CORRELATING VOLUME AND SURFACE FEATURES IN ADDITIVELY MANUFACTURED METAL PARTS

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INTRODUCTION

Additive manufacture (AM) is starting to become viable as an option for the production of high value parts that were not previously feasible because of spatial restrictions in machining operations. Metal AM, particularly, presents an attractive method of manufacture for parts in the biomedical and aerospace industries. However, notable barriers exist towards the adoption of AM technologies in industry, the most significant of which relates to requirements for further understanding of AM processes [1].

It is well accepted that measurement and analysis of manufactured surfaces can be used to develop an understanding of processes [2,3]. Surface topography measurement has been used extensively for this purpose in metal AM [4], but the majority of recent work solely involves examination of ISO 25178-2 [5] surface parameters. While these (and other) parameters are often vital in part verification, there exists a tendency to rely upon them for surface analysis and pay less attention to the specific features present on surfaces, which can in many cases contribute towards developing a deep understanding of a process. In recent work by the authors [6–8], we presented investigations of metal AM surface features, and novel methods of characterising these features. In this work, we discussed how such features can be considered a ‘process fingerprint’, telling a story about the physical interactions occurring during the manufacturing process.

Metal AM parts are known to suffer from porosity, resulting from various physical phenomena occurring during processing [9]. In previous work by the authors [10], an analysis was performed of the influence of melt strategy on porosity in electron beam powder bed fusion (EBPBF) parts, by using X-ray computed tomography (XCT). In this work, correlation was found between porosity and process conditions, potentially facilitating the reduction, or even elimination, of such porosity in future part production.

Porosity analysis using XCT is of great value in an academic setting and provides significant insight for researchers working on process development. For the industrialist, however, measurement of parts by XCT is expensive and slow [11]. If it is possible to correlate internal features (such as porosity) to external features (such as those present on a surface), it may be possible to infer information about a part volume from the process fingerprint remaining on the part surface. To this end, we present initial attempts to correlate internal porosity to surface features.

METHODOLOGY

In this work, we perform coherence scanning interferometry [12] measurements of surface features, present on a variety of (10.6 × 10.6 × 25.0) mm Ti6Al4V samples produced by EBPBF with varying process parameters (summarised in Table 1, and described in more detail elsewhere [10]). Specifically, we examine the geometry of individual weld tracks on the surfaces of samples [7,8], examining variation in weld track width along track length using a preliminary customised measurement pipeline. A description of this preliminary pipeline is presented in figure 1.

The methodology used progressed as follows. Measurements of the final weld track produced during manufacture of individual samples (the only weld track not partially covered by neighbouring weld tracks) were made using a Zygo Newview 8300 coherence scanning interferometer (CSI) [13] equipped with a 20× magnification objective (numerical aperture 0.4). The measurement was performed with optimised source and detection settings (as discussed in [12]). The measured region (approximately 9.5 mm × 1.5 mm) was obtained by stitching of individual height images, and was equivalent to an area slightly larger than the weld tracks of interest. The pixel size used was 0.41 µm and the Sparrow optical resolution was 0.68 µm. Stitching was performed in Zygo's proprietary software.

TABLE 1: Samples examined in this study. Full details available in ref. [10].

Sample designation	Modification
C0	None (control: speed function 36 & line offset 0.2 mm)
C7	Turning function disabled
S1	Speed function 28
S2	Speed function 20
S3	Speed function 12
L2	Line offset 0.1 mm

The raw data were processed using MountainsMap by DigitalSurf [14]. A levelling operation was initially performed on datasets in the form of a least-squares mean plane subtraction. Data were then filtered using a Gaussian convolution filter with a 0.8 mm cut-off, equivalent to the approximate width of a weld track. Following this operation, an ISO 25178-2 [5] morphologic segmentation was performed on the data, using 1 % of the *Sz* value (Wolf pruning) and 0.1 % of the total area (area pruning). Segments surrounding the weld tracks were manually removed from the data in order to separate the weld track of interest from the surrounding surface. The remaining segments were then used as masks and applied to the levelled raw data, resulting in height maps of individual weld tracks. Weld track widths were then manually measured along the length of the tracks, at approximately forty regularly spaced intervals. Width data for six samples were acquired and plotted against the position along the axis of the weld track.

Average weld track widths were then calculated and plotted against porosity for the examined samples (previously reported in [10]), acquired using a custom Nikon 225/320 kV XCT system.

RESULTS AND DISCUSSION

Quantification of the weld track widths with position revealed decreasing width along the examined weld track (see figure 2). This effect was true for all of the samples examined along a length of approximately 9 mm, indicating that melt pool conditions were not constant during the fabrication of the last weld track. This finding may imply that conditions were not constant also during the fabrication of the entire sample (to be verified in future investigations). Such non-uniformity could be inferred from previously published results regarding a non-homogenous distribution of porosity within similar samples [10], but this result confirms the hypothesis by direct measurement of the weld track width. Further investigation of this phenomenon may allow for on-the-fly tuning of process parameters to increase process stability and reduce the creation

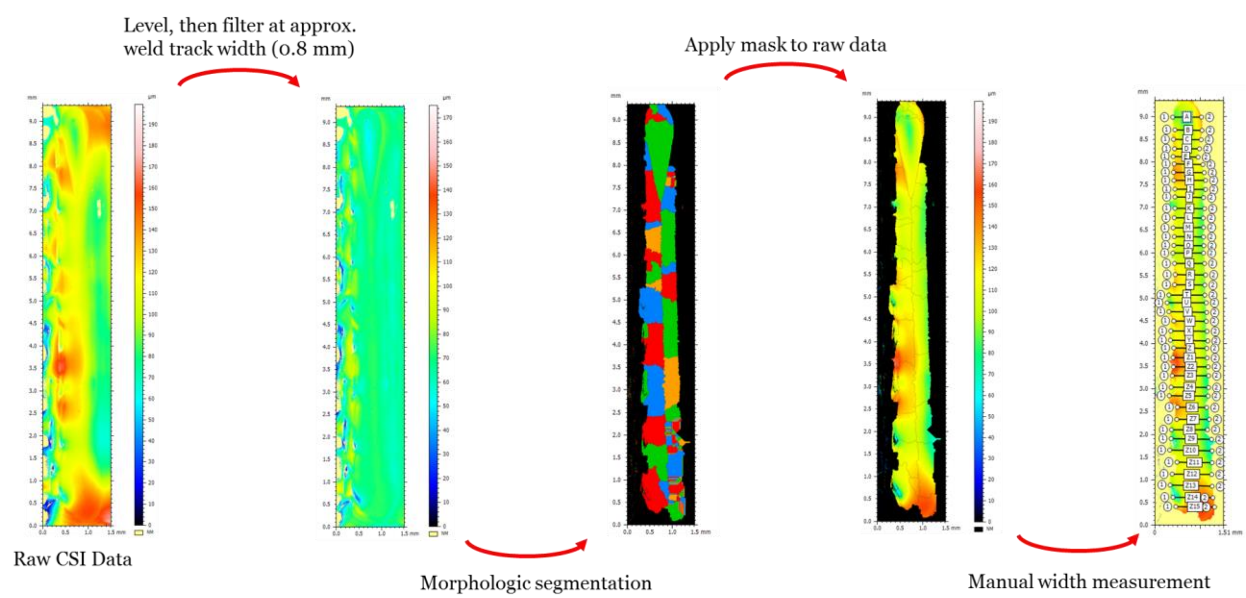

FIGURE 1. Weld track width measurement procedure.

of defects during the build. The caveat to this finding is that, while it is likely to be the case, there is currently no proof that weld track width correlates to melt pool depth (shown previously to have an effect on porosity formation [15]) and so further investigation is required to verify that this is the case. However, assuming a consistent beam spot size (as was the case in these conditions) it is not unreasonable to assume a positive relationship between weld track width and depth, and thus we can make inferences about the relative melt depths of different conditions, even if the absolute values remain hidden.

In previous work [10], analysis of the porosity present in these samples showed a repeatable, non-uniform, distribution of defects along weld tracks, which Tammas-Williams et al. suggested was a result of weld tracks increasing in width along their length. At the time, information about the local weld track size was not available. When weld track measurement results are considered, the converse appears to be true, with weld tracks decreasing in width along their lengths (figure 2); a new interpretation of the pore distribution is therefore required. From the data, it is likely that pores appear most commonly at the end of weld tracks, as opposed to at the beginning (as previously suggested in [10]), though further investigation is required to successfully explain why this is the case. It should be remembered that the vast majority of pores detected in these samples had an appearance suggesting they were caused by gas bubbles trapped in the melt [10]. It is apparent that the change in melt pool size is accompanied by a change in the probability of cavities forming in the build, including those caused by gas bubbles remaining trapped in the melt following solidification. With further investigation it may be possible to predict local porosity populations within parts.

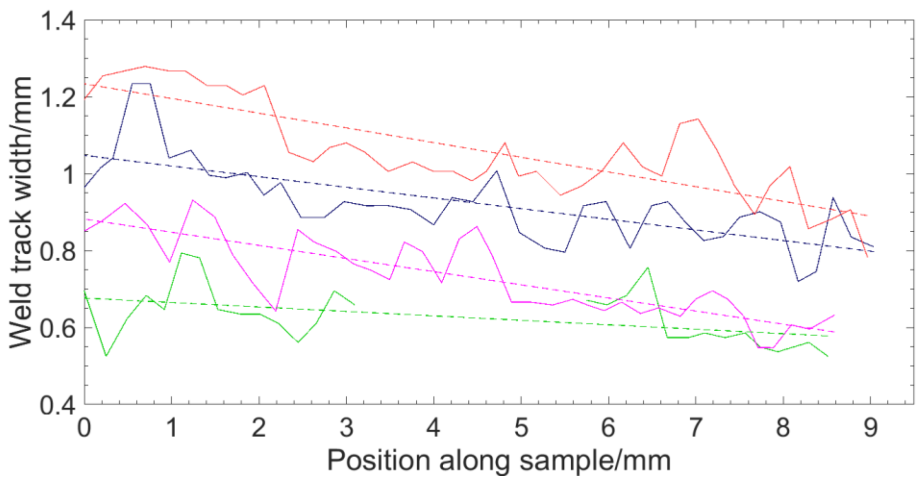

FIGURE 2. Weld track width along track length for 4 samples of varying speed (C0, S1-S3 in ref. [10]*)*

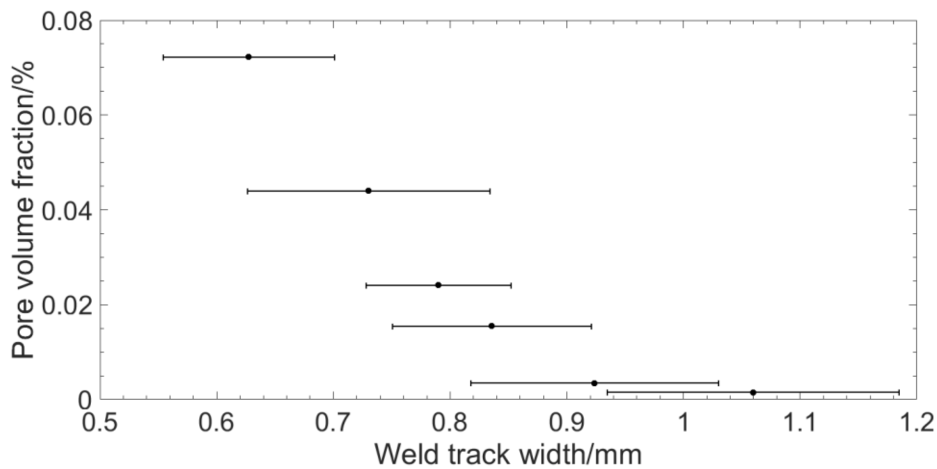

FIGURE 3. Correlation between pore volume and track width. Error bars are standard deviations.

While a quantitative correlation between local weld track width and pore population is yet to be defined, the overall global relationship is already apparent from the limited results presented here (figure 3). It is noteworthy and encouraging for future directions of this work that all the measured data appeared to fit on the same trend line, despite samples being made with a number of modifications. In addition to a range of overall energy densities and line energies being used, changes were made to the hatch offset, and samples were manufactured using both constant and variable beam speeds. Moreover, when the pore population is plotted against line energy, while a trend can be observed, the scatter is significantly increased (figure 4). Thus, using line energy alone is unsuitable for predicting the pore population, whereas the weld track width method (as used here), with further investigation, may prove to be more robust. This finding implies that it may be possible to use surface measurement to infer local and global porosity populations within components. This is a potentially interesting finding as, if confidence can be established in the technique, the technique may alleviate the requirement for XCT scanning in some industrial cases. XCT is well known to be costly in terms of monetary value and in time [11], and so the technique reported here potentially represents a significant saving in a number of industrial settings.

A note should be made about the validity of the width measurement technique. Specifically, it is the case that this initial research is based upon manual measurements of weld track width on the surfaces of electron beam melted samples, and is currently hindered by the requirement for human operation in weld track width measurements. In an ideal scenario, the method of weld track width measurement would be entirely algorithmic and have no reliance on human operator choices (such as that presented in [7]). Development of such an algorithmic method is planned for the future.

CONCLUSIONS AND FUTURE WORK

There is a link between weld track width and part porosity, with wider weld tracks resulting in lower porosity. Variation in width along weld tracks also has previously been shown to have an influence on the position of pores within parts [10]. The reasons behind observed track width variations in parts are to be explored, but application of acquired knowledge about width variations may allow for pore reduction in future part production, by deliberately varying parameters in-process to influence track width.

A number of avenues of future research have been identified during this work. In future research, we aim to elaborate upon these initial findings by developing a stable measurement pipeline to algorithmically determine weld track geometry in a repeatable manner (similar to that presented in [8]), and to apply this pipeline to a series of samples, both electron beam melted and laser melted. These samples will be representative of varying degrees of ‘reality’, i.e. as built samples, weld tracks deposited on existing metal AM surfaces and single weld tracks deposited on base plates. With these new techniques, we hope also to answer the questions raised by this research, examining why pores appear at the end of weld tracks. Correlation of the experimental findings with

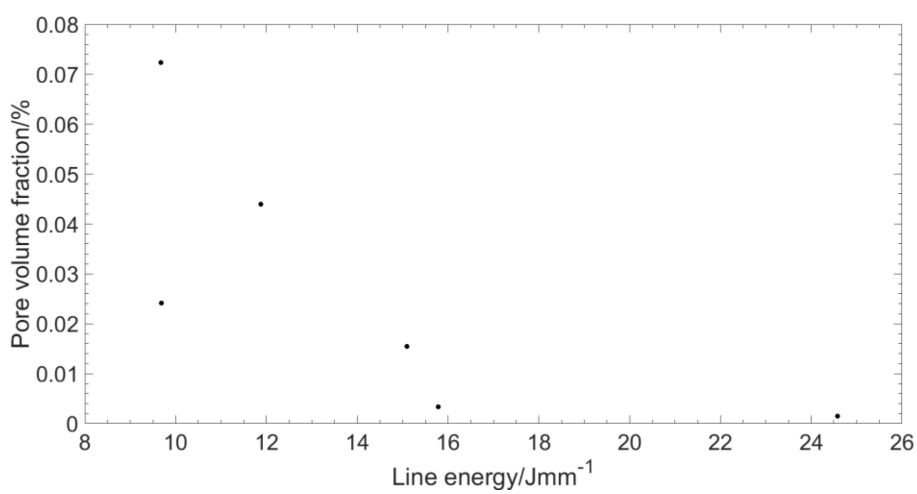

FIGURE 4. Correlation between pore volume and line energy.

theoretical models will also be sought.

Measurement of weld tracks in a repeatable manner will allow for the acquisition of a deep understanding of weld track geometry, and through correlation to porosity data acquired using XCT measurement, could allow for the detection and prevention of subsurface defects during processing.

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