. Their results showed that regions in the build experience thermal expansion and contraction based on the local temperature history and scan pattern. Their simulation demonstrated that the relationships between the melt-pool signatures and residual stresses are very complex; therefore, melt-pool monitoring may not provide enough information to predict residual stress formation. Nickel, Barnett, and Prinz (2001) specifically investigated effects of scanning pattern on residual stress and part deformation. Though this forms an excellent guide to optimal scanning patterns developed before the build takes place, it is unlikely that scan patterns can be effectively changed *in situ* to control stress without affecting other part qualities such as porosity, homogeneity or strength. Vasinonta et al. mapped residual stress in thin wall formation, and proposed that build plate and part preheating are much more effective in reducing residual stresses than varying scan speed or laser power (Vasinonta, Beuth, and Griffith 2000; Vasinonta, Griffith, and Beuth 2007). Though Vasinonta et al. did not include re-heating of lower layers or adjacent scan tracks, this may indicate that control schemes that target minimisation of residual stress may focus on monitoring build plate and chamber temperature, rather than monitoring melt-pool signatures. As mentioned, scan pattern has been shown to relate to residual stress formation, though this may be more difficult to adaptively control than build plate or chamber temperature.

The re-heating phenomenon also has an effect on metallic phase structure, (not to be confused with the more often modelled powder-liquid-solid phases). Wang et al. (2008) and Wang and Felicelli (2007) looked at metal phase change based on temperature cycle history and volume fraction of three possible phases (in 410 stainless steel) using commercial welding simulation software. In the simulation results in Wang et al. (2008), they observed that the high temperatures caused by the initial pass by the DED system laser would create a high-strength, martensitic microstructure. Key to these phase changes was the high rate of cooling observed in their model, a consequence of the material thermal properties, boundary conditions and overall geometry. In Wang, Felicelli, and Pratt (2008), they extended the model to predict thermally and mechanically induced residual strain vs. laser power, scan speed and powder flow rate (in a DED system), then compared to neutron-diffraction strain measurement results from Pratt et al. (2008) with good agreement for the range of parameters studied. Though results were complex and cannot all be detailed here, one interesting result showed that residual stress in the laser scan direction changed from compressive to tensile when scan speed doubled, while maintaining the steady melt-pool size by adjusting laser power (increasing with scan speed, but decreasing with pass number).

Modelling and simulation can link measurable melt-pool or process signatures to immeasurable but critical phenomena like instantaneous material phase and microstructure; however, these complex relationships require an organised and simplified methodology to implement in *in situ* control. Perhaps the best method is through development of process maps, which several research groups have developed using modelling and simulations for the DED process for process control. Vasinonta et al. used a FE method to develop process maps for the DED manufacturing of thin walls, and put results in term of non-dimensional parameters based on the Rosenthal moving point source solution (Rosenthal 1946; Vasinonta, Griffith, and Beuth 2000; Vasinonta, Beuth, and Griffith 2000). Bontha et al., used a 2D analytical (Rosenthal) and FE models to calculate cooling rates in DED processing of Ti-6Al-4 V as a function of laser power, traverse speed and increasing build depth (Bontha et al. 2006). These are overlaid onto previously developed process maps that detail expected microstructure forms for different ranges of thermal gradients vs. solidification rates (‘G-R plot’ or ‘solidification map’ Kobryn and Semiatin 2003). Soylemez et al., formed process maps that linked melt-pool signatures to laser power vs. scan velocity (called a ‘P-V map’) using a 3D FE simulation of single bead deposition (Soylemez, Beuth, and Taminger 2010), then later Gockel and Beuth combined the maps to show how specific combinations of laser power and speed can achieve constant grain size and tailored morphology in an electron beam wire feed process (Gockel and Beuth 2013). They proposed use of this hybrid microstructure map, which depends on simulation data to develop, for ‘real-time indirect microstructure control through melt-pool dimension control’. Though microstructure control is the primary focus in Gockel and Beuth (2013), it may be possible to extend this methodology to develop process maps for residual stress (Vasinonta, Beuth, and Griffith 2000; Vasinonta, Griffith, and Beuth 2007). Much of this reviewed process mapping work was centred at Carnegie Mellon and Wright State universities, and a thorough review of these efforts is given by Beuth et al. (2013) including a list of patent applications submitted by the authors.

## Real-time control in commercial systems

Process monitoring and controls are still very much in research and development phase, with varying levels of application in newer systems. Original Equipment Manufacturers (OEMs) of metal AM machines are rapidly incorporating process monitoring tools into new machines, which will likely change or improve with each new model. Several more recent reviews give an updated outline of the state of art. Dunsky provided reviews of commercial AM process monitoring both in the 2015 Wohler’s Report (Wohlers 2015), and in the Laser Focus World (Dunsky 2014). Everton et al. provided a thorough review, including a table of the commercial *in situ* measurement ‘modules’ available from OEMs, as well as overview of the measurement systems and standards efforts in process monitoring (Everton et al. 2016).

Several third-party companies provide process monitoring tools design or marketed specifically for AM systems, including Stratonics two-wavelength imaging pyrometer, B6 Sigma’s PrintRite3D Sensorpak and Plasmo Industrietechnik’s fastprocessobserver. These companies have continuing cooperation with OEMs, although the competitive nature of the market and guarded intellectual property make these collaborations somewhat unclear to the public apart from press releases.

Continuous feedback control in commercial systems is more easily realised in DED systems than in LPBF systems due to the much lower processing speeds and larger melt pool size. The Optomec LENS MR-7 offers the option of closed loop control, which is being tested and optimised by university collaborators (Nassar et al. 2015). In commercial LPBF systems, high-speed closed-loop control based on melt pool monitoring is not yet realised, however, layer-wise monitoring and control have been demonstrated. For example, Concept Laser’s QM coating module images newly formed powder layer surfaces, and actively detects and compensates for powder layer thickness variation.

## Implications for process control

### *Parameters-signatures-qualities categorisation*

The influence of AM process parameters on the resultant part quality in general has been widely studied and reported. To establish foundations for process control, we subcategorise the process parameters, process signatures and product quality according to the abilities to be measured and/or controlled. *Process parameters* are input to the PBF process and they are either potentially controllable or predefined. Controllable parameters (e.g. laser and scanning parameters, layer thickness and temperature) are used to control the heating, melting and solidification process and thus control the part quality. Predefined parameters include part geometry, powder material and build plate material, size and temperature. Controllable process parameters generally correlate to the observable and derived *process signatures* (e.g. melt-pool size, temperature, porosity or residual stress). Derivable signatures cannot be directly measured but can be calculated with a numerical model, such as the maximum depth of a melt-pool. For purposes of correlations, we further subdivide the process signatures into three categories, namely melt-pool, track and layer. Process signatures determine the final *product qualities (*geometric, mechanical and physical). Developing correlations between the controllable process parameters and process signatures should support feed forward and feedback control, with the goal of embedding process knowledge into future control schemes. Note that the correlations must be developed from benchmarked processes. Figure 2 categorises and lists the process parameters, process signatures and product qualities to derive needed correlations. Individual definitions can be seen in the NIST Report (Mani et al. 2015).

Most of the reviewed papers discussed the correlations between process parameters and product quality. Those papers that discussed process signatures mostly focused on melt-pool temperature and area. Process parameters along with signatures in general have not yet been directly related to product quality. Process and product usually follow a multiple input and multiple output relationship. The NIST Report (Mani et al. 2015) discusses detailed correlations

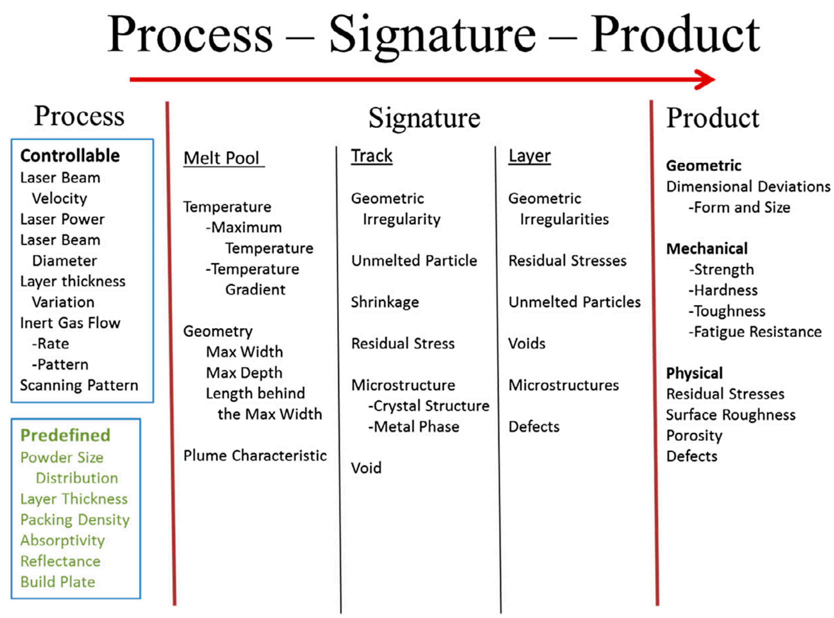


Figure 2. Process parameters, signatures and product qualities identified to derive correlations.

based on the observations from the reviewed literature. There could potentially be other missing parameters, for example, the heat absorption before the actual Melt-pool formation. The heat absorption signature can include the heat absorption rate and the temperature raising profile. However, more research in this subject is needed.

### *Research opportunities*

Existing process control implementations for the DMD process focus on measuring and controlling melt-pool signatures (size and temperature) by varying laser parameters (power and scan speed) are evidence that PBF process control can follow a similar approach. Therefore, further development of parameter-signature-quality relationships and relative sensitivities of those relationships through experiments and simulations, with particular focus on measureable melt-pool signatures, and controllable process parameters are needed to implement PBF process control.

New traceable measurement methods and identification of new measurable process signatures are necessary. Two issues, residual stress and varying metallic phase structure, are particularly challenging in PBF processes yet there are few or no *in situ*, nonintrusive measurement methods available to detect these phenomena as they vary during a build. Melt-pool signatures (e.g. size and temperature) are the most often considered measurands for *in situ* feedback control. However, there is a potential for other, less considered signatures that may offer greater sensitivity to process variations or simplified measurement, for example, measurements of the laser ablation plume size, or the spectral measurements of the ablation zone (Song and Mazumder 2012; Song et al. 2012).

Most of the reviewed literature has limited analysis of measurement error and traceability, and there is a need for better measurement uncertainty evaluations and reporting. First, simulations require *accurate* and *repeatable* measurements for validation. For example, there are simulations that correlate temperature to melt-pool size. In such cases, a large uncertainty in a temperature evaluation will result in an uncertainty of the melt-pool size, and therefore inadequate comparison of measurement data with the model output. Better understanding of measurement uncertainty assists system controller design by identifying the necessary level of precision required to attain the goals of the control system. It is well known that the relationships between parameters in the PBF process are complex. Process maps, such as those in Beuth et al. (2013), Bontha (2006), Bontha and Klingbeil (2003), Vasinonta, Griffith, and Beuth (2000), Vasinonta, Beuth, and Griffith, (2000), Vasinonta, Griffith, and Beuth (2007), will be a key tool to organise and communicate the complex, multidimensional parameter relationship topology. These maps will be essential for multi-input, multi-output (MIMO) control algorithm design, and model-based predictive controller design.

The AM process control design landscape is so far limited in variety, with most examples using melt-pool temperature and/or size to control laser power or speed. This method could very well be the most effective; however, there is wider potential for different levels of control loops. For example, control loops may occur discretely between completion of each build layer rather than continuously (e.g. the powder bed temperature mapping by Craeghs et al. (2012)). However, it is yet unclear which signatures are best modelled or measured, and which input parameters are best controlled for which timescale (either continuously or discrete inter-layer). It is a worthwhile endeavour to create an AM control loop architecture that identifies the multiple potential control loops, and provides a basis for identifying which loops are optimal for controlling which parameter-signature-quality relationship.

Further work should involve the development of monitoring techniques through the use of new sensors and measurement methods that will enable the integration of materials, process control and feedback (NIST 2013). Future work should also involve the development of an open architecture AM research platform to test and demonstrate the in-process measurement and control methods. Such a platform will enable the observation of melting and solidification of metal powders, integrate process metrology tools and implement software interfaces and data acquisition for process measurements, as well as test the control algorithms. NIST is currently pursuing research in this direction (Vlasea et al. 2015) and anticipates that the AM community will benefit from such a test platform to implement, test and validate a real-time and closed-loop control of AM processes.

## Conclusions

This paper presented a review aimed to identify and summarise the measurement science needs that are critical to real-time AM process control. The paper was organised to present the correlations between process parameters, process signatures and product quality. Based on the review, we presented the implications for process control highlighting the research opportunities and future directions. For example, we found reported correlations between the laser power (process parameter) and the melt-pool surface geometry and surface temperature (process signatures) on the resulting relative density of the part (part quality). Melt-pool size and temperature have already been used as feedback parameters in closed-loop control schemes. Considering residual stresses as another example, researchers have identified that an increase in the build platform temperature leads to lower residual stresses. There were also reported correlations on the residual stress to the scan strategy and layer thickness used to build. In the future work, newer process signatures and corresponding correlations will have to be investigated for newer control schemes.

## Disclosure statement

Certain products or services are identified in the paper to foster understanding. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products or services identified are necessarily the best available for the purpose.

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