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Targeted rework strategies for powder bed additive manufacture

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ABSTRACT

A major factor limiting the adoption of powder-bed-fusion additive manufacturing for production of parts is the control of build process defects and the effect these have upon the certification of parts for structural applications. In response to this, new methods for detecting defects and to monitor process performance are being developed. However, effective utilisation of such methods to rework parts in process has yet to be demonstrated.

This study investigates the use of spatially resolved acoustic spectroscopy (SRAS) scan data to inform repair strategies within a commercial selective laser melting machine. New methodologies which allow for rework of the most common defects observed in selective laser melting (SLM) manufacturing are proposed and demonstrated. Three rework methodologies are applied to targeted surface breaking pores: a hatch pattern, a spiral pattern and a single shot exposure. The work presented shows that it is possible to correct surface breaking pores using targeted re-melting, reducing the depth of defects whilst minimising changes in local texture. For the hatch rework and spiral rework, a reduction in defect depth of 50% and 31% were observed, respectively, however, no improvement was seen after the single shot exposures. This work is part of a programme to develop a method by which defects can be detected and the part reworked in-process during SLM to enable defect specification targets to be met. Although further work in developing build-characterise-rework strategies for integrated and targeted defect correction is needed, the feasibility of the underlying method of identifying and selectively reworking to reduce a defect has now been demonstrated for the first time.

1. Introduction

Selective laser melting (SLM) is a powder-bed-fusion additive manufacturing (AM) process that is being increasingly considered as an alternative to current manufacturing methods in a number of high value-added industries [1–4]. However, this technology is still hindered by an inability to guarantee component build quality alongside a lack of robust inspection techniques suited to AM components [5]. Part integrity is associated with the presence of surface and subsurface micro defects, which cannot currently be reliably predicted or controlled for SLM. The reduction of these defects to a level consistent with a specified structural integrity is necessary if SLM is to be adopted for components operating in safety critical applications.

One of the most common defects to occur in powder-bed-fusion is porosity, which act as stress concentration sites and have been shown to significantly reduce the fatigue [6] and elongation [7] performance in SLM components [8]. Furthermore porosity negates the mechanical benefit offered by the finer lamellar microstructure characteristic of SLM by reducing the yield strength [7]. It has been shown that these voids can present in a range of sizes, <5–500 μm [9], and can either spread throughout the bulk or be located primarily between the internal hatching area and the external border [10]. Further investigations have developed a classification system for porosity based on morphology which relates defects to processing parameters; spherical pores caused by gas entrapment, or acicular pores due to lack of fusion between layers. As such, component defects occur as a function of processing parameters, material feedstock and build methodology, for example a lack of material fusion due to incorrect laser power, impurities in the feedstock or improper gas flow [11–14]. The definition of a critical defect size, resulting in scrappage of the component, is industry and application dependent [15]. Better understanding of the root causes of

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such defects in SLM components is a focus of ongoing research. However, the large number of process parameters (>50) [16] and inter-dependency between complex effects such as denudation, and material spattering [17] mean, despite many studies in process optimisation, it is still impossible to predict or control defect size and distribution. As stated by Leuders et al. the development of porosity defects during fabrication cannot be avoided currently [8].

As these defects cannot be avoided several techniques have been developed by the industry to optimise AM part integrity. For example, Hot Isostatic Pressing (HIPing) is currently a common post-processing technique for reworking internal porosity in superalloy components. However, it has been shown that this costly additional step is not capable of closing surface connected pores [18]. Furthermore, accurate control of the surface microstructure is not possible [19]. Previously, laser re-melting by applying additional skin scans has been employed to improve surface roughness [20,21]. It was shown, however, that compressive residual stresses were created as a consequence of this re-melting process. Further to this, Yasa et al. [22] showed that complete layer re-melting for defect rework on steel SLM components could reduce near surface porosity, but at the expense of a change in microstructure akin to a recast layer. This approach has been reported to yield SLM parts with unpredictable and anisotropic microstructures [23]. Mireles et al. [24] used infra-red imaging for in-situ monitoring in a selective electron beam melting process, reworking artificial defects in Ti-6Al-4 V components via large area re-melting. It was shown that re-melting successfully restored component integrity, however the authors used two inspection methods, thermography and X-ray computed tomography for defect sizing, yielding significantly different results, thus the efficacy of re-melting the artificial defects remains unclear. Furthermore, the defects seeded in the component were an order of magnitude greater than those seen to commonly occur in SLM in practice.

This necessitates research into both identifying and correcting such defects. As reported by Everton et al. [9], in-situ non-destructive evaluation (NDE) techniques have been subject to rapid development for use in AM processes. It was concluded that there was a clear industrial pull for in-situ monitoring, particularly for technologies that could be coupled with a form of closed-loop feedback to optimise processing parameters. In a closed loop system, an automated decision can be made to i) scrap the build – saving valuable build time and material – or preferably ii) enact an on-the-fly rework to allow completion of the part [15]. It has been proposed that spatially resolved acoustic spectroscopy (SRAS) is an NDE technique that is well suited to inspect SLM components, based on the capability to inform upon microstructural texture of the part [25], the ability to differentiate between surface and sub-surface defects [26], and potentially measure rough surfaces [27]. SRAS is a laser ultrasound technique which uses surface acoustic waves (SAWs) to probe the elastic properties of the sample in order to determine crystallographic orientation information, whilst additionally generating a separate optical image; the technique and instrumentation is described in previous work [28,29].

The focus of this study is to show defects, identified using NDE techniques at the surface of a given layer, can be reworked using defined scan strategies. SRAS is utilised in this study to locate and characterise surface defects and a number of targeted rework strategies are investigated for their ability to repair the defect. The reduction in the size of an array of defects within an SLM build subjected to these various strategies is then presented. Information on the defect type, location and morphology measured pre- and post-rework is shown, along with a texture map. Finally, a methodology in which the proposed technique can be integrated into SLM builds to guarantee part integrity is discussed.

2. Methodology

SLM test samples were manufactured using a ReaLizer SLM50 with the nickel superalloy, Inconel 718, the composition of which can be found in the literature [30]. A 10 × 10 × 10 mm cube was built using a meander scan strategy with a hatch spacing of 60 μm and a 67° rotation between each layer. A laser power of 100 W, spot size of 40 μm and scanning speed of 560 mms^{-1} were used to build layer thicknesses of 40 μm. Gas atomised powder sized 15–45 μm (measured with a Malvern Mastersizer 3000) was used as the powder feedstock.

After manufacture, the sample was polished to an average R_a ∼100 nm prior to inspection by SRAS and optical microscopy. The SRAS system operates on a raster-point scan principle [28]. Each point was obtained by pulsing (T = 1–2 ns) a 1064 nm Q-switched laser (AOT-YAG-10Q) (generation laser) through an optical grating at a repetition frequency of 2 kHz. As a result, a surface acoustic wave (SAW) is generated. The SAW is detected with a split photodiode using a 532 nm continuous wave laser (Laser Quantum Torus 532). Measurement of the frequency of each SAW packet allows calculation of the velocity of the wave, which can be used to output an image showing texture contrast. The generation patch size was ∼200 μm, giving an acoustic image resolution of ∼100 μm. In addition to obtaining velocity information, the system recorded an optical dataset of the measured surface; the optical image resolution being 10 μm/px. The prepared surfaces were also imaged using a focus variation microscope (Alicona InfiniteFocus G5) with a 20× lens and in-built image stitching tool. The lateral and vertical resolution of the 3D micrographs was 2.94 μm/px and 0.1 μm/px, respectively. The original build parameters were reused for the rework operation. In order to solely investigate the effect of re-melting, no additional powder was used in the rework process.

Three pore rework strategies were investigated, as shown in the schematic presented in Fig. 1: A hatch melting pattern, a spiral melting pattern and single shot melting for pores similar in size to the laser spot size. A single shot exposure was defined for defects ranging in sizes of 20–40 μm, with the laser being centred on the defect. A minimum and maximum exposure time of 30 μs and 100 μs, respectively, was defined based on standard manufacturing parameters. An exposure time of 95 μs was calculated for an exemplary defect of ∼40 μm whilst scaling this for larger defects. The hatch melting pattern was selected since the samples were manufactured identically. The spiral melting pattern was proposed by Jhabvala et al., showing optimised thermal gradients in both the x and y direction designed to avoid overheating [31]. Since re-melting hatch patterns are based on the size of defects (∼<500 μm), assuming optimised working parameters, more complex melting patterns such as fractal scans, chessboard scanning and ‘paintbrush’ scanning are not feasible as these are designed for bulk part processes.

In order to generate rework paths, an automated algorithm was developed, based on the flow chart in Fig. 2. The original optical SRAS data is shown in Fig. 2(a). A size thresholding step was then used to disregard defects and outliers smaller than 20 μm from the SRAS optical scan data, shown in Fig. 2(b), given the image resolution of 10 μm (pixel size) and the defined minimum cluster size of 2 × 2 pixels [15]. This step can be adjusted to ensure that only those defects that take the part out of specification are reworked. A filtering step, based on eroding and dilating, closes non-uniform surface defects, Fig. 2(c). This step is necessary for avoiding partial or uncontrolled splitting of hatch patterns on a targeted defect. The resultant binary image from these steps is then processed to segment defects based on their aspect ratio; the centroid and dimensions are obtained, Fig. 2(d), to only target pores. The final processing step is the generation of the rework paths, Fig. 2(e). In this step the rework area is defined by dilating the