A METROLOGY HORROR STORY: THE ADDITIVE SURFACE

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INTRODUCTION

Additive manufacturing (AM) includes several technologies, where parts are fabricated from 3D model data by adding material in a layer by layer manner [1]. Due to the increased freedom of design offered by AM processes, complex and intricate geometries can be manufactured in a near net-shape fashion. However, without significant post-processing, AM technologies have not typically been capable of achieving the design requirements of many function-critical parts, often failing in their ability to attain the desired structural integrity, mechanical properties or geometric accuracy required by the designer, in comparison to the properties expected from a conventionally manufactured counterpart [2,3].

Surface topography investigation is widely recognised as a fundamental tool for improvement of process-related knowledge [4]. Qualitative and quantitative assessment of topographic formations can help to shed light on the physics involved in the surface fabrication process, thus facilitating the identification of how process and material parameters influence the structural, mechanical and geometrical properties of the manufactured part.

This paper focuses on the topography of the surfaces produced using selective laser melting (SLM) of metals; a process which belongs to the powder-bed fusion family of AM technologies (see [1] for details). During the SLM process, several physical interactions take place between the laser, the powder bed and the layers underneath, and it is such interactions that must be fully investigated and understood, in order to improve the SLM process. The typical surface features encountered on an SLM layer, and representative of the manufacturing process fingerprint, are summarised in figure 1. The weld tracks are the most evident features, appearing as ridge-like formations indicating the path followed by the processing laser while traversing the powder bed. Smaller-scale ripples on the weld tracks are formed as a result of the cyclical process of liquefaction and solidification of the melt pool as the laser moves across the surface [5]. Unmelted powder particles typically appear as small, randomly distributed sphere-like protrusions [6]. Larger, similarly sphere-like, formations are usually an indication of spatter, i.e. the ejection of molten droplets from the melt pool, that solidify in mid-air and adhere to the area surrounding the weld track [7]. Surface recesses are indicative of multiple phenomena: localised discontinuities of the weld tracks due to balling effects, incomplete welding between adjacent tracks and micro-scale porosity due to gas entrapment [7].
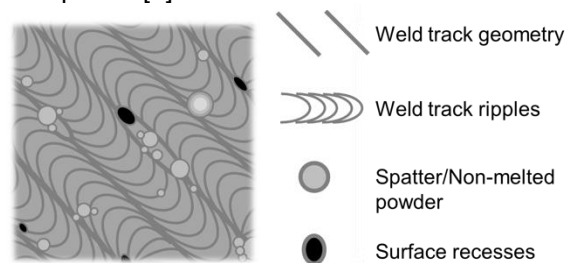

FIGURE 1. Topographic features relevant to investigation of the manufacturing process fingerprint, as they appear on a layer of an SLM metallic part.

All of the above topographic formations present significant measurement and characterisation challenges: high slopes, undercuts and step-like transitions are frequent, as well as significant changes of optical properties within the field of view; for example, because of the presence of highly reflective and opaque regions, and/or more varied and more uniform colour patterns [8]. AM surfaces have freeform geometry, and are a combination of structured surface texture with random features – a veritable horror story for metrology. In this paper, we will summarise our work in trying to establish an infrastructure for measurement and characterisation of SLM surfaces. This study is part of a wider investigation, in which we intend to rigorously examine additive surfaces for the purpose of designing future measurement strategies.

METHODOLOGY

A portion of the top surface of an SLM artefact was selected as representative of the typical features encountered on a metallic surface produced by SLM. The region of interest (ROI) is a square of approximately (2 × 2) mm in size, taken from the top surface of a (20 × 20 × 20) mm cube artefact, manufactured from Ti6Al4V using a Renishaw AM250 SLM machine from a CAD model of a cube with nominally flat faces. The size of the ROI ensures that the field of view (FOV) is adequately representative of the topographical formations expected to be found on the top surface, in order to demonstrate the relevant measurement challenges.

The following commercial instruments, measurement technologies, measurement setups and types of returned datasets were considered. Philips XL30 scanning electron microscopy (SEM): at 61× magnification in secondary electron mode; 2D intensity image. Keyence VHX-5000 digital optical microscopy (DOM): ; 100× to 1000× variable objective at 200× (FOV 3.05 mm × 2.28 mm) with focus stacking (FS); 2D colour map. Alicona InfiniteFocus G5 focus variation microscopy (FVM): 20× objective lens (NA 0.40, FOV 0.81 mm × 0.81 mm, lateral resolution 3 µm) with FS, stitching of multiple images performed in the Alicona software; height map and colour map. Olympus LEXT OLS4100 confocal microscopy (CM): 20× objective lens (NA 0.6, FOV 0.64 mm × 0.64 mm), stitching of multiple images performed in the Olympus software; height map. Zygo NewView 8300 coherence scanning interferometry (CSI): 20× objective at 1× zoom (NA 0.40, FOV 0.42 mm × 0.42 mm), stitching of multiple images performed in the Zygo software; height map. Nikon MCT 225 X-ray computed tomography (XCT) [9]: geometric magnification of 44.1×, voxel size of 4.53 µm, 3142 X-ray projections with two frames per projection, tube voltage of 145 kV and current of 66 µA, 0.25 mm copper pre-filter; triangulated mesh. Data were reconstructed in the Nikon CT-Pro software, using a second order beam hardening correction. Surfaces were determined in VGStudio MAX 2.2 [10], using the maximum gradient method [11].

Colour maps, height maps and triangulated meshes were examined as acquired by the various measurement technologies. Colour maps are calibrated images where pixels are mapped to (x,y) coordinates. Height maps are maps whose pixels contain height information. Height maps are intrinsically limited to 2.5D data (i.e. no undercuts or vertical surfaces), while triangulated meshes are not (i.e. they are "full 3D" geometric models). Currently, however, triangulated meshes must be resampled into height maps in order for texture parameters (such as those defined by ISO 25178-2 [12]) to be computed. The investigation focused specifically on how challenging topographic formations are processed by the various measurement solutions, analysing in particular the features discussed above that typically make SLM surfaces problematic to measure.

The raw data were analysed in the surface metrology software MountainsMap by DigitalSurf [13]. Areal topographies were levelled by least-squares mean plane subtraction using a common reference region, and truncated to homogenise colour scales in height maps. Datasets were manually aligned via visual inspection of topographic formations, and small areas were extracted for feature comparison.

RESULTS

Investigation of optical images (see figure 2) highlights the difficulties experienced when utilising reflected light in measurements. While amplifying smaller-scale features, (e.g. weld track ripples), using reflected light can lead to bright, highly saturated regions corresponding to the most exposed parts of the topography, strongly contrasted with the darker, deep recesses. This is a typical issue with optical imaging and measurement of SLM surfaces: higher intensity incident light is needed to illuminate recesses, but increases the chances of saturation in more reflective regions, with the consequent loss of topographic detail. This issue is in stark contrast to the output of SEM imaging, where it is generally easier to obtain clearer images overall.

Both optical and SEM images are characterised by artefacts specific to each measurement technology, which the expert eye must recognise when visually inspecting the result. Multiple reflections, projected shadows and optical chromatic/geometric aberrations are common for optical imaging; while charging artefacts, smears and bright and dark halos are typical of SEM imaging [14]. For optical imaging, a surface can look considerably different if imaged through coaxial or ring light, polarised or non-polarised light, monochromatic or polychromatic light, and if processed with different detector settings (saturation, contrast, etc.). Analogously, SEM

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imaging is affected by multiple parameters, such as electron beam energy and detector sensitivity.

Investigation of close-up views of height maps and images obtained via different measurement solutions (see figure 3), highlights some of the features which are most challenging to measure for each measurement solution. The large recess in the bottom left quadrant is particularly interesting, as the returned information varies substantially between measurements. The protruded singularities are also of interest, as they result in a range of different measurement artefacts depending on the technology used to acquire the specific dataset. Figure 3b and figure 3e highlight the presence of an exogenous particle removed during stylus measurement also performed on this sample as part of a wider study (data shown in figure 3a, figure 3c, figure 3d and figure 3f were taken after the stylus measurement). Figure 3a also highlights the presence of the scratch left by the stylus, which is barely perceptible in the CSI data (figure 3d).
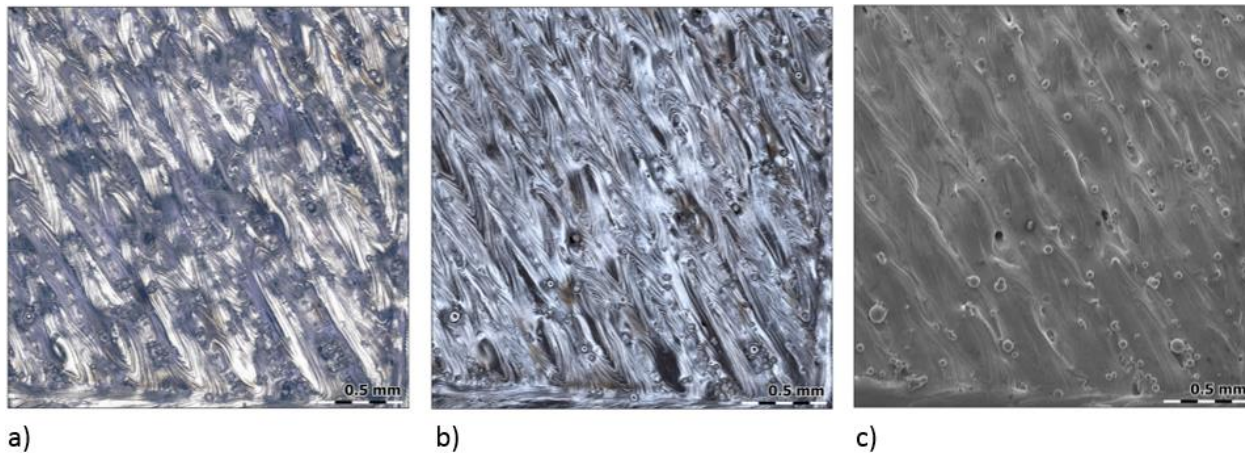

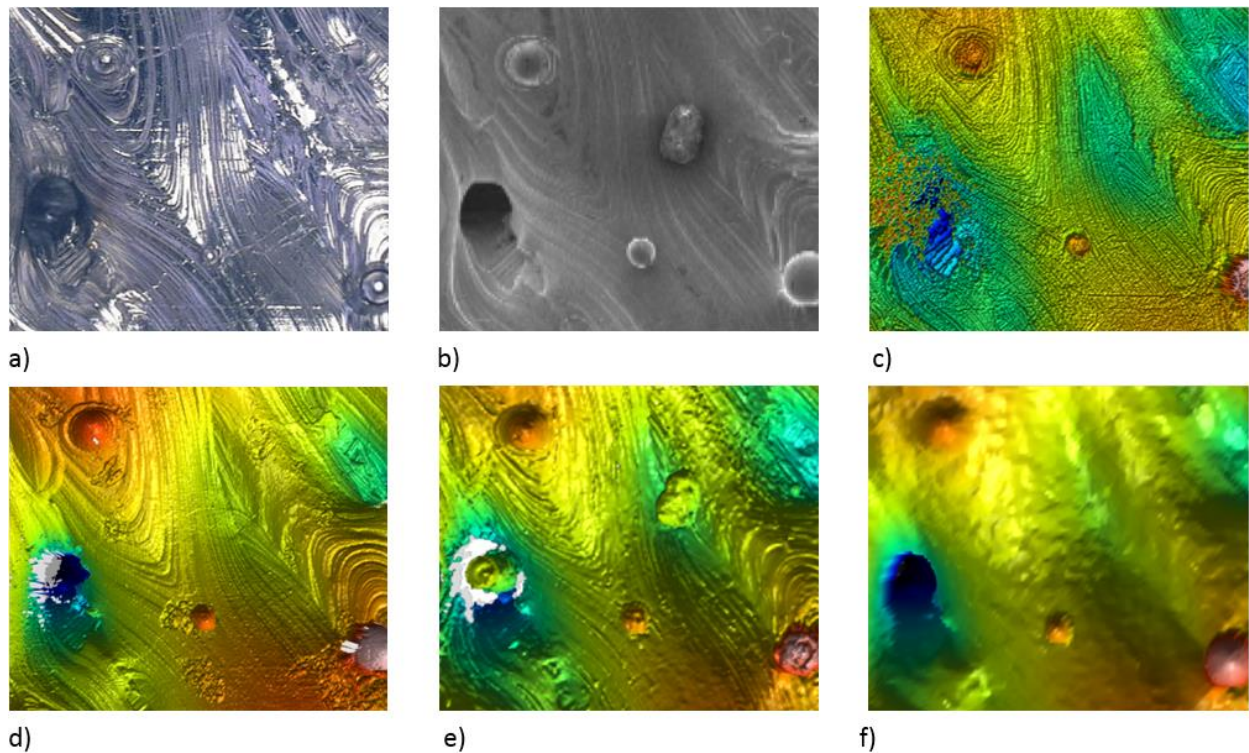*FIGURE 2. Colour and intensity maps: a) DOM; b) FVM; c) SEM.*

FIGURE 3. Topography details (field of view approximately 0.3 mm × 0.3 mm) captured with different measurement solutions; a) DOM; b) SEM; c) CM; d) CSI; e) FVM; f) XCT.

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DISCUSSION AND CONCLUSIONS

Some interesting considerations can be drawn from the available data. Firstly, when an opinion needs to be reached about the topography of a SLM surface, it is intrinsically unadvisable to rely on any measurement result taken individually. Experimental findings demonstrate that no single measurement technology or setup is optimal for the measurement of all notable features that need investigation. Secondly, no measurement technology or setup amongst those compared can be considered "higher class" than the others and thus act as reference; in other words, there is no "truth" to rely upon. Incorporation of traceable stylus measurement may be able to provide this reference, but alignment of stylus profiles to 2.5D height maps is non-trivial.

The work presented in this paper highlights the main challenges in measurement of metal additive surfaces, through visual comparison of measurements made using a variety of technologies. It is clear from the measurements made during this initial phase that the features present on these surfaces are represented in substantially different ways by each instrument, and, therefore, that individual measurements may not always be able to provide the information required. Substantial further work is, therefore, required in quantification of these differences, as well as in extension to a wider array of metal and polymer AM surfaces.

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