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# Assessing the capability of in-situ nondestructive analysis during layer based additive manufacture

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ABSTRACT

Unlike more established subtractive or constant volume manufacturing technologies, additive manufacturing methods suffer from a lack of in-situ monitoring methodologies which can provide information relating to process performance and the formation of defects. In-process evaluation for additive manufacturing is becoming increasingly important in order to assure the integrity of parts produced in this way. This paper addresses the generic performance of inspection methods suitable for additive manufacturing. Key process and measurement parameters are explored and the impacts these have upon production rates are defined. Essential working parameters are highlighted, within which the spatial opportunity and temporal penalty for measurement allow for comparison of the suitability of different nondestructive evaluation techniques. A new method of benchmarking in-situ inspection instruments and characterising their suitability for additive manufacturing processes is presented to act as a design tool to accommodate end user requirements. Two inspection examples are presented: spatially resolved acoustic spectroscopy and optical coherence tomography for scanning selective laser melting and selective laser sintering parts, respectively. Observations made from the analyses presented show that the spatial capability arising from scanning parameters affects the temporal penalty and hence impact upon production rates. A case study, created from simulated data, has been used to outline the spatial performance of a generic nondestructive evaluation method and to show how a decrease in data capture resolution reduces the accuracy of measurement.

## 1. Introduction

Through the continued development of additive manufacturing (AM) processes part manufacture for high value applications is continuing to gain traction (e.g. in aerospace, medical and tooling industries) [1]. An AM process uses localised material addition on a layer per layer basis to build up three-dimensional (3D) parts [2]. Mordfin et al. define three main assumptions about manufactured materials [3]: (1) all materials contain defects; (2) these defects are expected and do not definitively mean the part is unfit for use (i.e. for service life); and (3) the detectability of defects increases with the size of the defects. These assumptions hold true for parts produced with AM processes, hence it can be deduced that inspection is essential in high value components in order to assure that the manufactured part is fit for use.

Inspection can be conducted destructively, where statistical information can be gathered in order to give a confidence interval for a part produced under similar conditions (e.g. base material consistency, temperature and atmosphere). However, for many applications in the high value added industries, destructive inspection may not be suitable (where individual part information is required). Nondestructive evaluation (NDE) of a part is, therefore, often the only method that can be employed to gather the defect data required. Everton et al. have reviewed recent research on in-situ monitoring techniques of metal AM processes [4]; an overview is given of the direct and indirect measurement instrumentation currently employed to measure parts and machine operation in AM, which has been found to be limited to a small number of commercial systems; however, there is a range of inspection techniques that are currently being developed [4] and yet there is no overarching contribution which explores their utilisation.

Measurement methods currently being considered for AM can be sorted into two principal categories: indirect and direct. Indirect measurement techniques investigate effects on part manufac-

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ture based on the manufacturing environment; for example, AM machines may contain a closed-loop control for laser power in order to reduce fluctuations in the power delivery to the part being built. Contrary, direct measurement techniques assess the part based on its physical observations in order to determine quality, as a result of manufacture.

To some extent, direct measurements can be performed after the part has been produced – ex-situ (see [5–7] for recent reviews of ex-situ measurement technology applicable to AM). Ex-situ measurement allows a degree of freedom for the inspection instrument, as there are fewer space or time constraints; this is often how parts are evaluated in conventional manufacturing. However, AM provides a good opportunity for parts to be inspected as they are being built – in-situ. NDE methods that can inspect the surface and/or the subsurface region can now be used to build up an image of the internal structure of a manufactured part, ensuring it is produced to meet design parameters. In addition, measurements made and analysed in-situ can detect errors within the build process; feedback could then be used to pause the build to avoid scrappage of the flawed complete part, reducing material waste. Alternatively, the scan data can be used to enable to the AM machine to react autonomously and rework the defective layer, 'saving' the build [8]. These approaches may improve the economic viability of using AM processes and improve its adoption into more fields [9]. While the underpinning machine tool technology to allow in-situ repair is not available in current generation machines, this presents an interesting research area which will significantly enhance the capability of AM tools.

In-process monitoring is an important next step in AM methods due to user, machine and material induced errors affecting the success of manufacture from a geometrical and material point of view [4]. The study presented here investigates generic parameters of NDE tools and their influence on the productivity on the rapidly advancing AM process when incorporated in-situ. Analysing the spatial opportunity and temporal penalty associated with it, that the AM process presents for a measurement system, is a key concern when designing and selecting instruments. An NDE capability analysis approach is demonstrated in two case studies and simulated defect data is used to outline the effects of low NDE spatial capabilities.

### 1.1. *Current inspection methods*

In order to frame the methodology of determining and optimising inspection strategies, it is useful to review current measurement strategies. Indirect NDE methods currently being investigated include thermal and optical analysis – conducted either in-situ or online, have shown to yield data that can be used for feedback in selective laser melting (SLM) [10,11]. Melt pool analysis enables part failure detection. The process will infer formation of defects based on observations of the melt pool. In work by Krauss et al., artificial defects in a range of 40 μm to 500 μm were introduced into an SLM build at the design stage [12]. During part manufacture with Inconel 718 powder, the build was analysed using thermography (detecting with an infrared camera) with defects of less than 100 μm identified by detecting a variation in the cooling rate. However, as an indirect measurement method, the sizing and nature of the defects were not obtained. Doubenskaia et al. have shown that an optical system can be used for solid versus unfused powder differentiation (whilst also determining the geometry of the part in-situ) [13]. Similarly, Schwerdtfeger et al. have shown that infrared imaging, used in-situ in electron-beam powder bed fusion processes, yields layer per layer data that outlines areas of defects as a reduction in intensity [14] – in this study the minimum sampling size corresponded to 830 μm. The size range of interest for most defects in metal based AM processes is in the range of 10 μm to 100 μm [15,16].

Direct measurements investigate physical phenomena on the part in-situ. Rieder et al. have employed an ultrasonic transducer situated below the build platform to measure inconsistencies in SLM manufacture, which were tested with designed voids in the build [17]. This detection method provides limited information on the size and location of defects, providing only the layer number where a defect had been detected during the build. Research into selective laser sintering (SLS) inspected by optical coherence tomography (OCT) has shown that it is viable for in-situ process monitoring with surface and subsurface information. This was shown by Guan et al. scanning polymer test samples produced using an SLS system with embedded artificial defects [8]. Surface defects and roughness wavelengths with a minimum of 9 μm could be resolved and identification of loose powder under sintered material was possible down to 200 μm below the surface. Subsurface defects up to 100 μm in size could be identified.

Direct ex-situ part interrogation methods include the use of X-ray computed tomography (XCT) (see [7] for a thorough review), which can deliver measurements consisting of a high resolution data set of the build. For a full 3D data acquisition, Tammas-Williams et al. utilised a high resolution XCT system to scan electron-beam powder bed fusion samples with both coarse and fine scans to detect defects and relate the distribution to the processing environment [15]. The XCT analysis of electron-beam powder bed fusion samples has been shown to enable the determination of defects larger than 120 μm. Maskery et al. conducted a pore characterisation and quantification study on $AlSi_{10}Mg$ samples produced using SLM [18]. The XCT results were segmented and pores were characterised based on relative count and shape descriptors. Relative porosities of the samples were calculated to be less than 0.1% and predictions of service life were made based on the pore distributions, showing that XCT is a valid approach to SLM monitoring.

## 2. Defining NDE capability

Given the level of research activity in the area of NDE for AM parts, alongside the emergence of new AM machines, there is a need to evaluate how measurement techniques perform in service. The timeline of a basic in-situ analysis for an AM process is outlined in Fig. 1(a). In this case, employing an NDE method between the manufacture of a single layer will extend the time to part completion; the manufacture and measurement process need to occur in succession. Online analysis, outlined in Fig. 1(b), assumes that NDE measurements can be conducted during the manufacturing process and process measurement data on-the-fly, reducing the bottleneck apparent in the layer completion time. Full online monitoring systems can only yield indirect measurements as the solidification of the material in the manufacturing stage has to have occurred before collecting direct information.

The requirements for measurement instrumentation are dependent on the type of AM process, the materials to be used, the expected defects and the end user tolerances. This includes the spatial opportunity and temporal penalty afforded to the instrument. A definition of capability of an NDE instrument is needed in order to ascertain that it meets these requirements.

One requirement that an end user may have for production is the part completion time, $t_{manufacture}$, and is given by

$$t_{\mathrm{manufacture}} = t_{\mathrm{build}} + t_{\mathrm{reset}} \tag{1}$$

where the two key time variables are the layer build stage, $t_{build}$, and the reset stage of each layer, $t_{reset}$; both expressed per layer. The layer build stage is dependent on the layer dimensions, the