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In- situ Monitoring of Metal Additive Manufacturing Processes: Sensing and Intelligent Data Analysis

Bianca Maria Colosimo, Marco Grasso

Dipartimento di Meccanica, Politecnico di Milano, Via La Masa 1, 20156
biancamaria.colosimo@polimi.it, marcoluigi.grasso@polimi.it

***Abstract* – Metal Additive Manufacturing (AM) processes have gained an increasing interest in many sectors as they provide novel production capabilities that may fit new challenging applications. However, regardless of their great potentials, the actual usage of metal AM systems in the industry is still limited by different issues. Among them, the problems related with the quality, capability and repeatability of additive processes represents a major issue, which imposes the need for novel and advanced sensing and monitoring solutions. This study reviews the quality issues in metal AM processes and investigates different monitoring solutions based on in-situ machine sensorization.**

I. INTRODUCTION

Metal AM processes have been gaining an increasing industrial attention in different sectors (e.g., aerospace, biomedical, tooling and molding, etc.). The applications of major interest involve innovative structures and highly customized products, i.e., short run or one-of-a-kind productions, where there is no availability of training phases for quality control tool development. Moreover, additively produced parts exhibit complex features and lightweight structures that can not be produced with conventional processes, which implies difficult and expensive post-process quality inspections. Eventually, current AM technologies imply long processes with expensive materials, which imposes the need to avoid, as much as possible, defect onsets and re-manufacturing operations. Because of all these issues, recent keynote studies [1 – 7], European projects [8] and roadmaps [9] pointed out the central role of process monitoring via in-situ sensing and novel control strategies to achieve a zero-defect-oriented AM production.

High value added products produced via AM involve complicated textures (e.g., medical applications), topologically optimized shapes (e.g, aerospace applications) and conformal cooling (e.g., in the tooling industry). In all those applications, the qualities (geometrical, surface, physical) and the performances of the part are of fundamental importance. Thus, in-situ sensing is needed to determine the quality and stability of the process during the layer-wise growth of the part itself, since the quality, repeatability and capability of AM processes still represent one of major concern for their industrial breakthrough. In-process signal data collection and analysis guarantee a continuous monitoring of the process even in the presence of a one-of-a-kind production, where a training phase on previous parts of the same type is not applicable. The goal is to push the metal AM process development towards a zero-defect production, by considerably enhancing its repeatability and capability and by reducing the number of process runs required to tune the process parameters and to achieve the desired quality targets.

II. DEFECTS IN METAL AM PROCESSES

As a matter of fact, different kinds of defects and process errors may originate during the layer-wise production of metal parts, with a detrimental impact on the dimensional accuracy, the surface finishing, the mechanical, physical and microstructural properties of the part.

As far as powder bed processes are concerned (i.e., Selective Laser Melting - SLM and Electron Beam Melting - EBM), different kinds of defects have different sources related with the choice of process parameters, the powder bed thickness and homogeneity, the choice of supporting elements, metal powder contamination, etc.

Some geometric features are known to be critical, like overhang zones, acute corners and thin walls. Overhang features are down-facing surfaces and contours where the powder is melted over an underneath non-molten powder layer. Since powder is heat insulating, the scanning of an overhang part may yield a local overheating due to a lack of heat conduction to the surroundings. The AM of acute corners and thin walls may generate a heat conduction problem too, as those features are largely surrounded by loose powder. In correspondence of those critical features, overheating phenomena may occur, leading to super-elevated edges and local geometrical distortions, which reduce the dimensional and geometrical accuracy of the part. An example of local geometrical errors corresponding to wrong melting conditions in overhanging acute corners of an AISI 316 part produced via SLM is shown in Fig. 1.

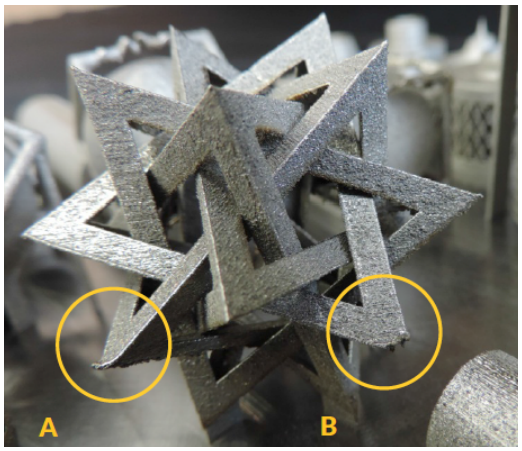

Fig. 1. Example of local geometrical errors and defects corresponding to overhanging acute corners in SLM (AddMe Lab – Politecnico Milano)

Another kind of defects is caused by the residual stresses originated during the melting process. Non-optimal support distributions and/or scanning strategies may produce thermal stresses that result in delamination of the part from the substrate and/or cracks, especially in large components. Residual stresses can influence the dimensional accuracy of the part and reduce its functional performances (see the examples in Fig. 2).

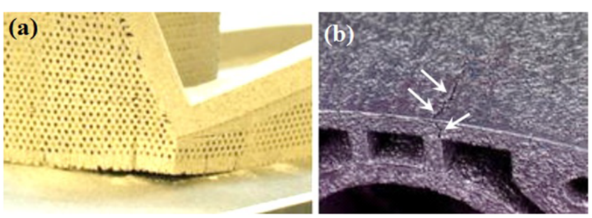

Fig. 2. Delamination of a part from the substrate (a) and internal cracks (b) [10]

As far as internal defects are concerned, the porosity of the part play a central role. Depending on the choice of process parameters (e.g., scan speed, laser power, exposure time, hatching distance, etc.) different porosity conditions can be obtained. In case of over-melting, sub-surface porosity can be produced due to gas bubbles trapped inside the part. Insufficient melting can produce porosity as well, with higher pore shape irregularity with respect to the previous case [7] – see Fig. 3. Some authors [7] pointed out that a narrow region of the parameter space can lead to fully dense parts, and the selection of optimal parameters sets also depend on the slice geometry. Wrong choices of the parameters may also produce the balling effect [5 – 6], i.e., a formation of small spheres of solidified material with the approximate size of the beam diameter. The incapability of guaranteeing optimal process conditions motivates the critical role of in-process monitoring tools.

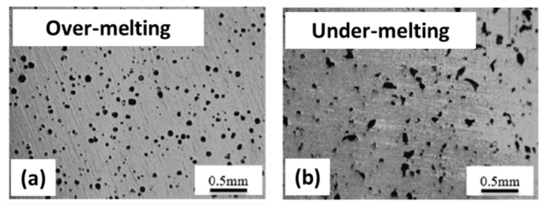

Fig. 3. Two kinds of porosity in SLM, corresponding to an excessive power condition (a) and insufficient power condition (b) [7]

Other sources of defects include powder contamination (e.g., inert gas bubbles trapped into the material), non-homogeneous powder deposition due to a work recoating system, out-of-control environmental conditions in the chamber, insufficient substrate heating and/or wrong substrates, etc.

III. PROCESS MONITORING LEVELS

The AM process can be characterized by controllable (hundreds) parameters that include the scanning strategy and the power source settings, together with the factors defined during the build design stage (powder properties, supports type and distribution, layer thickness, type of substrate, etc.). All of them influence the qualities and performances of the final product (including geometric, surface, physical and mechanical properties). An experimental characterization (possibly supported by simulation analysis) of the AM process leads to a mapping of causal dependencies between the input parameter selection and the output product properties. In-situ sensing provides an additional knowledge level, which was referred to as the "signature" level in [6]. This knowledge level includes all the information that can be gather during the process itself by using in-situ monitoring solutions. To this aim, a large part of the recent literature on powder bed fusion processes for metal AM [11 - 24] focused on machine sensing methodologies for the development of in-process monitoring tools. Analogously, most AM system developers are placing machine sensing and process monitoring among the key technologies to push forward the system innovation and the achievement of challenging quality and capability requirements. Generally speaking, the types of signatures that can be gathered during the process regards three different scales (see Fig. 1).

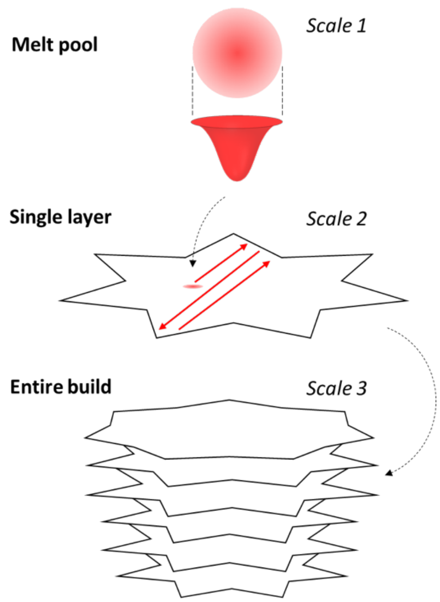

Fig. 4. Three monitoring scales

The first scale involves the characterization of the melt pool and the surrounding heat-affected zone [17 – 21].

The melt pool temperature distribution together with its shape and size are influences by several build design factors and process parameters, including the powder characteristics, the layer thickness, the scan speed, the beam size, the beam power, etc.

Moreover, the dimension, shape and temperature distribution of the melt pool influence most the final product qualities and performances. Because of this, the melt pool properties provide relevant information about the process stability and the occurrence of local defects.

The second scale regards the analysis of the entire layer, to detect errors in different areas of each slice. In this case, different authors focused on the temperature distribution over the slice [22 - 24], on the surface pattern observed at the end of the laser scanning [24] and the reconstruction of the 2D slice geometry [22]. Inclusions, debris and worn wipers cause an inhomogeneous powder deposition that may have a considerable impact on the slice quality. In addition, the surface pattern of the slice is influenced by the stability of the melting process, and hence represents a fundamental source of information to determine the quality of the process on a layer-wise basis.

The third scale regards the volumetric growth of the build, from layer to layer. This implies repeating the previous analysis for each layer in order to monitor the overall evolution of the process and its stability along the vertical growth direction.

IV. IN-SITU SENSING SOLUTIONS

Depending on the monitoring scale, the type of signature to be characterized and the nature of defects to be detected, different in-situ sensing solutions can be considered. With regard to the first monitoring scale (i.e., the melt pool), the exploitation of the laser optical path is required in order to collect high speed data to follow the beam along its scanning path. To this aim, different authors [17 - 21] proposed co-axial cameras (either in the visible or in the infrared range) and/or photodiodes. Photodiodes are suitable to monitor the average or maximum temperature over the melt pool. Since they provide one numerical value, they are suitable to provide very high frequency information about the melt pool stability (as an example, the scanning speed can be in the order of 1000mm/s). On the other hand, the photodiode captures only an integrated temperature value, which is not sufficient to fully characterize neither the temperature distribution over the melt pool nor its shape and size. Because of this, the use of coaxial cameras (either in the visible range or in the infrared range) was proposed [17 – 21]. Their spatial resolution does not need to be very high due to the very limited field of view provided by the coaxial mounting. However, high frame rates are required to avoid information losses during the high speed scanning of the slice. As an example, a resolution of about 60x60 pixels with a frame rate of 10 kHz was used in [19]: the authors adopted an IR camera in the wavelength range of 400 – 1000 nm. An example of the difference between the melt pool in SLM under in-control conditions (top panel) and in the presence of an overhang feature (bottom panel) is shown in Fig. 5 [18]. The melt pool width does not increase significantly from the first case to the second one, but the melt pool length is much larger on the overhang zone.

The use of off-axial cameras is not suitable for melt pool monitoring due to the very low ratio between the size of the melt pool (e.g., about 120 μm) and the off-axial field of view. Nevertheless, some authors showed that off-axial monitoring set-ups could be used to collect data about the temperature distribution over the heat affected zone, which is larger than the melt pool. Generally speaking, a good compromise between spatial and temporal resolution is needed, since the field of view is larger and the size of the target signature is small with respect to it. As an example, an off-axial infrared camera was used in [23] to this aim, having spatial resolution of 640x480 pixels with an IR camera in the range 800-14000 nm. The frame rate of about 10 kHz. Standard cameras can be used for the in-process characterization of the melt pool size and geometry, where image processing techniques are applied to determine the boundaries of the melt pool after pixel intensity thresholding. The thermal characterization of the melt pool instead requires the use of infrared sensors. In this frame, a critical issue is represented by the sensor calibration, which must be sufficiently accurate if absolute temperature data are needed [6].

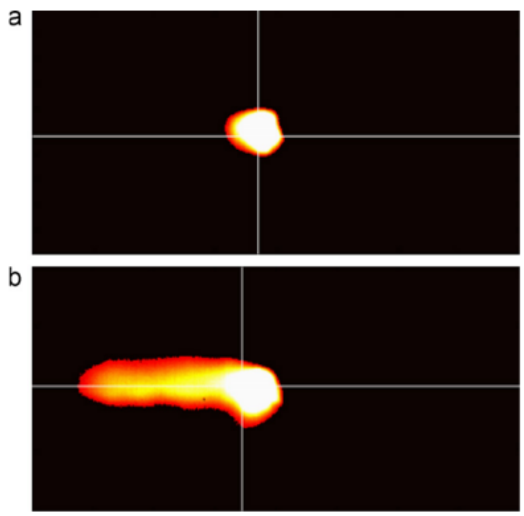

Fig. 5 – Example of a melt pool image during SLM process under in-control conditions (a) and melt pool image during the same process during overhang scanning (b) [18]

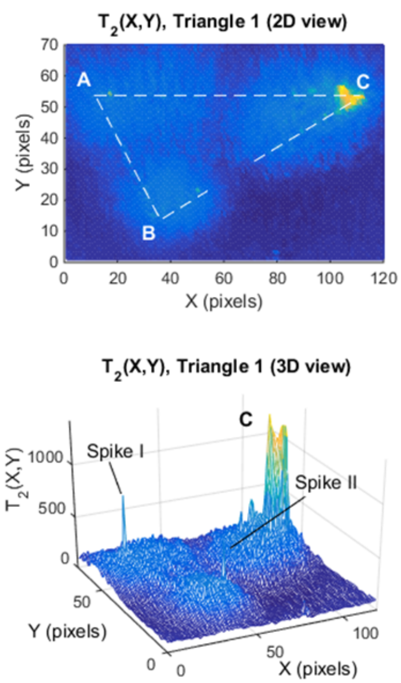

Fig. 6 – Example of a statistical method to detect and localize local defects in SLM by using an high-speed of-axial camera [25].

The second monitoring scale (i.e., the monitoring of the entire layer) involves the use of off-axial cameras.

High-speed cameras may be used to capture transient phenomena like local over-heating and cooling transitory and to follow the laser kinematics [25]; on the other hand, high resolution cameras are useful to collect images of either the powder bed or the surface pattern of scanned slices. An example of a statistical method for local defect detection and localization presented in [25] is shown in Fig. 6. The acute corner (corner C in Fig. 6) of a triangular feature was affected by an overheating phenomenon that finally yielded a local geometrical deformation. The proposed statistic, based on combining principal component analysis to cluster analysis and multivariate control charting, was able to signal the presence of an anomalous thermal transitory, which could be used to rapidly signal an alarm during the defect onset stage. In this case, an high-speed (10 kHz) standard camera place off-axis was used to monitor the process.

As far as the second monitoring scale is concerned, in-process data can be acquired either:

- Before the scan: two different signatures are of interest at this stage, i.e., the homogeneity of the powder deposition all over the layer and the vibration of the powder deposition system. The two signatures are strongly correlated to each other. Discontinuities of the powder bed like super-elevated edges or contaminations may accelerate the wear evolution of the recoating system with a consequent increase of its vibration; on the other hand, a worn recoating system has detrimental effects on the powder bed homogeneity. Off-axial cameras can be used to detect any contamination or local inhomogeneity of the powder bed, but high spatial resolutions are required. Accelerometers [26] can be used to monitor the recoating system vibration as well.
- During the scan: different authors [22 – 25] proposed methods that can be used to detect local defects associated with anomalous cooling transitory and variations of the temperature distribution over the entire slice. Either cameras in the visible or infrared range can be used to this aim, but they must have both high spatial resolution and high frame rates (larger than 1 – 10 kHz). If standard cameras are used, the pixel intensity is used as a proxy of the local temperature. A spatial map of pixel intensities or actual temperature values can be created to determine if some parts of the slice exhibit anomalous patterns that can be the symptom of a geometric defect onset.
- After the scan: the surface patters of the scanned slice can be captured with either standard or infrared cameras placed off-axis [24]. Local deformations, super-elevated edges, porosities and other defects can be detected at this stage (as an example, see Fig. 7, where the effect of the hatch distance of the surface pattern of the scanned slice is shown). Pores and internal defects can be very small: the minimum diameter of a pore or an inclusion can be in order of

10 – 40 µm, whereas larger pores and defects may have diameter greater than 100 µm. The larger is the space resolution of the monitoring system, the higher is the defect identification and localization accuracy. Time resolution is not a constraint, instead, since one single picture at the end of each layer is needed. Surface patterns of interest also include the temperature homogeneity of the slice, since any departure from the spatial homogeneity may influence the heat exchange and melting quality during the next layer.

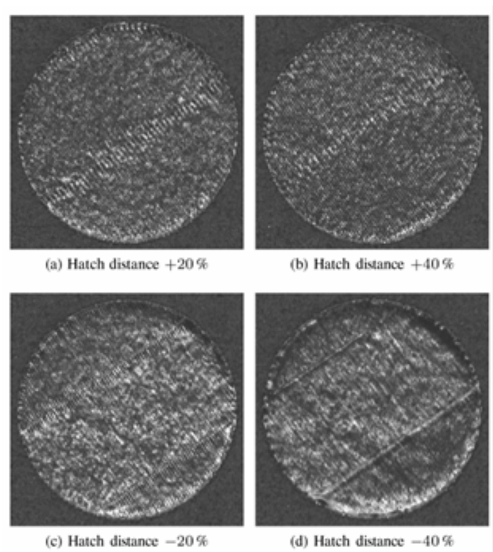

Fig. 7. In-situ acquired surface patterns of scanned slices with different hatch distances [24].

The development of in-process monitoring tools for metal AM implies several challenges. First of all, the high-speed stream of images represents a big data source. Image processing and statistical analysis of image-based descriptors need to be performed at thousands of frames per second. Therefore, novel monitoring methodologies are required to comply with computational constraints. Another issue regards the definition of alarm rules in the absence of repeated process runs, which involves a perspective change with respect to traditional statistical quality monitoring approaches. The monitoring tools must also be sufficiently flexible to be applied to continuously changing slice geometries and process settings.

The third monitoring scale involves the capability of surface and volume modeling of complex geometries, including lattice structures, free form features and internal channels. Novel statistical modelling and functional analysis methods are needed to this aim. A further challenge regards the fusion of information from different sensors and belonging to different formats. The mainstream literature on metal AM processes still lacks such methods, but they represent a key issue for an actual industrial breakthrough of the technology.

V. CONCLUDING REMARKS

Quality, stability and repeatability of metal AM processes need to be considerably improved to meet challenging industrial requirements in different application fields. In-situ machine sensorization including both co-axial and off-axial cameras together with other kinds of sensors is necessary to acquire in-process information about the layer-wise evolution of the process. Highly efficient and flexible statistical methods are needed to cope with big data streams acquired at high speed and the small-lot and one-of-a-kind nature of most AM applications. Due to the length of AM processes, the cost of involved materials and the short run / one-of-a-kind nature of the most relevant applications, in-process monitoring tools must be able to signal the onset of defects as soon as possible. This information may be used to abort the on-going process if there is no possibility to recover the observed defect, with consequent avoidance of material and time wastes. On the other hand, the availability of reliable and effective monitoring tools is the first step towards the development and implementation of on-line fault recovery systems, able to suppress a defect or to mitigate its effects and propagation to the following layers via feedback control actions. This kind of adaptive/reactive controllers represents a key technology for the next generation of AM systems, and a necessary step towards zero-defect-oriented metal AM productions.

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