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A novel melt pool mapping technique towards the online monitoring of Directed Energy Deposition operations

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Abstract

Although Directed Energy Deposition (DED) has more than a two and a half decade history, the difficulty of consistently controlling this process is still limiting its adoption. Achieving robust printing of arbitrary shapes with high-fidelity (macro-scale) geometry and uniform pre-determined microstructure throughout relies on careful coordination of many factors (some of which still rely on the knowledge of the system user). Key to this endeavor is controlling the activity of the melt pool and managing its influence on surrounding material (including due to reheating cycles). Even with emerging in-process melt pool control methods, translating ideal steady state melt pool models into practical use while creating arbitrary shapes on-the-fly can be difficult to visualize and validate. Despite recent advances in the field of melt pool control, intuitive visualization of melt pool signatures and confirmation of how they affect the quality of the deposition is yet to be found. A process control indicating possible flaws or defective regions in the material component, as well as certifying the uniformity of characteristics during deposition would be of great help to improve the process itself and further diffuse its application. This study presents the development of a novel and innovative method for acquiring, processing and visually showing DED process signatures to assess progress toward fully automated melt pool control. This methodology relies on incrementally building a map of actual process conditions by merging multiple data streams collected during the deposition process for each layer and then plotting the recorded signatures along the 2D toolpath position. This concept has been realized with a new software application called HeatMAP. This application uses data supplied by the AMBIT™ Melt Pool Measurement 'MPM' system wherein images from the melt pool are acquired by a CMOS camera and processed. A second data stream is simultaneously collected directly from the CNC including the actual feed speed and the nozzle positions by using the DTConnect software (an application developed in this study based on FANUC FOCAS library). A visualization of the merged data sets in the HeatMAP software then imparts to the user an intuitive way of assessing the process quality using visualization as an indicator of metallurgical quality. To demonstrate the utility of this approach, two sets of experiments were undertaken: one as a benchmark, where process signatures were captured by the MPM system in monitoring only mode and another with active closed-loop laser control. When the melt pool measurement system is used in closed loop mode, the laser power is varied in order to maintain a target melt pool area within a specific range. At present, image data was acquired and processed throughout two deposition strategies, which were used to prove the mapping concept, its capabilities and methodology. The methods behind HeatMAP and DTConnect presented in this study, demonstrate the potential for these applications to accelerate the development of more stable deposition parameters, and process planning and control in the future. Using the proposed control, improvements to material quality are expected in the DED process.

Keywords: Additive Manufacturing; Melt pool monitoring; Feedback control; Software development

1. Introduction

Directed Energy Deposition (DED) technology is a deposition technique where a feedstock material, typically in powder

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or wire form, is introduced into a focused thermal energy source (such as laser, electron beam or plasma arc) at or near a substrate so a melt pool is formed and material can be added. The melt pool is moved around and parts are them built up, layer by layer through a pre-defined cladding toolpath [1]. DED is one of the seven Additive Manufacturing (AM) techniques categorized in ISO/ASTM52900-15 (formerly ASTM F2792), capable of directly producing metal parts [2, 3, 4]. The quality and application of each of the derivative DED processes will be mostly established from the combination of feed material and energy source, as well as by the process development and control.

DED technologies are capable of covering a range of applications including the repair of mechanical components [1, 5, 6], and offer optimized production of near-net shape components while mitigating intermediate supply chain operations and reworking [7]. However, the complex thermal activity during the printing process, through reheating cycles, affects the material properties, turning the reproducibility of parts, consistency of microstructure and defect-free deposition into a production challenge [8, 9, 10].

Considering this, the application of monitoring and control techniques to enhance DED can dramatically improve the production process, with high geometric fidelity and good microstructural properties [8, 11]. The intent of monitoring techniques adopted in DED processes is to non-destructively measure the effects of the main inputs to the process [11, 12, 13, 14], such as laser power [10, 12, 15, 16, 17, 18] and material feed speed [14], rate control of gases flow, and toolpath optimization. It has been learned that these parameters in conjunction with the feed speed can lead to the variation of the weld bead height and the track width, which if not well controlled can lead to of cladding defects. Therefore, matching these to the target build geometry prevents variability and leads to the development of stable and high-quality process parameters, which contributes to the enhancement of deposition quality and process repeatability [8, 9].

In all DED operations, understanding the thermal activity due to the movement of a high energy source, in terms of temperature gradient and the geometry of the melt pool, contributes in understanding the microstructure and shape at the end of the process [2, 9, 19]. Important fundamentals on this matter are described by Liou et al. [20], who provided an early overview of the DED process and pointed out different sensors for selection, which was reinforced by Yan et al. [21] whilst presenting a review on the thermal analysis in laser-based AM. In a complementary way, Thompson et al. [8] and Purtonen et al. [13] offer valuable reviews towards monitoring of thermal activities in laser-based DED process. Two primary categories of thermal sensors that have been applied in this field: contact and non-contact optical sensors.

Bohlen et al. [18] and Amine et al. [22] considered the use of contact techniques by applying K-type thermocouples. Different from Amine et al. [22], who embedded them into the substrate and evaluated the temperature gradient through deposition, Bohlen et al. [18] attached two thermocouples to the sides of a build wall. By arranging the thermocouples in different positions, Bohlen et al. [18] could estimate that the maximum cooling rate per layer, considering the lowest point of measurement, is found within 14 K/s and 62 K/s, as for the upper point of measure, the cooling rate goes from 346 K/s to 47 K/s. Amine et al. [22], on the other hand, evaluated the reheating cycles and cooling rate at the substrate level, and its influence on the previously deposited layers and the resulting microstructure and mechanical properties.

Regarding non-contact temperature sensors, such as infrared (IR) thermometry – or pyrometry –, the two-color pyrometer has been used due to the rationing on the radiation intensity of two adjacent wavelength bands to estimate the temperature [8, 20]. This category of sensors is independent of emissivity, and less prone to contaminants interference in signal capture, therefore the measurements are independent of target size, enabling accurate readings within the field of view.

Photodiode (a single-color pyrometer) and ratio pyrometer (digital camera) concentrates the majority of applications in monitoring and controlling DED operations [2, 4, 8, 12]. The spectral range of most digital cameras for in-situ melt pool monitoring, e.g. Charged Coupled Device (CCD) and Complementary Metal Oxide Semiconductor (CMOS) cameras, is found within the short-infrared (IR) (0.78–2.50 μm) and mid-IR (2.5–14.0 μm) wavelengths [4]. The leading use of sensors for melt pool monitoring of laser-based AM processes have been concentrated on image acquisition from CCD and CMOS cameras [8, 13, 20].

Bi et al. [12] measured the melt pool temperature by means of a single-color IR pyrometer integrated to the powder feeding nozzle [12], which was later used as an input for feedback control. The relation between workpiece geometry, temperature and cladding quality was investigated. The elevated energy resident in the upper layers during the printing of thin rods induced high oxidation levels and an increased dilution into the substrate material due to the limited heat conduction of the workpiece material. Oxidation free pieces were achieved by implementing a control to the heat source, based on IR signature from the melt pool. Additionally, Bi et al. [12] highlighted that there is a limited range in which the laser can be defocused in order to prevent an excess of laser power exposure during cladding.

Doubenkaia et al. [5] developed a new methodology for monitoring the true temperature profiles in laser cladding operations through IR data. To estimate the emissivity of the process, a comparison between the brightness and temperature of a liquid–solid transition with known melting point was conducted, considering the gray-body hypothesis. Sun et al. [23] determined the cross-sectional geometry of the deposited single and multiple-layer beads by means of *in-situ* monitoring of the melt pool. The monitoring data from the cameras were also used to predict the grain orientation during a high deposition rate laser-based DED operation, in which the melt pool boundary shape was considered in order to estimate the crystal growth direction.

Sampson et al. [24] created a new methodology for image processing, consisting of advanced machine vision techniques for improving the image quality obtained by the melt pool monitoring system. The higher the image quality enabled a better edge detection and accuracy of measured melt pool width. There is a complex variation in bead width during solidification, as this method does not accurately predict the layer width yet. Also, the developed emittance-based algorithm can detect the melt pool edges by comparing intensity variations due to surface normal vectors, wihch are not being subjected to the different intensity thresholds and thereby often disturb the measurements of emissivity-based detecting algorithms [24].

Based on the literature, imperative data have been monitored by cameras, for various characteristics of laser-powder DED operations, with the aim of contributing to better shaping and production reliability. Gathering this knowledge is crucial to understanding the build up of layers in complex shapes. Although the data from IR cameras have been explored in vastly different ways, the contribution to enhanced processing and visualization of collected data to improve part quality and uniformity of properties is still needed.

The present research aims to develop an innovative method for processing and visualizing feedback data, which relies on the build up of a map superimposed on the tool path in a CNC environment. The map can display process signatures from DED operation, such as those observed from the melt pool by means of a CMOS camera (using the MPM module), the laser power, as well as the actual feed speed and cladding position obtained from the CNC. In order to read the CNC data, an interfacing software was implemented into the CNC laser-powder DED Hybrid machine. Tests were performed to demonstrate the concept of the mapping methodology and the workpieces were analyzed qualitatively.

Nomenclature

P	laser power delivered to the melt pool (W)
S	melt pool area (mm^2)
f	feed speed (mm/min)

2. Experimental configuration

2.1. Equipment set-up

The DED tests performed in this study were conducted at the Hybrid Manufacturing Technologies (HMT) facility in Leicestershire, United Kingdom, in a CNC machine equipped with an AMBIT™ laser-based DED system made by Hybrid Manufacturing Technologies with data analysis undertaken remotely at The University of São Paulo thereafter. For the initial round of benchmark trails, the laser source was programmed to emit a constant power of 350 W with a laser spot diameter of 1 mm. The geometries of a zig-zag line (Fig. 1a) and thin wall (Fig. 1b), both with a single track width of 1.3 mm, were performed to validate the concept of the mapping method.

All the deposition tests were carried out with a constant Z increment of 0.6 mm for the thin wall geometry at the parameters shown in Tab. 1. The deposition parameters were chosen to

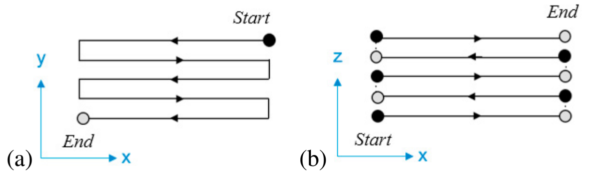

Fig. 1: Toolpath geometries of (a) zig-zag pattern and (b) stacked single bead walls.

build a good bead geometry and to promote material adhesion to the substrate (and previously deposited beads after the first layer). The quality of the deposited beads was also evaluated in terms of microstructure, in which the combination of parameter that leads to the minimal amount of porosity and avoided thermal cracking, were considered as the chosen inputs to the tests presented in this paper.

Table 1: Cladding settings for testing the melt pool monitoring and control system.

Geometry	Dimensions (mm)	P (W)	f (mm/min)	$\dot{m}$ (g/min)	h (mm)
Zig-zag	$20x70x0.8$	350	360	4.0	0.8
Thin wall	$2x50x9$	350	350	4.0	0.6

Colmonoy 227R powder from Wallcolmomony (see Tab. 2 for powder composition) with particle sizes of -140 $mesh$ + 15 μm distribution was delivered at the rate of 4 g/min by the conveying line of Argon gas at 3 L/min. Shielding gas at the rate of 8 L/min prevented the melt pool from oxidizing whilst the nozzle gas at the rate of 3 L/min protected the lenses on the laser head against back-flow of contaminants.

Table 2: Material composition ($W_t\%$) of Colmonoy 227R powder.

B	Si	P	Ni
1.0	2.7	2.1	94.2

2.2. Data acquisition and signal processing

The monitoring module is equipped with a CMOS camera Genie Nano model G3-GM10-M0800, with c-mount lens (back focal distance of 17.52 mm) and On-Semi 0.5M sensor (Python500 P1). The camera is responsible for receiving the emittance back from the melt pool and capturing images of light intensity at the exposure setting of $10,000$ μs. Images from the melt pool captured by the CMOS camera were used as input data for an image processing algorithm developed by Hybrid Manufacturing Technologies. This software is responsible for calculating data such as melt pool area, melt pool center coordinates, etc. from the images frames. Such image processing stage is time consuming, thus although the MPM capture rate can be as fast as 1 to 2 ms, the data can only be written and sent to the CNC at a maximum rate of 12 Hz in the current setup. Thus, the data from monitoring the actual laser power, feed speed and the melt pool area in this work, were acquired at the rate of 12 *Hz*. This rate was defined as the highest feasible rate that allows the delivery of steady and reliable data without any considerably delay the system activity.

In order to showcase the mapping concept, builds were performed in monitoring only mode and with active control of the laser power. For adjusting the laser power on the fly, a target laser spot size range is entered into the MPM system and the power is adjusted to keep the area of the measured spot within that range. The range for these trials was between 0.9 and 1.0 mm^2, which is significant since small variations in melt pool area are expected due to the way the shape of the melt pool changes with the trajectory of the nozzle. The area of the melt pool is based on the number of pixels found withing the boundary of the image, in black and white. The pixel size of the camera is 6.5 μm and the nominal frame rate is 566 fps. The data from the controller was then sent to the CNC via PROFINET protocol.

Possibilities are vast towards the extraction of further information from the melt pool, which is to be developed in future work. The data acquired from the sets of experiments by DTConnect were evaluated offline to showcase the conceptual design of the mapping methodology applied to deposition parameters, which in this paper is introduced as HeatMAP. Both software concept and development are presented in the next subsection.

2.3. The HeatMAP and DTConnect

For acquiring the current position of the cladding head and the actual feed speed, DTConnect – an application that uses the FANUC FOCAS library to access the CNC data – was developed. DTConnect is a custom developed application in C++ that allows the reading and writing of CNC variables and parameters, for realtime monitoring of the process, via direct connection over a network protocol, such as TCP; and also for offline analysis, through file export. The program is multi-threaded, where one thread gets data from the CNC and enqueues it for saving, and another one dequeues the data and writes/saves it to the desired file. It is worth mentioning that the functions for acquiring CNC data are implemented by the FANUC FOCAS library. To add compatibility to different CNC systems, similar libraries, provided by the CNC manufacturer, can be included in the program – expanding its ability to monitor any CNC environment.

Conceptually, DTConnect is a standalone software that can work as a file generator to build the HeatMAP plots. These characteristics, makes this application useful to monitor the machine activity and status (useful tool for preventive maintenance, process follow-up in factory floor, etc.) as well as providing the data stream for the HeatMAP.

Furthermore, data from MPM have been presented in charts and in images from the camera as captured. Yet, little is shown in an easy-to-understand way, which would speed up the process of inspection and intervention in case an out of tolerance condition or failure is detected. This demonstrates the clear need to intuitively visualize the data collected from the monitoring of main DED & CNC process conditions with respect to the 2D-toolpath geometry of the part. Details on the data flow that is base to the HeatMAP is presented in Fig. 2.

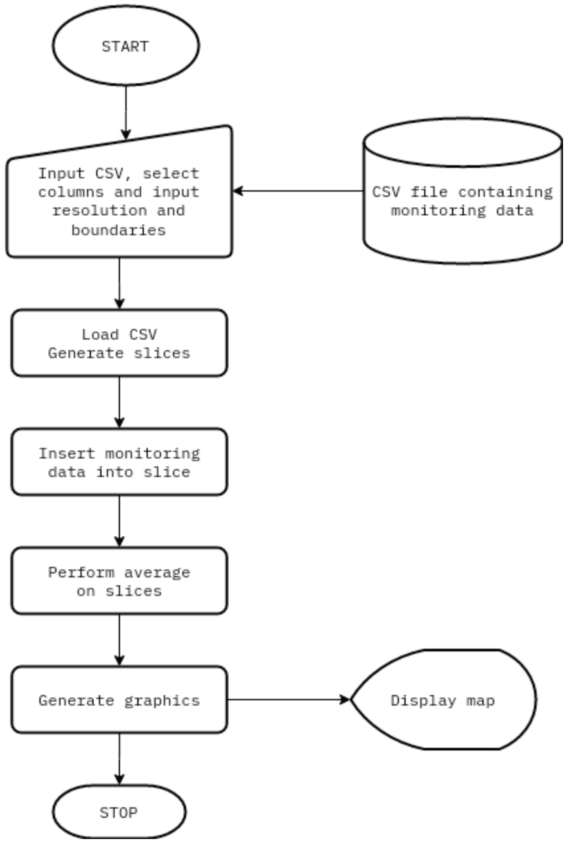

Fig. 2: Flowchart of the HeatMAP software.

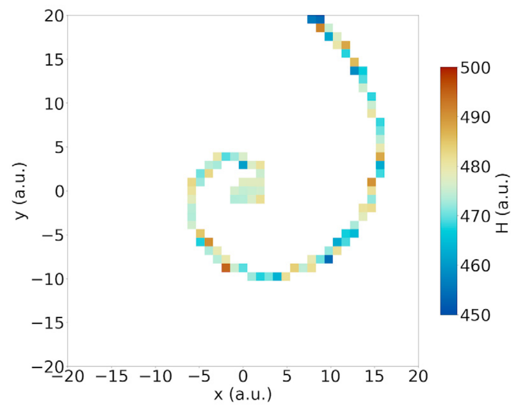

Fig. 3: Hypothetical example of HeatMAP. Spatial values (x, y) and monitored parameter (H) are in arbitrary units.

HeatMAP is an application developed in this research to allow better visualization of the monitoring data of the main

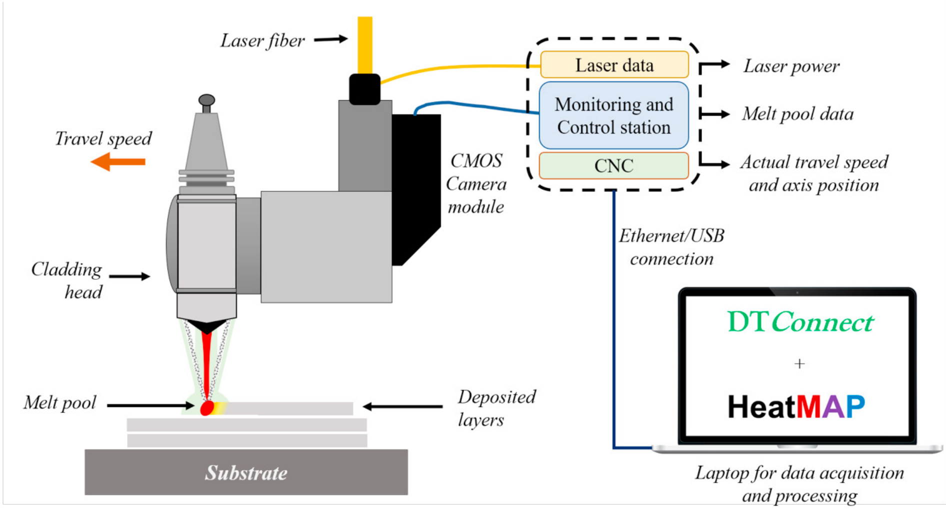

Fig. 4: Schematics for melt pool monitoring

deposition parameters. It is currently available in LabVIEW, Python and C++ implementations. In all versions, the input data for HeatMAP is a 'Comma Separated Values' (CSV) file with the values for coordinates and monitored parameters of interest to be plotted. One possibility of input for this processing algorithm is the data files from the melting pool, which contains, in this particular showcase, the current laser power (P), the melting pool geometry characteristics such as melt pool area (S), and the spatial information on the process (deposition toolpath).

Regarding the HeatMAP algorithm, the concept of 'gridding' was created. In this scope, a single square of the grid refers to a spatial portion of the manufactured part. For instance, if the part to be analysed consists of a 10 *mm* x 10 *mm* mm square and the chosen resolution for the map is 1 *mm* x 1 *mm*, then for each map direction a grid pattern with 10 squares will be generated, so the map will consist of 100 squares. An example of a plot generated by HeatMAP can be seen in Fig. 3.

Supposing that the toolpath resembles a logarithmic spiral (Nautilus shell), the monitored parameter is shown as the color information over the slices of the HeatMAP, where actual values are mapped onto the color bar. The expected HeatMAP use case for this study is presented below:

i User selects the CSV file consisting of captured data. The columns must contain information on spatial coordinates (x, y, z), and monitoring data (P, f, S). The user also inputs spatial boundaries, resolution parameters and data columns;
ii Load the monitoring data, filtering it over the specified coordinates for the 2D plot;
iii Generate a data matrix, representing the map slices;
iv Iterate through the monitoring data and insert each entry into the corresponding slice;
v Perform an average of the values corresponding to each square of the grid;
vi Generate graphic.

The data displayed into the HeatMAP plots can be decided on a case by case basis, however in the field of Additive Manufacturing as illustrated here, it has the potential to represent the quality of the deposition, and thereby highlight regions of possible defects. This immediate and intuitive system feed-back aids users to determine more stable deposition parameters, and to contribute to the development of better parts. In addition to the presently illustrated application, HeatMAP and DTConnect can both expand their capabilities to any other manufac turing process where monitoring is undertaken and needs better visualization, such as machin ing, grinding, etc.

It is worth mentioning that the HeatMAP program can be fed with data acquired from any software solution able to export to a CSV file. The format choice was due to the ubiquitous nature of the CSV file format. In this research, the software used for position and feed speed was DTConnect, and the data from laser power and melt pool monitoring was provided by the MPM software solution by HMT, that was also available at the CNC environment, then enabled to be read and written by DTConnect. Thus, for this particular proof of concept, the Python application of the HeatMAP and DTConnect was explored. A schematic on the system for melt pool monitoring and control is presented in Fig. 4.

In order to obtain a reliable and accurate imaging of the process, the acquisition rate from the melt pool monitoring and the CNC must be matched. To achieve this, readings were taken in parallel loops and then sequenced together using the timestamp associated each data stream. This was done in order to allow future investigation on the synchronicity of the data acquisition. The validation of the method for data processing was visual inspection compared to the physical samples.

3. Results and Discussion

The data acquired from both MPM software and DTConnect during the deposition of a zigzag line track and a thin wall are shown for the validation of the HeatMAP concept and discussed in this section.

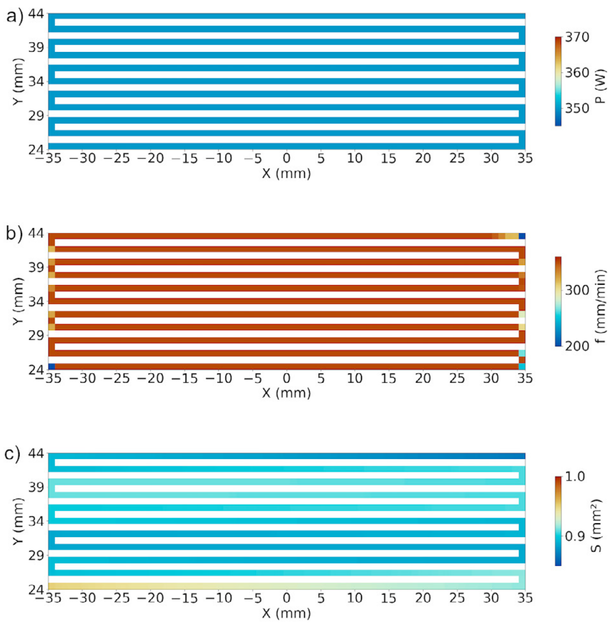

Fig. 5: HeatMAP of (a) laser power; (b) feed speed; and (c) melt pool area from the build of a zigzag track with no active feedback control (monitoring only).

Figure 5 presents the monitoring data from the zigzag track in monitoring only mode of the MPM (no intervention from the controller on the laser power). For this set, the color from the HeatMAP displaying laser power laser power (Fig. 5a) was expected to be constant since the laser power was not varied, as shown. However, a higher variation of the melt pool area (Fig. 5b), was expected, since the CNC machine deviates from the target feed speed based on the geometry it follows. These deviations of acceleration and deceleration of the feed speed vary the laser exposure duration at each point of the part during the build. Additionally the heat sink effect of the substrate is not accounted for by the generic parameters. The feed speed is one parameter that has high influence on the produced part, which makes its monitoring imperative to the process besides laser power, mass flow rate, etc.

The variation of feed speed in CNC machines is expected to happen during a change of motion direction (due to inertia), as well as through some readings of lines in G-code and sub programs. In this respect, when the feed speed is lower than the programmed one, more material will be delivered at that specific region, introducing variability of layer height to the build. The same defect can occur when a higher feed speed is obtained during deposition, generating a lower layer height in this case. The HeatMAP for feed speed has identified a decrease in the feed speed at the corners of the zigzag toolpath, leading to a gain of material thus a higher layer height at these turnabouts.

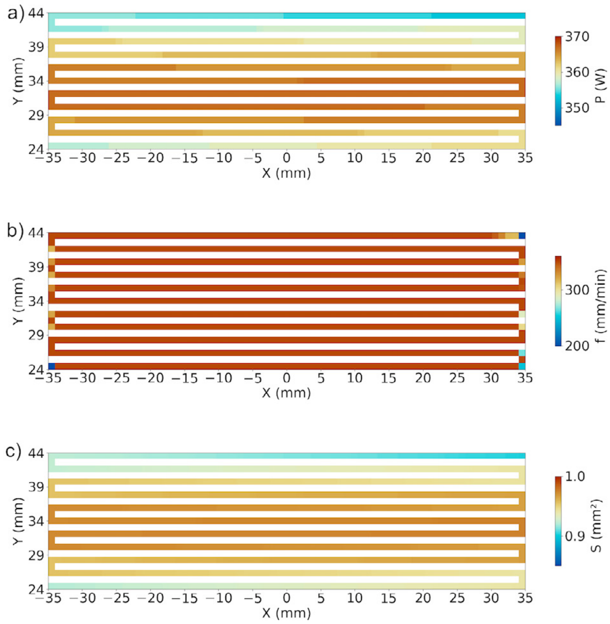

Fig. 6: HeatMAP of (a) laser power; (b) feed speed; and (c) melt pool area from the build of a zigzag track with active feedback control on.

By adding feedback control to adjust the laser power within the specified range, the deposition rate can be influenced by the melt pool shape. Figure 6 shows the plot for laser power, feed speed and melt pool area. In this case, the change in laser power is shown in the plot (Fig. 6a), and it can be seen that laser power above the nominal power used for the benchmark test was needed to maintain a more consistent melt pool size. As for the feed speed (Fig. 6b), there was no substantial change from the results aforementioned since the G-code from both sets of zigzag track geometry is the same. This culminates in a highly reproducible behavior on the position and motion from the CNC. Last but not least, the melt pool area (Fig. 6c) and shape will also have significant changes during the process, as it also varies with laser power and the powder capture efficiency into the melt pool.

The as-built geometries are shown in Fig. 7. Visual inspection of these parts, particularly at the beginning and end of each deposition track shows an improved outcome with the closed loop control on. Additional analysis is needed to further quantify the melt pool behavior in the corners (where acceleration and deceleration effects are the strongest). This sample set provided initial validation that both DTConnect and HeatMAP have succeeded in acquiring data and visualizing them in an easy and straightforward way. This fulfills the aim of the combined software concept.

The geometry of a thin wall increases the challenges of building and the inspecting due to the cumulative effect of the reheating cycles often coupled with reducing cross-sectional area. As multi-layer deposits grow features higher off of the

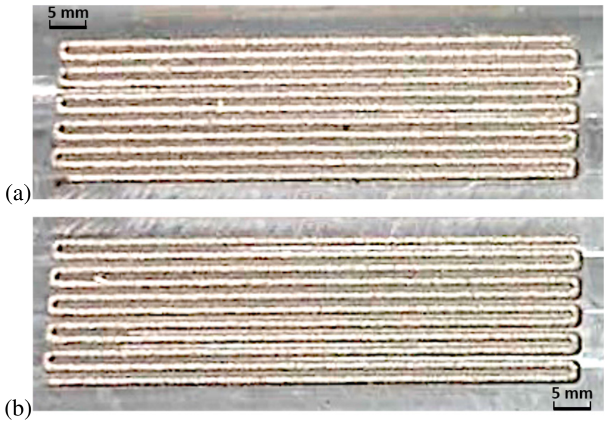

Fig. 7: Image from the zigzag line built with (a) monitoring only mode; and (b) active closed-loop laser control on.

build surface, the cross-sectional area (through which heat can be conducted down into the substrate) is fixed which often slows the cooling rate. A fixed set of build parameters does not account for this changing condition. This can have a significant effect on the cumulative height of the deposited beads. Figure 8 presents the monitored data from the build of a thin wall with no feedback control. Note that the height of the build in the Z direction is illustrated in this map.

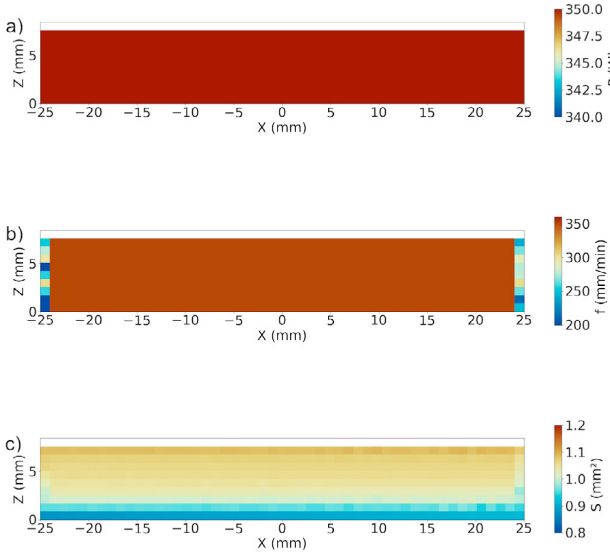

Fig. 8: HeatMAP of (a) laser power; (b) feed speed; and (c) melt pool area from the build of a thin wall with no active feedback control (monitoring only).

In Fig. 8, there is no variation in laser power (Fig. 8a), and an expected amount of feed speed variation at the beginning and end of each deposited layer. This variation in the feed speed data is due to the inertia of the CNC machine, since it will slow down at the end of each layer to change direction and move up to build the following layer. The bead area is shown to be lower at the first layers. This is because the substrate starts at room temperature and the laser energy must heat the substrate as well as melt the feedstock powder on the first layer. The required energy input is the highest on the first layer. Therefore, at a constant laser power, this will also generate the smallest bead area. As the deposition continues, the following layers are added to pre-heated material since the underlying layer would still carry energy from the last deposit. This favors the generation of larger melt pool areas.

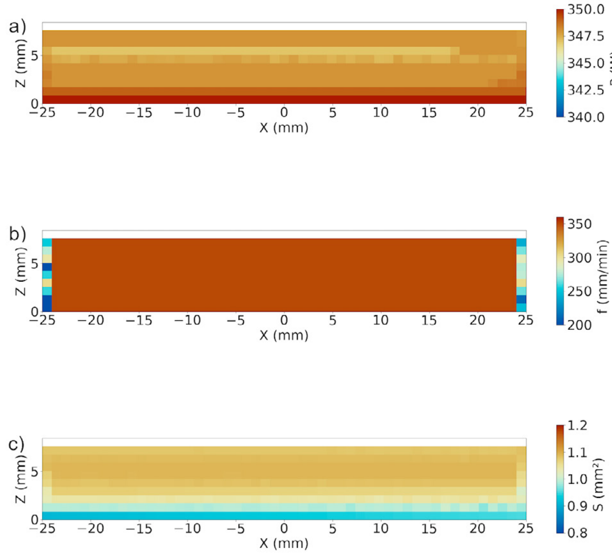

Fig. 9: HeatMAP of (a) laser power; (b) feed speed; and (c) melt pool area from the build of a thin wall with active feedback control.

By adding active feedback control while building a thin wall, the influence of the substrate on the first layers is considerably reduced, as shown in Fig. 9. Areas of the melt pool that are achieved in the second layer of this set (Fig. 9c) would only be achieved in the third layer of the build with no active feedback control (Fig. 8c).Similarly, areas achieved by the 5th layer in the set with feedback control (Fig. 9c), are only achieved at the last layer of the monitoring only set (Fig. 8c). This is a result from the adjustment of laser power from the MPM system during the deposition, which can also be identified with the HeatMAP visualization. This is reassuring that only the necessary energy will be delivered during the process with positive impacts on the overall form and resulting microstructure.

This effect into the part shape can be better explored in Fig. 10, which presents images from the wall printed in monitoring only mode (Fig. 10a) and with active control on settings (Fig. 10b). A rounder edge shape to the wall built with constant laser power, is representative of accumulated deviation from form due to the higher and uneven energy (added by laser plus the remained one from the previous layer) found at the melt pool and the heat transfer phenomena. With the active feedback control, this behavior can be managed towards a better part with better defined edge shape.

(a)
(b)


Fig. 10: Image from the thin wall built with (a) monitoring only; and (b) active closed-loop
laser control on.

Overall, regarding these two setups, both DTConnect and HeatMAP concepts and applications were presented and validated. HeatMAP has been shown to be a feasible tool for visualizing captured data, and DTConnect to capture and export data and monitor the CNC activity (including from the DED processes in this case). This makes the HeatMAP a potential tool to speed up the identification of critical regions for post-build inspection. It also makes the visualization and the interpretation of data collected easier. This can lead to faster identification of builds that are experiencing difficulty and that need operator intervention. In order to evolve these concepts, further studies are being developed and effort has been employed to the implementation of the HeatMAP 3D with realtime data collection as explained in the Future Work section. This paper has illustrated one possible use of these collection and visualization tools. The concepts undergirding the development of these software tools can also be used for a wide variety of processes when paired with appropriate sensors, data collection, and automatic error detection algorithms.

4. Conclusions

In this study, a novel methodology for collecting and visualizing data including laser power, feed speed, and melt pool area in DED operations was developed. The HeatMAP inputs are files containing MPM and spatial data – acquired from the CNC by the newly developed DTConnect communication protocol. These tools have been demonstrated using a proof-concept case where two geometries (zigzag and thin wall) were tested under monitoring only and with active feedback control of the laser power. In these conditions, the HeatMAP has been shown to be able to display the process variables of interest, making human identification of minor changes in the data easier, by returning such information in a color path. Currently the HeatMAP and DTConnect, are able to illustrate where the variation of the parameters took place spatially. This can be a signal for regions that may have anomalies and should be inspected more carefully and in future may motivate operator intervention before the build ends. This is a software tool set to accelerate the correlation between monitoring parameters and the as-built workpiece quality and geometry representation by qualitative means.

Future Work

Future possibilities for this approach are vast. Although the demonstration herein was an early stage of offline data processing (to refine the algorithm development), the ultimate aim of this research is to evolve into data processing techniques that will enable the detection of defects in realtime. Other opportunities for future work include increasing the sensitivity and accuracy of the HeatMAP application. Generation of 3D plots, real time feedback for feed speed, and increased data sampling frequency will all add operational flexibility to this solution. Additional evaluation of metallurgy correlated to spatial combinations of parameter and process signatures will help increase confidence in the HeatMAP and DTConnect tools as quantitative evaluation tools with the potential for identifying possible zones of defects, such as high levels of porosity, thermal cracks, lack of fusion. etc.

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