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Metal based additive layer manufacturing: variations, correlations and process control

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Abstract

Additive layer manufacturing is emerging as the next generation in part manufacture. It is being adopted by aerospace, tool making, dental and medical industries to produce and develop new conceptual designs and products due to its speed and flexibility.
It has been noted that parts produced using additive layer manufacturing are not to a consistent quality. Variations have been recorded showing inadequate control over dimensional tolerances, surface roughness, porosity, and other defects in built parts. It is, however, possible to control these variables using real-time processes that currently lack adequate process measurement methods. This paper identifies process variation and lists parameters currently being recorded during a commercial additive manufacture (AM) machine build process. Furthermore, it examines correlations between manufactured parts and real time build variations.

Keywords: Additive layer manufacturing; Variations; Process control; Correlations

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1. Introduction

Product quality is a critical consideration when producing any product for commercial use. Quality is the main driver that directly influences customer satisfaction, which in turn drives success in a competitive market[1]. Quality can be measured in many different ways; performance, reliability, durability, serviceability, aesthetics and conformance to standards; depending on the product one or more of these measures may be more appropriate. To achieve any of these critical qualities in a product, manufacturing control has to be optimised. Currently, metal based additive layer manufacture (ALM) has been utilised to produce parts for aerospace, tool making, dental and medical

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industries[2]. Originally, the adoption of additive layer manufacturing was to provide designers with time efficient access to prototype parts. Engineers and manufacturers soon realised that ALM could offer a faster route to market if the products that the process produced could be consistently manufactured to industry standards.

Currently there is a body of research being aimed at process control in regards to metal based additive layer manufacture[3,4] These papers consider the enactment of the process citing the need for extra sensors integrated into existing AM machines to improve manufacturing quality. There are a number of suggested approaches, including the use of in-process cameras that capture; the layer quality[5,6,7,8,9], melt shape[10,11,12,13] and melt temperature[14,15,16,17]. There are also researchers considering process quality evaluations relating to temperature change within the build chamber. At present no work has been reported looking at the overall number of variations in the build process.

This paper will aim to identify all of the variables that occur within the undertaking of an AM process using in-process control parameters that are applied by the machine operator. The sensor logs are normally hidden from machine operators, but have been made accessible for this research by the machine manufacturer. It is currently assumed that the levels set for these parameters and variations experienced during a process will contribute to dimensional inaccuracies, feature errors, porosity, layer delamination, curling and poor material properties. It is not known how variations in and potentially interactions between these parameters may be linked to process quality. In part, this is because the process parameter settings are chosen on a trial-and-error basis[4]. However, there is a clear need to investigate the information held in relation to the enactment of a particular process in order to determine the required levels of process control. Future research can then explore potential process optimisation.

The key element of work to be reported here is an initial assessment of the information held within the process log data. This will include the nature of the data associated with each variable and the level of information that can be extracted, either from individual data streams or more holistically by considering several variables together. This in turn will require consideration of suitable data processing tools and the application of knowledge based analysis approaches, with a view to enabling wider consideration of how research currently being conducted within the sector can be applied.

This paper will firstly introduce the powder bed fusion process. It will then go on to outline the process variables before describing how these variables are recorded within the build log. The aim of the work is to engineer a knowledge based solution that will enable better process control by using the information contained in the log.

2. Powder Bed Fusion Process

Selective laser melting (SLM) utilises a laser to provide energy to a metallic raw material. Figure 1 shows the build chamber of an AM250 selective laser melt (SLM) machine.

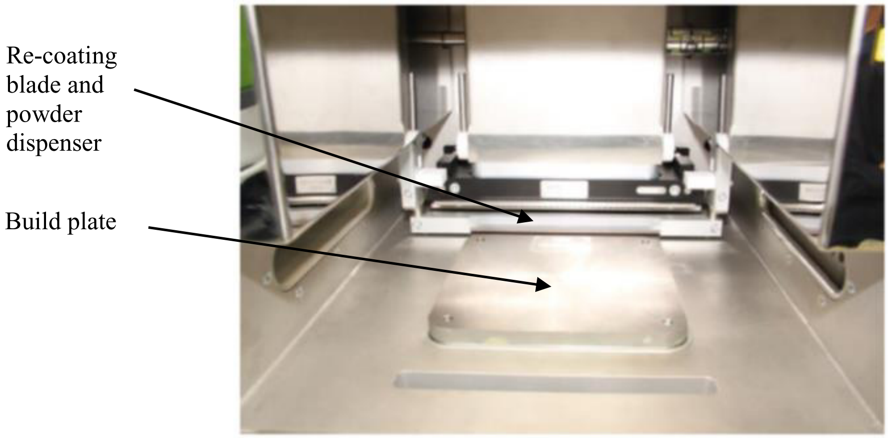

Fig. 1. Renishaw AM250 Build Chamber

The process begins with raw material being deposited on a build plate in the build chamber of an additive layer machine. A high power laser beam traces a geometry on to the powder layer. The energy from the laser is absorbed through radiation by the powder and the heat transfer produces a phase transformation. The powder changes from a solid to a liquid, forming a melt pool. Once the laser moves, this melt pool solidifies to produce a consolidated layer. When the scan finishes the geometry for the layer, the build bed is lowered and a fresh layer of powder is deposited. The process will then be repeated until the end of the build program and the part is finished. When the build is completed, the solid metal part will be embedded in powder in the build platform.

3. Process Variables

It has been estimated that powder bed fusion (PBF) has more than 130 variables[18]. To understand the variables and what they can affect, these variables have been broken down into four main areas; Feedstock, Build environment, Laser and Melt pool.

Feedstock is established as being vitally important to the quality of a part[19]. Material suppliers provide composition limits, size distribution and spherical measurements, but do not provide information on the stock condition, for example, if it has been exposed to moisture which alters some of the powder's characteristics chemically. It has been reported that gas atomised powder produced for AM has porosity in the material[20]. The size distribution has been found to be a major factor in producing dense parts and that recycling the powder can increase the size of the powder particles. Recycling Ti6A14V up to 5 times did not affect the part quality, but the size distribution did increase each time the powder was recycled[21]. Investigations in powder size distribution have found that with an increase of powder size there is an increase in part porosity[22].

Thermal conductivity effects the finish on a build. When the build process occurs and an object is being produced there is a major difference in the thermal coefficients between powder and the consolidated metallic material. The consolidated material acts as a heat sink and is more conductive than the powder surrounding it. A large differential in temperature between the powder and the consolidated metallic material can cause the "edge-effect" [23]. E. Yasa and J. Deckers were unable to eliminate raised edges completely on the top surface of a build, but proved that these edges could be minimised with different scanning strategies. Random-fill scan strategies were found to minimise the high ridges from the surface because heat could be dissipated more evenly across the build surface.

The build environment in most processes is the natural starting point for process monitoring. Many variables can be monitored and from this a quality management system can be produced. The variables in this AM build environment are common to all AM processes. Chamber gas state, Oxygen level and chamber pressure are usually measured because the presence of Oxygen in the build environment can cause defects in the build. Oxygen presence will cause oxidisation on the material and can also be a safety risk. Metallic powders can catch fire in the correct environment where Oxygen is present, therefore the chamber must have a minimum Oxygen content. In this AM machine Argon is used to produce a positive Argon rich atmosphere. The pressure inside the build chamber is kept higher than atmospheric pressure so that Oxygen cannot leak into the chamber if the seals on the machine fail. The AM machine monitors the oxygen levels using a Bosch LSH 25 Oxygen sensor. The Bosch sensor measures from 0% - 21% Oxygen content and converts this information to parts per million. Two sensors are placed in the machine, one at low level near to the build surface and one at high level at the top of the build chamber. These sensors provide feedback to the operator regarding the Oxygen level in the build chamber during the build and only activates the alarm if the Oxygen level peaks over a pre-set value.

Build chamber temperature and build plate temperature is measured in the AM machine using TD Thermal LTD SEN-106-090-001 thermal couplers. The thermal coupler used has an accuracy of +/- $(0.3 + 0.005t)$°C (so at a temperature reading 100°C the actual reading is +/- 0.8°C). This error increases the hotter the build chamber gets. The information is recorded throughout a build and can be viewed on the log files. The temperature at the build surface and the powder temperature are not monitored during the process.

In other research it has been found that large temperature differences between the solid powder and melt point affect the residual stresses when creating a part. Residual stress within Chrome Molybdenum steel was measured using strain gauges mounted to the build platform[24]. The authors found that the largest tensile value was found in the top layer of a build irrespective of the scan speed. Heat treatment at 600°C and 700°C for an hour would reduce the residual stress by 70%. If the parts were rescanned prior to a new powder layer being applied the tensile stress would decrease by 55% and if the base plate was heated to 160°C the residual stress would reduce by 40%. Most researchers have linked process parameters with residual stress and they have investigated many different ways to reduce these residual stresses. The main way identified is through post process treatment[25, 26].

Material delivery feed rates and powder delivery system quality are important factors in a PBF AM process. The amount of powder delivered to the build bed and its distribution has a direct impact on the quality of the part being manufactured. The powder needs to be delivered so that the distribution and density is as even as possible over the complete build plate. Disturbances in the powder distribution is usually left to the operator to assess. For example, if the re-coater blade is damaged the powder will not be distributed evenly over the build area, the only way the AM machine can be stopped in this case is by manual intervention. Research in this area has pointed to the introduction of a camera in the build area. Such a camera can be used to assess the powder bed for powder distribution[27] or the melt pool when in laser operation, removing the need for the operator to visually check the operation.

Laser characteristics have been documented as being an important factor in any build. Laser power combined with scan speed, hatch spacing and layer depth effects the energy density being supplied to the powder surface. The consistency at which the laser meets the powder surface is also important. During the build the laser must move around the build bed. This is achieved in the AM250 by altering mirror angles. During mirror angle changes, the laser's characteristics change the spot size and shape, reducing or increasing the energy density supplied to the powder surface. A consistent energy source is one variable that is required to produce parts that are fully dense. The energy density is a factor that can be used to ascertain the final density of a part being produced. Energy density relies on a number of the factors mentioned above:

$$Energy\ Density\ (ED) = \frac{P}{V \times \emptyset} \qquad (1)$$

Where P = Laser power, V = scan velocity and Ø = laser spot diameter[28]. Some research literature replaces the laser spot diameter with the scan spacing. This is because scan spacing is reliant on the spot size. Scan 'wait' time is another factor that is overlooked in some build programs. When a CAD model is split into layers using a slicing program, different layers will contain different size scan areas to form the consolidated metallic object. Some of these slices will produce areas with long scan times. Where this is the case the area of the part being built will have a longer period of cooling compared to slices that only contain small scan areas. When this occurs the scan velocity does not change, nor does the time between the laser finishing and the start of the next layer. The duration spent on a layer means that parts of the build will have had longer to cool than others, producing larger temperature changes in parts of the build when the next layer of powder is applied. This could cause differences in parts mechanical properties.

The age of a laser has a direct link to the power output. The longer a laser is in operation, the less power it produces. Laser calibration should occur in the setup of an AM machine showing the actual and requested power output. If the requested power is different to the required power, Equation 1 will not provide an accurate energy density and the parts produced on this machine will no longer match the expected mechanical requirements. Melt pool monitoring has become an area of major research due to the complexity of the variables that change the geometry of the molten material. The melt pool can provide information regarding the production temperatures, penetration and in-plane geometry. Measuring the melt pool temperature in real time provides an opportunity to correlate temperature with powder feed rates and scan speeds. Inconel 718 has a strong sensitivity to fluctuating laser power and thickness[29], the reverse can also be monitored; cooling time and rate. These properties are summarised in Table 1 and are further classified into controllable and predefined parameters. 'Controllable' parameters can be altered at the start and during the build cycle. 'Predefined' parameters are fixed at the start of the build and are either already built into the software running the AM machine or fixed by the operator during the start of the build. Some of these fixed variables in this table could, on other machines, be altered. Table 1 also provides the reader with information regarding which of these parameters are monitored throughout the build, with the current sensor arrangement in the commercial AM machines from which the data has been received.

Table 1. Summary of key process parameters in AM adapted[30]

	Parameter	Description	Controllable or predefined	AM Plc Log
Feed Stock				
1	Bulk density (ρ_b)	Material density, limits maximum density of final component	Predefined	-
2	Thermal conductivity (k_b)	Measure of material's ability to conduct heat	Predefined	-
3	Heat capacity (cp,b)	Measure of energy required to raise the temperature of the material	Predefined	-
4	Latent heat of fusion (L_f)	Energy required for solid-liquid and liquid-solid phase change	Predefined	-
5	Melting temperature (T_m)	Temperature at which material melts; for alloys the difference between the liquidus and solidus temperature is typically of greater interest	Predefined	-
6	Boiling temperature (T_b)	Temperature at which material vaporizes; may only be important in certain process conditions	Predefined	-
7	Vapor pressure (p_v)	Measure of the tendency of material to vaporize	Predefined	-
8	Heat (enthalpy) of reaction (H_r)	Energy associated with a chemical reaction of the material (e.g., oxide formation), not always relevant	Predefined	-
9	Material absorptivity (A_b,m)	Measure of laser energy absorbed by the material, as opposed to that which is transmitted or reflected	Predefined	-
10	Particle morphology (A_R, f_{circ}, f_{elong}, etc.)	Measures of shape of individual particles and their distributions, e.g., aspect ratio, circularity, and elongation	Predefined	-
11	Surface roughness (R_A)	Arithmetic mean of the surface profile	Predefined	-
12	Particle size distribution	particle sizes, usually diameter, is a powder sample	Predefined	-
13	Contamination	Ill-defined factor describing change in properties of powder due to reuse as dust and other particles added to powder	Predefined	-
Build environment				
14	Shield Gas	Usually Ar or N2, but may also be He, or something else	Predefined	Yes
15	Oxygen level (O_2%)	Probably most important environmental parameter; oxygen can lead to oxide formation in metal, change wettability, energy required for welding	Controllable	Yes
16	Shield gas molecular weight (MW_g)	Influences heat balance, diffusivity into and out of part	Predefined	-
17	Shield gas viscosity (μ_g)	May influence free surface activity of melt pool, convective heat balance	Predefined	-
18	Thermal conductivity ($k_{c,g}$)	Term in heat balance	Predefined	-
	Heat capacity of gas ($C_{p,g}$)	Term in heat balance	Predefined	-
19	Pressure (p)	Influence vaporization of metal as well as oxygen content	Controllable	Yes
20	Gas flow velocity (v_g)	Influences convective cooling, removal of condensate	Controllable	Yes
21	Convective heat transfer coefficient (h_c)	Convective cooling of just melted part by gas flowing over the surface	Predefined	-
22	Ambient temperature ($T\infty$)	Appears in heat balance, may impact powder preheat and residual stress	Controllable	Yes
23	Surface free energy (γ_{gl})	Between liquid and surround gas influence melt pool shape	Predefined	-
24	Density (ρp)	Measure of packing density of powder particles, influence heat balance	Predefined	-
25	Thermal conductivity (k_p)	Measure of powder bed's ability to conduct heat	Predefined	-

	Parameter	Description	Controllable or predefined	AM Plc Log
26	Heat capacity ($c_{p,p}$)	Measure of energy required to raise the temperature of the powder bed	Predefined	-
27	Absorptivity (A_p)	Measure of laser energy absorbed, dependent on Ab and state of powder bed	Predefined	-
28	Emissivity (ϵ)	Ratio of energy radiated to that of black body	Predefined	-
29	Deposition system parameters	Recoater velocity, pressure, recoater type, dosing	Controllable	-
30	Layer thickness (L)	Height of a single powder layer, limiting resolution and impacting process speed	Controllable	Yes
31	Powder bed temperature (T_p)	Bulk temperature of the powder bed	Controllable	Yes
Laser				
32	Average power (P_L)	Measure of total energy output of a laser	Controllable	-
33	Mode	Continuous wave or pulsed	Predefined	-
34	Peak power (P_{peak})	Maximum power in a laser pulse	Predefined	-
35	Pulse width (PW)	Length of a laser pulse when operating in pulsed mode	Predefined	Yes
36	Frequency (f)	Pulses per unit time	Predefined	-
37	Wavelength (λ)	Distance between crests in laser electromagnetic waves	Predefined	-
38	Polarization	Orientation of electromagnetic waves in laser beam	Predefined	-
39	Beam quality (M_2)	Related to intensity profile and used to predict how well beam can be focused and determine minimum theoretical spot size (equal to 1 for a Gaussian)	Predefined	-
40	Intensity profile I (x,y,t)	Determines how much energy added at a specific location	Predefined	-
41	Spot size (d_x and d_y)	Length and width of elliptical spot (equal for circular spots)	Controllable	Yes
42	Scan velocity (v)	Velocity at which laser moves across build surface	Controllable	Yes
43	Scan spacing (S_s)	Distance between neighbouring laser passes	Controllable	Yes
44	Scan strategy	Pattern in which the laser is scanned across the build surface (hatches, zig-zags, spirals, etc.) and associated parameters	Controllable	Yes
Melt pool				
45	Melt pool viscosity (μ)	Measure of resistance of melt to flow	Predefined	-
46	Coefficient of thermal expansion (α)	Measure of volume change of material on heating or cooling	Predefined	-
47	Surface free energy (γ_{sl})	Free energy required to form new unit area of solid-liquid interfacial surface	Predefined	-
48	Solubility (S)	Solubility of solid material in liquid melt, unlikely to be significant	Predefined	-
49	Melt pool shape	Length (in scan direction), depth, width and area	Controllable	-

4. Build log and correlations

The AM log files contain a variety of information and some of this is shown in Table 1. Part of the raw data log is shown in Table 2. The additive layer machines program loops through the sensors every 5 seconds. If during this cycle a value relating to the oxygen level, gas pressure or temperature changes the new value is record in the process log file. Currently this process log and as such does not provide any automatic mechanical adjustment to the manufacturing process of a build but it will stop the system when a value is reported which is outside the allowable process parameters.

Table 2. Part of the process log file from a Cobalt Chrome build cycle

Plc To Pc - layer Number	Current layer number	75	76	77	77	78	79
	Accumulative Time (s)	1666	1686	1706	1721	1736	1751
	Time per layer (s)	35	20	20		30	15
Plc To Pc - Oxygen Bottom Level	Recirculation circuit oxygen sensor value (ppm)	3549	3549	3542	3542	3542	3555
Plc To Pc - Oxygen Top Level	Vent point oxygen sensor value (ppm)	4967	4967	4967	4958	4958	4958
Plc To Pc - Gas Pressure	Chamber gas pressure (Bar)	9	9	9	9	9	9
Plc To Pc - Vacuum Temp	Vacuum chamber temperature (ºC)	24	24	24	24	24	24.1
Plc To Pc - Elevator Temp	Elevator temperature (ºC)	45.2	45	45	45.1	45.1	46.5
Pc To Plc - Laser Time On	Laser on time (s)	66610119	66610137	66610158	66610173	66610188	66610203
Pc To Plc - Laser Time Firing	Laser firing time (s)	11132538	11132547	11132558	11132569	11132578	11132585
	Firing time per layer (s)	26	9	11		20	7

The build log information can be used to identify correlations between variables and as-built characteristics. Currently this information is only collected and is part of an open loop process. Figure 2 provides one such correlation that can be seen and analysed with the information shown in Table 1.

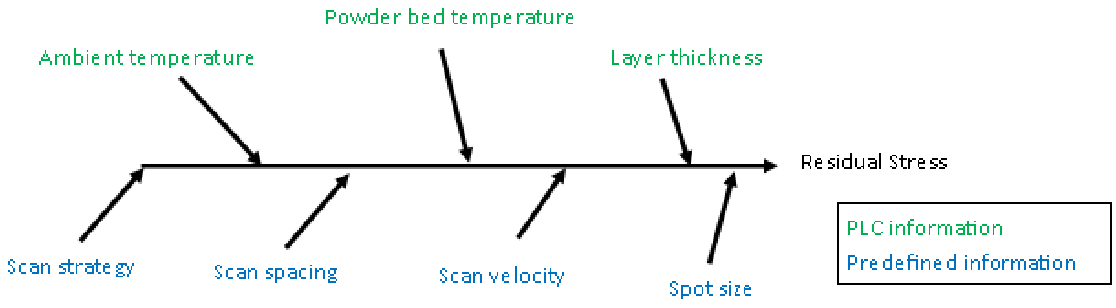

Fig. 2. Correlations between build environment and product residual stress

Figure 3 shows the correlation that currently cannot be analysed due to the lack of data being collected by the PLC.

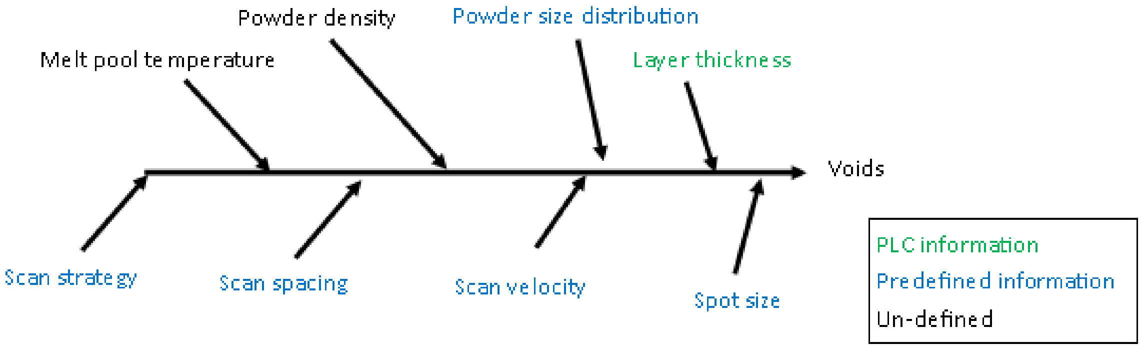

Fig. 3. Correlations between build environment and product voids

The production log is limited by the sensors and the information it can gather. Twenty correlations have been identified in[4] some of these correlations cannot be assessed with the sensors currently available on current industrial manufacturing machines due to the complexity of the correlation and the lack of valid information the sensors are able to supply. This research aims to bring together the information contained within the build log without adding extra sensors this will require the application of as yet undecided knowledge engineering techniques.

5. Conclusion

The ultimate goal of additive manufacturing process monitoring is to develop effective real-time, closed-loop feedback control. Currently this state of the art process relies on process trial and error, using an operator's observations and knowledge to produce a fully functional part. This is far from acceptable, particularly given the current lack of skilled process practitioners. Computer numerically controlled milling machines have now been in operation since the 1950's. Thousands of hours researching and testing has been carried out to inform users of the correct operating parameters (speeds, cutting angles and what tools to use) to produce parts that are completely in tolerance and are fully process controlled. The deployment of ALM processes cannot rely on such expertise development as the time required would delay the adoption of this important technique. What is required are more knowledge based solutions.

This paper presents the information available to the knowledge based community to ascertain what analytical methods can be used to produce effective control algorithms to bring AM under process control. The challenge is to relate in-process sensor data to system control and quality matrices. The continual monitoring within the build chamber produces massive amounts of data. The size of the data and data sets will continue to grow and processing all this information in real time will provide a challenge. Understanding the relationships and correlations between the available data and the part quality is a critical consideration to reduce the data required and therefore the processing time. Traditional operator control is not a viable option with this state of the art process, but process control is required to address production quality issues. Once the process has been brought under control these control algorithms can be used to optimise the process.

Currently, information on a number of process logs have been made available by one of the companies currently producing metallic AM machines. Researchers can request the information which has been produced in a neutral format for process analysis with an aim to produce process optimization processes. This reduces the need for post process quality assurance and provides a closed-loop feedback control system for AM.

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