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Multi-physics data registration for the improvement of Additive Manufacturing process control

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Abstract

The work presented in this paper is to tend towards a goal of developing a methodology and associated software module to establish cross-correlation between real time process monitoring data and characterization data. To implement this methodology, a number of steel specimen were built following a design of experiment approach. During the manufacturing, all monitoring data was recorded in log files with a precise timestamp, the data collected being then temporal signals. Subsequently, these parts were inspected by high resolution X-ray tomography, and the defects present in the part were characterized, resulting in 3D volumetric dataset. The software module developed on CIVA platform then enables the registration of these multi-physics data.

KEYWORDS: Additive Manufacturing; process monitoring; WAAM; X-ray CT

1. Introduction

Production of metal parts by Additive Manufacturing (AM) techniques can inherently, due to the processes complexity, generate defects, which are usually only detected after fabrication, using offline Non-Destructive Testing (NDT). However, AM techniques offer new perspectives of defect detection thanks to the monitoring of manufacturing parameters throughout the process. Indeed, in the particular case of WAAM technique, which is also known as Directed Energy Deposition-arc (DED-arc), there are several process aspects, such as part design, feedstock material, process parametrization and process planning, with the geometry, laser power, scanning speed and material flow rate which could be attributed to the appearance of defects. Furthermore, temporal history in terms of heating and cooling rates has a significant influence on part properties and potential defects such as cracks [1-4]. The combined interpretation of these data sets and cross-correlation with characterization data could eventually allow to anticipate the

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appearance of defects, and to undertake corrective actions. Nevertheless, it is also important to have a holistic approach for the characterization of the parts. Over the years, X-ray computed tomography has established itself as the main tool for the characterization of AM parts non-destructively [4, 5].

A new module was developed within the CIVA software framework. The preliminary results obtained show therefore that it is possible to establish links between certain types of defects and singular monitoring data, such as a clear link between voltage peaks and the occurrence of pores.

2. Experimental work

2.1 Manufacturing

MX3D's engineers designed a manifold that incorporates four different types of corners (each one with a different rounding factor in relation to the weld bead width) to explore potential correlation between layer thickness and deposition on sharp corners. Moreover, the new shape has a branching feature in the centre to allow the analysis of the merging area between two walls. The coupons fit in a bounding box of 30mm (W) × 50mm (L) × 30mm (H). In each of the coupons (except for the control one) MX3D purposely planned defects to help validate the inspection method's relevance for WAAM and help investigate the correlation between the defects and different events visible on the data logs through clear labelling. A total of 13 coupons have been planned, in each of them a different type of action is carefully planned to result in the desired defect. To guarantee repeatability and facilitate data collection each defect-generating action is carried out at least two times in three separate locations. To facilitate traceability MX3D has drafted the AMPS (additive manufacturing procedure specifications) for each coupon both to guide the manufacturing process by indicating precisely the printing procedure and to help tracing how and where the defects were planted.



Figure 1. The nominal size of the coupons (left) and the all the manufactured coupons

2.2 Tomography Inspection

A robotized X-ray tomography micro-focus system was used for the NDT inspection with an optimised set of parameter settings (namely: Voltage: 165 kV, Current, 180 μ A, 900 projections) achieving voxel size of 70 μ m. The post-processing of the tomography acquisition was performed in VGStudioMax 3.5 software. It provides the dedicated modules for flaw identification and quantitative information related to defects.

3. Additive Manufacturing Analysis in CIVA Software

3.1 Framework for Additive Manufacturing Monitoring Analysis

CIVA is a software dedicated to the simulation and analysis of Non Destructive Evaluation (NDE). On the conception side, simulation can be used in order to define sensors, trajectories, settings that will maximise the ability to detect flaws. Simulation can also be used to demonstrate the performance of a control by assessing the maximal size of the flaws that will be detected by a given procedure. On the analysis side, it can be used for the interpretation of data through novel imaging techniques. While CIVA handles several NDE techniques, we will here focus on the module dedicated to X-ray Inspection and Tomographic Reconstruction. For the sake of the specific needs of additive manufacturing, this module has been enhanced in order to include tools corresponding to the comparison of monitoring data logged over time and the 3D representation offered by tomographic reconstructions. Fig.3 illustrates the integration of specific tools for additive manufacturing in the CIVA graphical interface. Four stages have been identified for utilization of this module, which are discussed in the following sections.

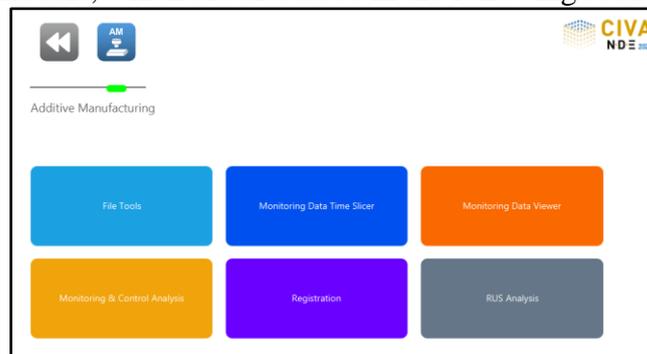


Figure 2. CIVA Framework

3.2 Registration

The registration module available in CIVA aims at registering tomographic data against the reference data coming from the CAD file. The two information having different natures (description of the skin of the part and description of the volume), it is necessary to bring them to comparable shapes in order to achieve registration. This is performed by the following stages: Segmentation of the tomographic data; Extraction of the skin of the segmented data; Smoothing of the resulting mesh and Point Cloud Registration (PCR) between the obtained mesh and the reference mesh

3.3 Annotation of monitoring data

Monitoring data can represent an interesting source of information regarding the detection of events that may be related to the occurrence of defects. However, these data are often huge which makes it difficult to analyse them in their entirety. Moreover, the data recorded during the non-manufacturing phases (beginning and end of the process, inter-layers) are generally not interesting and could be discarded. To overcome these drawbacks, the *Monitoring Data Time Slicer* module allows to analyze data acquired during the process in order to detect the different manufacturing layers. This module has two main views: 1. A representation of the complete time series associated to a variable from the monitoring file and 2. A 2D representation of the signal intensity for each detected layer as a function of time

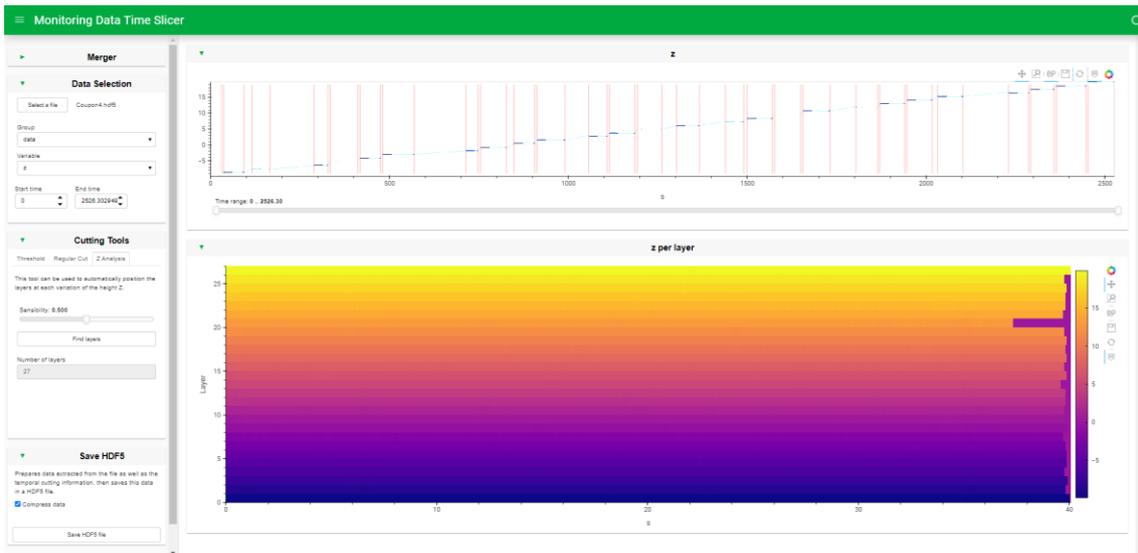


Figure 3. Monitoring Data Time Slicer

To be able to adapt to a majority of cases, this module has three tools to perform the temporal cutting of the data:

- **Regular Cut** aims at positioning the layers by taking a regular hypothesis (identical manufacturing time for each layer)
- **Z Analysis** allows layers to be positioned automatically with each variation in the Z-height signal.
- **Threshold** allows the layers to be positioned semi-automatically each time a given threshold is crossed.

3.4 Inter-layer comparisons

The module offering inter-layer comparisons takes advantage of the registration and the annotation of monitoring data in order to present the monitoring data and offer several views:

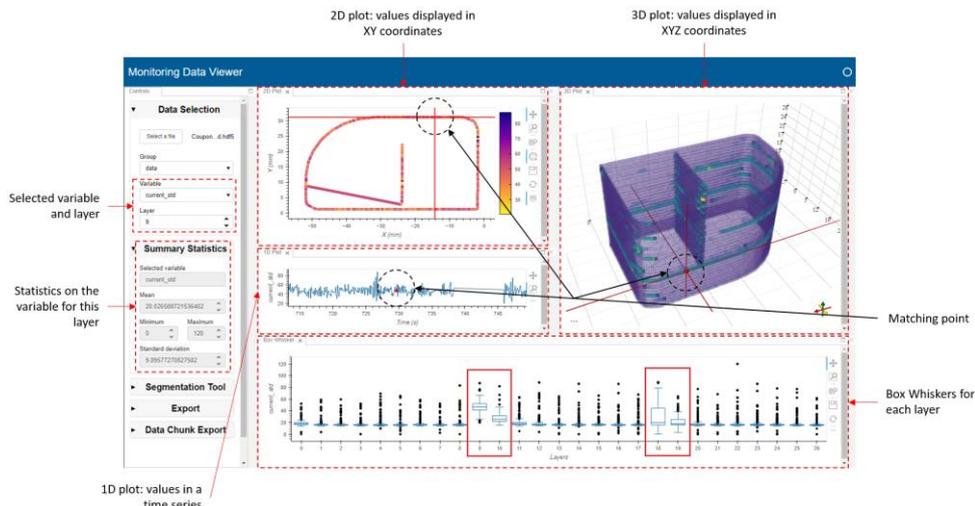


Figure 4. Monitoring Data Viewer

- 3D representation with a colour map in order to spot the outlying values observed during the process
- 2D representation in order to focus on a given layer

- Statistical analysis for each layer in order to compare the layers and identify the layers containing abnormal values

3.5 Tomography / monitoring comparisons

The module offering tomography / monitoring comparisons is dedicated to the comparison of 3D tomographic data with monitoring data. It requires data coming from additive manufacturing builds with a constant fabrication direction (referred to as z in the following explanation). It takes advantage of the registration of tomographic data and the annotation of monitoring data in order to allow the comparison of horizontal 2D slices coming from the registered tomography and analysis of the monitoring data from the layer with the value z corresponding to the z of the tomography layer.

4. Results and discussion

Some results obtained from the coupons are presented here. First thing, which is observed that there are always peaks at the extremes (start and end) of the manufacturing cycle of a layer; which may or may not results in a defect. Fig.5 shows two different layers of a coupon which was manufactured as with “no gas on specific layers”. The three graphs contain the voltage, current and power variations during a specific layer. The layer 7 gives an example of a defect free layer with the monitoring data being very consistent throughout the manufacturing but there are peaks, however no defects are observed. The layer 10 shows an example with inconsistent process data which results in an entirely defective layer. Fig.6 presents a layer from a coupon 4 with “molten tip on layer”. In this layer (Layer 24) we distinguish a peak in the signal of the current_std variable (slightly visible in the signals voltage_std and power_std) that matches spatially and temporally to a porosity visible in the corresponding slice from the X-ray tomography. Moreover, this peak is located outside the usual zones in which the porosities appear, i.e. the turbulence areas visible in the different signals and that are due to the start of the manufacturing process of a given layer.

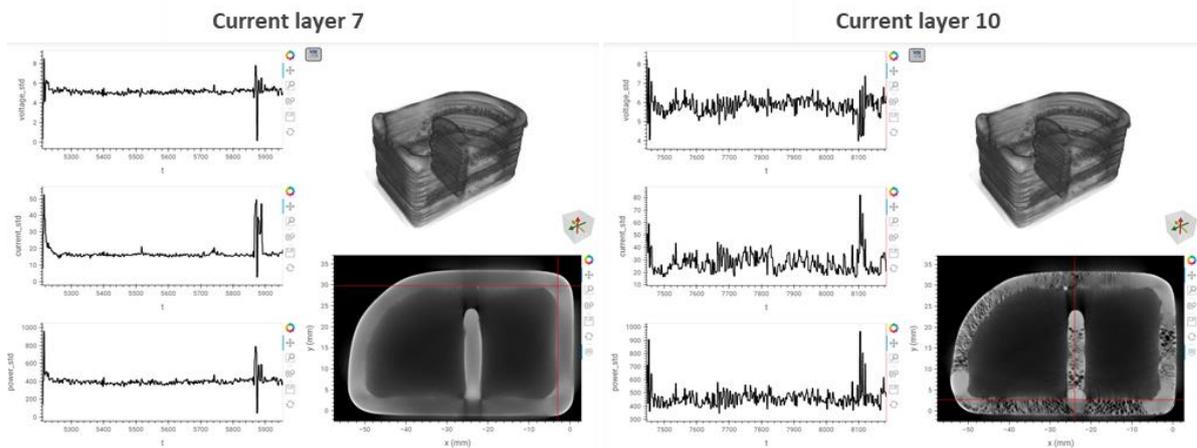


Figure 5. Results for coupon 2 at a defect free layer (left) and a defect layer (right)

5. Conclusions

In this work, we presented an approach for multi-physics data registration for the improvement of additive manufacturing process control by using cross-correlation of temporal process monitoring data with tomography based 3D characterization. A new module was developed within the CIVA software framework, the results obtained show therefore that it is possible to establish links between certain types of defects and singular

monitoring data, such as a clear link between voltage peaks and the occurrence of pores. These results are an important step, not only to initiate real-time manufacturing correction processes, but also to facilitate the certification of Additive Manufacturing techniques.

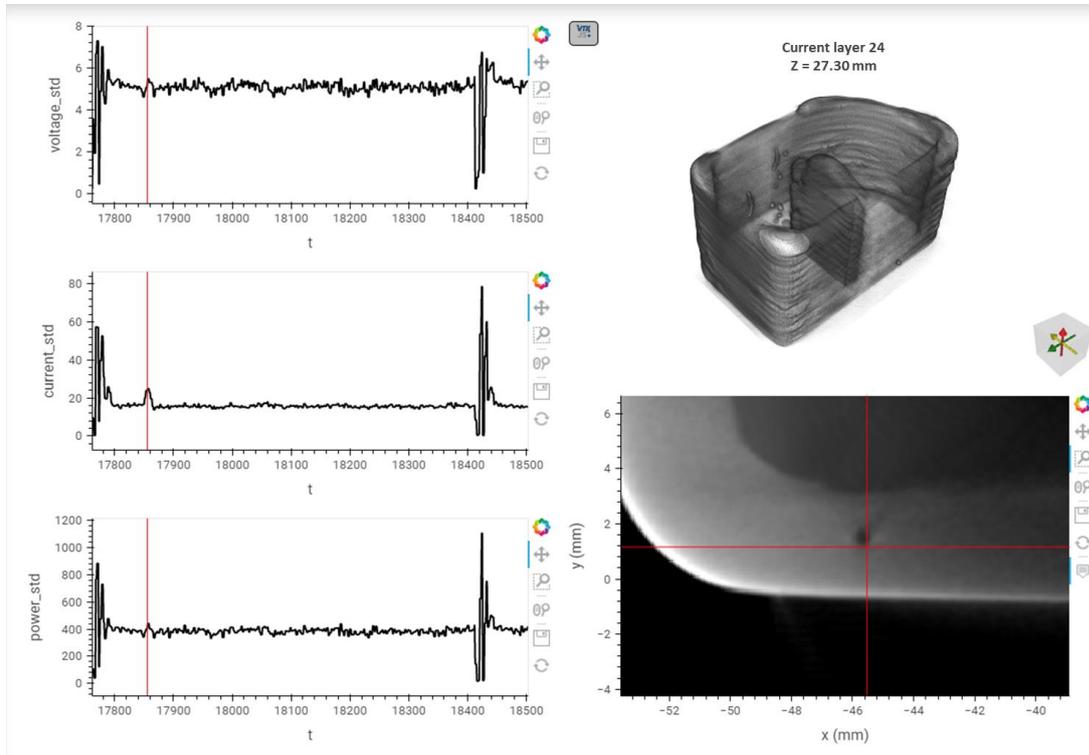


Figure 6. Peaks at the beginning of manufacturing correlated with defects (coupon 4)

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