TOWARDS AN ADDITIVE SURFACE ATLAS

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INTRODUCTION

There is little doubt that additive manufacturing (AM) will have a profound effect in many industries, and there are countless examples of polymer products. But, if AM is to be used in earnest in high-value, advanced manufacturing, for example, in the aerospace or medical industries, then it will be metals and ceramics that will be the game-changers. However, right now, the integrity of metal or ceramic parts essentially made with powder bed fusion AM processes, is not equivalent to that expected from more conventional manufacturing techniques (casting, forming, machining). AM parts made from metal powders tend to have high surface roughness values and can suffer from undesired material characteristics (e.g., high porosity or large numbers of defects). Also, where one would not dream of manufacturing a part with subtractive techniques without a dimensional tolerance scheme, it is still not clear exactly how to apply tolerance principles to AM parts [1]. AM does not currently have the benefit of the over one hundred years of research into the production of components that is the hallmark of precision subtractive techniques [2].

From the metrology standpoint, AM should be no different to conventional manufacturing. In fact, we would argue, that a lack of metrology in current AM machines and processes is hindering the commercialisation of the resulting products. Whilst the form of an AM object is critical, it is often the surface texture that has the biggest impact on the object's functionality. Surface texture is the fine-scale geometry and is often the limiting factor when considering the tolerance of an AM part. Whereas surface texture height structures can be produced on the nanometre scale using precision subtractive technologies, due to the nature of powder-based AM techniques, surface texture height structures of tens of micrometres are more normal [3, 4]. This throws up a number of metrology questions, some of which include:
(i) Can we use conventional surface texture instruments to measure AM surfaces – high slope angles and undercuts, resulting in multiple reflections and shadowing, causing problems for optical instruments? (ii) Can we use conventional filtering methods and texture parameters with AM surfaces? (iii) Can we examine the surface texture of an AM part to elucidate how the surface was manufactured – AM processes involve some highly complex physics, so this involves a significant amount of experimental and theoretical research? (iv) How can we measure surface texture in-line?

Before answering these questions, it is necessary to understand what is actually present at the surface of an AM part. To this end, we are embarking on a comprehensive measurement and analysis campaign that will result in an atlas of AM surfaces at many different scales of observation. For this campaign, we are using a host of instrument types: contact, optical and scanning electron microscopy (SEM). This paper will present some preliminary results from this campaign – the work is in progress, but some conclusions can already be drawn.

METHODOLOGY

In order to begin building the atlas, a Ti6Al4V, cube-shaped test artefact of size (20×20×20) mm was generated using selective laser melting (SLM) [5]. Measurements were performed on a single portion of the top surface (i.e. the last layer deposited in the AM process). The cube was produced with a Renishaw AM250 SLM machine, using processing parameters for Ti6Al4V as provided by the machine manufacturer. It should be noted that due to the nature of the SLM process, significantly different topographies are typically observed on the top, side and bottom surfaces [3]. The top surface was chosen for this initial study as the most representative of the physical phenomena involved in layer generation [3], but work is in progress to also characterise the side and bottom surfaces. The portion of the surface chosen for measurement (region of interest – ROI) was approximately a (2×2) mm corner region; the corner was chosen so that visible edges could be used to align multiple measurements for comparison purposes. The chosen ROI was visually inspected to ensure

that it was representative of the surface as a whole.

The following technologies and instruments were used to acquire topography data:
- FV: focus variation (Alicona Infinite Focus G5), with multiple objectives and lighting conditions;
-FS: focus stacking (Keyence VHX-5000) with 100× to 1000× objective and coaxial lighting;
-CSI: coherence scanning interferometry (Bruker Contour GT) with multiple objectives.

Note that FV and CSI are supported by ISO specification standards ([6] and [7] respectively), while FS is a term used in this work to refer to a different implementation of the same focus-finding principle as FV, i.e. identification of in-focus points by contrast detection on images. Given the significant importance of software processing in these technologies, differences between implementations can be dramatic.

In addition, conventional optical microscopy (Nikon Eclipse LV100, using 5×, 10×, 20×, 50× and 100× objectives with coaxial light) and SEM (Philips XL30, at 61× magnification, in secondary electron mode) was used to acquire orthophotos of the ROI.

Details on the measurement set-ups
Focus-based technologies (FV and FS) are highly dependent on surface appearance to identify conditions of maximum local contrast, essential to determine the distance of each measured point from the focal plane. Focus-based technologies are, therefore, significantly influenced by lighting conditions [8]. For FV, multiple lighting conditions were investigated, consisting of combinations of coaxial, polarised and ring light with different intensities. With FS, it was only possible to test coaxial light, albeit at different intensities. The following objective lenses were used with FV: 5× (NA 0.15, FoV 2.82 mm × 2.82 mm, lateral resolution 7 μm), 10× (NA 0.30, FoV 1.62 mm × 1.62 mm, LR 4 μm), 20× (NA 0.40, FoV 0.81 mm × 0.81 mm, LR 3 μm) and 50× (NA 0.60, FoV 0.32 mm × 0.32 mm, LR 1.5 μm), where LR is lateral resolution. Topography datasets were acquired using a single field of view at 5×, and multiple, stitched fields of view at 10×, 20× and 50× (stitching done in the Alicona software). Two additional magnifications, 2.5× and 100×, were considered, but ultimately discarded; the former being too low to capture relevant topographic details, the latter being too time consuming to achieve equivalent lateral coverage, and resulting in too large datasets. Due to limited availability, only the 100× to 1000× variable objective at 200× was used with FS (FoV 3.05 mm × 2.28 mm); coaxial lighting was manually tuned to achieve the best possible result by visual inspection. When using FV and FS both topography data (height maps) and colour data (colour maps) of the ROI were obtained.

CSI measurements were taken using 2.5× (NA 0.07, FoV 2.5 mm × 1.9 mm) , 5× (NA 0.12, FoV 1.3 mm × 1.0 mm) and 20× (NA 0.4, FoV 0.3 mm × 0.2 mm) objective lenses; initially considering only a single FoV. The intention was to verify the actual feasibility of acquiring rough topography with CSI technology, before attempting to cover larger portions of the surface. From CSI measurements, only topography data (height maps) were obtained.

SEM and optical images were taken with the purpose of achieving a comprehensive visual investigation of the topography. For optical imaging, lighting conditions were set to achieve the best possible visual result; however, due to poor depth of field at higher magnifications, optical images were discarded in favour of the higher quality output of the focus-stacked images from both the FV and the FS microscopes.

The raw datasets acquired from each instrument were analysed in the topography analysis software DigitalSurf MountainsMap. The datasets were levelled by least-squares mean plane subtraction. Alignment of areal topography data from FV and FS measurements was performed by using dedicated functions in the software and manual refinement via visual inspection. Topographic formations at the cube edges and other visible landmarks were used to perform alignment. CSI datasets were not aligned given their low quality, owing to an excess of measurement artefacts and non-measured points. SEM image data was also overlaid to the areal topography datasets, by means of manually aligning visually identified landmark correspondences, within the software.

The purpose of the alignment procedure was to investigate how each notable topographic feature located within the ROI would be captured if measured with different technologies and measurement set-ups. At this stage of the

research, the investigation was purely qualitative and based on visual comparison of the results, rather than on the computation of some texture parameter or other quantitative descriptor. The following notable topographic features were targeted, as summarised in Figure 1. *Weld tracks*: directly resulting from the interaction of the laser with the powder bed, along the traversal path, during layer generation; *weld track ripples:* higher-frequency, semi-periodic features appearing on the weld track, as a result of the melt pool formation process; *balling and spatter*: localised, protruding features, sometimes similar to spheres, classifiable either as balling or as spatter depending on size and conformation of surroundings; *pores*: small recesses, sometimes showing portions of the layer underneath, typically due to incomplete welds [9-11]. These notable topographic formations carry significant measurement challenges: high slopes, undercuts and step-like transitions are often featured, as well as significant changes of optical properties within the field of view, e.g. alternation of highly reflective and opaque regions, alternation of more varied and more uniform colour patterns.
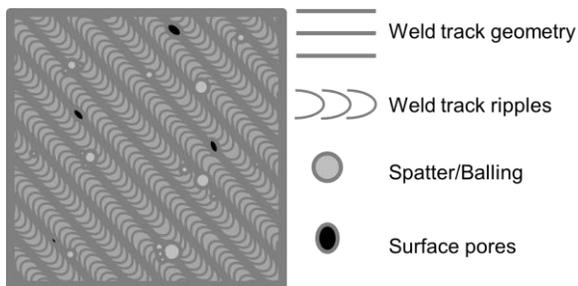

Figure 1. Schematic diagram displaying a top view of features found on a typical SLM top surface.

Within the MountainsMap software, visual comparisons were performed on the *xy* (image) plane, i.e. by observing the aligned topographies from above, but also on cross-sections, i.e. by looking at aligned topography slices from the side. In cross-section view, only height data was investigated; however, on the image plane, both height maps and colour maps were investigated.

RESULTS
Visual inspection of colour maps
Colour maps are a powerful tool for gathering qualitative information about surface appearance and the shape and layout of its most relevant features. For optical instruments, the downside is that surface appearance is evidently related to a combination of the optical properties of the surface and the type of incident illumination. The same surface can look considerably different if imaged through coaxial light, polarised light and/or ring light, colour wavelength plays also a relevant role. Analogously, different set-ups at the image detector will determine the amount of saturation, contrast, etc., which can make colour maps appear different. Similar considerations apply to non-optical imaging, more specifically to SEM, in this case pertaining to electron beam energy and sensitivity parameters at the detector. In Figure 2, the ROI is shown as it appears in the colour maps generated from FV, FS and SEM (in grayscale) measurements. Differences between FV and FS should be attributed mostly to different illumination conditions and optics, and not to the measurement technology (FS vs. FV). At first glance, it is evident how light plays a fundamental role in highlighting the higher frequency details in the FS and FV images (e.g. weld track ripples); saturation and reflection effects are greatly reduced on the SEM image.
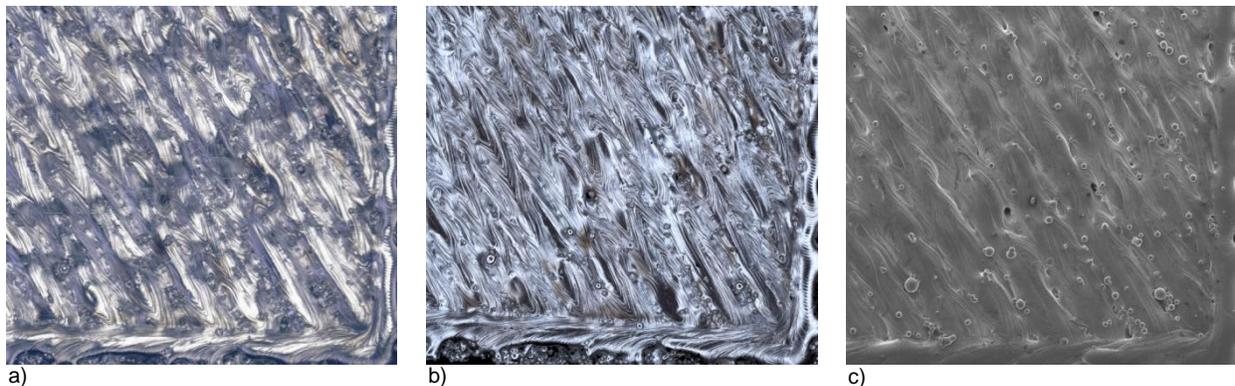

a)   b)   c)

Figure 2. Colour maps (2 mm × 2 mm): a) FS 500× magnification, coaxial light, multiple stitched fields of view; b) FV 20× magnification, ring light, multiple stitched fields of view; c) SEM, 61× magnification.

Visual inspection of height maps

Concerning height maps, the first notable result is the poor quality of CSI data. Figure 3 refers to one of the most successful measurements, obtained with 20× magnification, highlighting how the technology is capable of capturing some high frequency components (weld track ripples) but fundamentally fails at capturing most of the highly irregular topographic features (e.g. weld tracks). Further investigation of CSI capability to acquire SLM topographies is needed, but it is suspected that the high slope angles are causing significant image artefacts [12]. Amongst focus-based technologies, FS showed poorer performance than FV, consistent with the different nature and purpose of the Alicona and Keyence microscopes. The importance of lighting conditions in determining FV performance at a given magnification is highlighted in Figure 4 (and discussed in detail in [8]). Ring light appears to provide the better conditions for reconstructing the topography (e.g. less visible noise, clearer depiction of localised features), presumably due to ring light better supporting FV with contrast detection.

As with most optical technologies, in FV an increase in magnification allows the capture of finer detail (higher frequency features). In Figure 5 it can be seen how the weld track ripples become increasingly more visible at higher magnifications. Somewhat less evident is higher magnification being better capable of capturing more difficult regions (e.g. higher slopes). The price to pay with higher magnification is an increase of measuring time and difficulty, as stitching is increasingly needed to cover the same area. Quantitative analyses should be used to determine to what extent stitching may

alter topographic content. On the other hand, the cross-section profiles in Figure 6 show that in FV, magnification can be kept low, while still capturing many of the salient traits at lower frequency (e.g. profile of the weld tracks).

Figure 3. Height map obtained with CSI, 20× magnification (0.24 mm × 0.3 mm).

Reconstruction of localised features

Finally, it is interesting to see how fidelity in reconstructing localised topographic features is altered with measurement technology, magnification and set-up. In Figure 7, small formations due to balling/spatter are visible, together with a small number of pores. The same protruded features may appear more or less round, larger or smaller, symmetric or asymmetric depending on measurement technology; and the pore may be misinterpreted as a protruded feature with some technologies [12]. These results suggest that caution should be advised when visually inspecting topography measurement results.

DISCUSSION

The current results already provide a preliminary idea of the topography of an SLM surface when
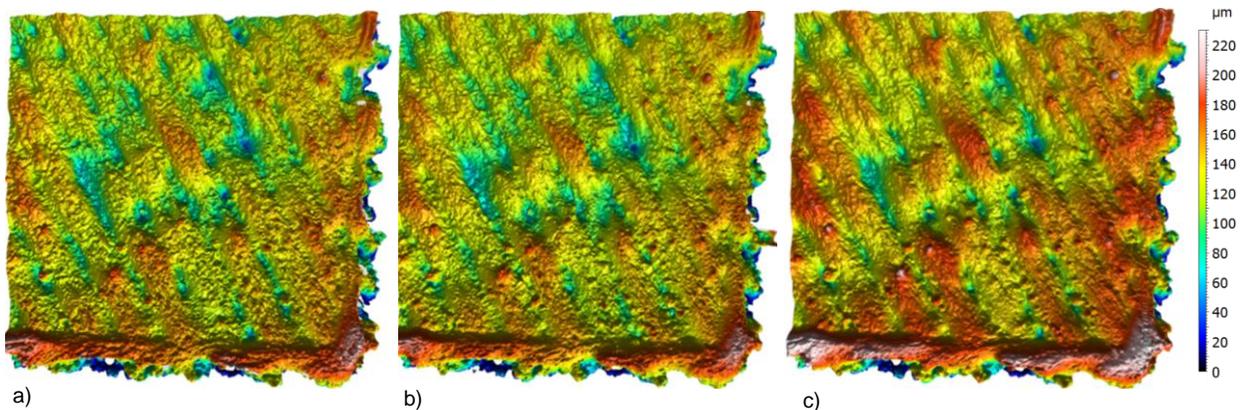

Figure 4. Height maps from FV (2 mm × 2 mm); a) 5× magnification, coaxial light; b) 5× magnification, polarised coaxial light; c) 5× magnification, ring light.
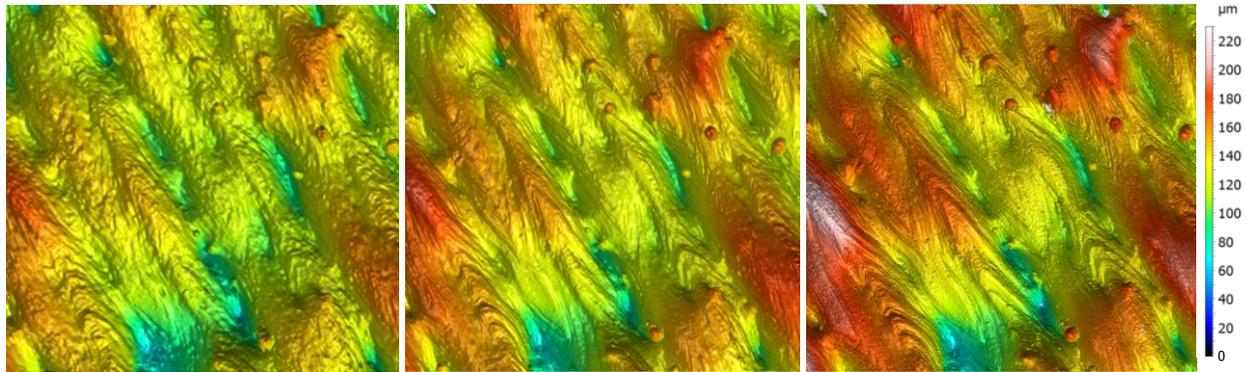
Figure 5. Height maps from FV (0.8 mm × 0.8 mm); a) 10× magnification, ring light; b) 20× magnification, ring light; b) 50× magnification, ring light
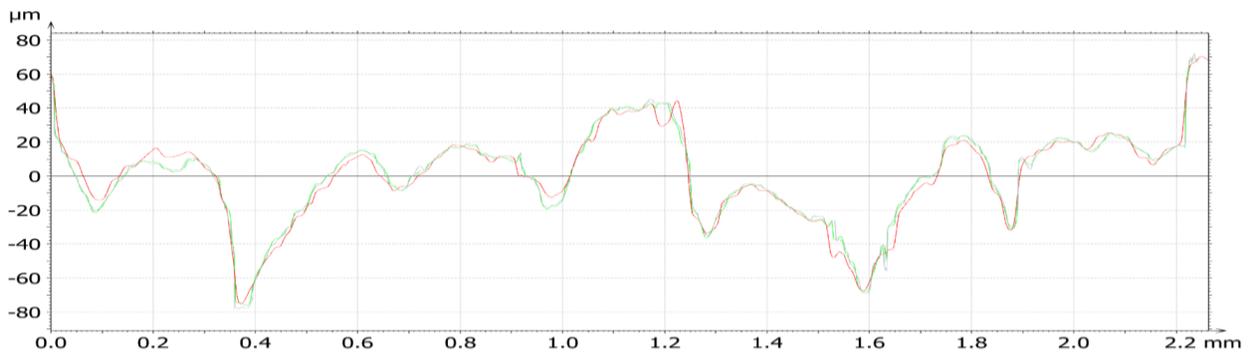

Figure 6. Aligned cross section profiles from FV data: red - 5× magnification, ring light; green - 10× magnification, ring light; blue - 20× magnification, ring light
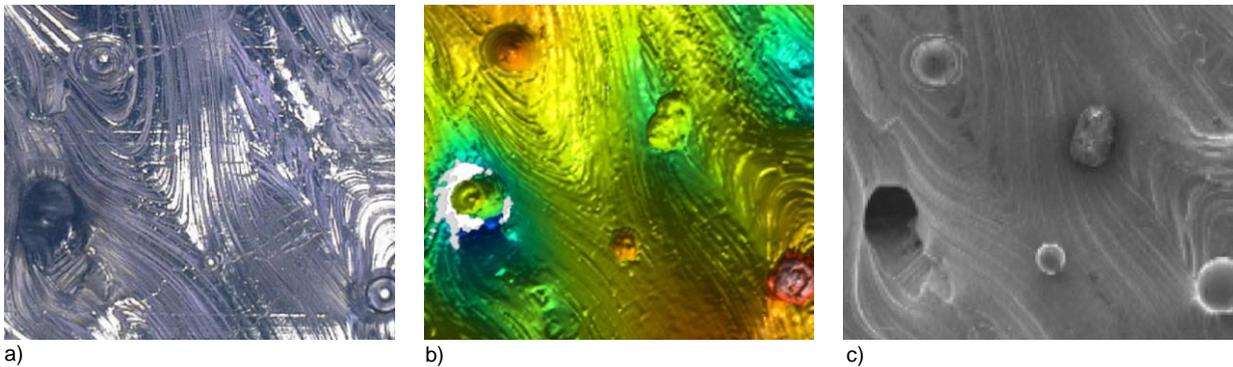

Figure 7. Details of height maps and colour maps (0.3 mm × 0.3 mm) showing localised features (spatter, balling, pores) a) FS 500x magnification, coaxial light; b) FV 50x, ring light and c) SEM 61x magnification.

measured with some of the most common, mainstream technologies. However, the measurement campaign is still in progress, with plans to include atomic force microscopy (for observing at smaller scales), confocal and point-autofocus microscopy, and X-ray computed tomography (to overcome limitations with high slopes and undercuts). A more complete investigation should not only include more measurement technologies, but also a more quantitative and robust way to compare results: research is in progress to optimise the dataset alignment process and to quantify local and global topographic differences in multi-sensor scenarios. This includes, e.g., bandwidth matching, i.e. the process of identifying the correct ranges of spatial frequencies shared by multiple measurement technologies [13]. In addition, a proper quantitative comparison implies the execution of measurement repetitions, and the statistical treatment of results, as well as the incorporation of measurement and manufacturing process uncertainties.

Despite the above considerations, a few interesting conclusions can be drawn from the available data: a) 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 technology/set-up is optimal in respect to the notable features that need investigation; 2) no measurement technology/set-up 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 at this stage; c) consistent output of multiple technologies and at multiple scales, i.e. agreement across technologies/set-ups in regards to a specific feature/topography detail, is likely a sound starting point for establishing feature-specific references, at least until a more theoretically sound validation, or a higher accuracy instrument, is available.

CONCLUSIONS AND FUTURE WORK

Some of the most popular mainstream measurement technologies were used to measure a region of interest on the top surface of a Ti6Al4V cube fabricated by SLM. Notable topographic formations were identified and their digital reconstructions in the different measurement configurations were compared via visual inspection. Qualitative results allow the identification of some key aspects in regards to agreement and disagreement of measurement results, as well as advantages and weaknesses specific to each measurement technology and configuration. Additional research work is needed to complete the experimental campaign by adding more measurement technologies, and to provide a more theoretically sound and quantitative approach to the comparison. Future work includes also the extension to different types of surfaces, materials and AM processes.

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