



Studies on Closed Loop Laser Power Control in a Dynamic Fashion through Temperature Distribution Measurement in LAM System

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ABSTRACT: We observe/record thermal behaviour of the molten pool and manipulate the laser power via a closed-loop controlled processing in which the laser power is controlled to keep the width and depth of the molten pool constant which is important for the consistency in the layered deposition. As a result a methodology will be developed for closed loop control of Laser Additive Manufacturing. The figure of merit of closed loop control will be quantified. It will open new avenue for the deployment of closed loop control on other LAM process parameters. This architecture is capable of dynamically predicting the temperatures and part geometry at various used defined input parameters.

KEYWORDS: Closed loop control, Laser additive manufacturing.

I. INTRODUCTION

Laser Additive Manufacturing (LAM) is one of the next generation feature based design and manufacturing technique. This is one of the advanced manufacturing processes that are capable of fabricating engineering and prosthetic components directly from a solid model through layer-by-layer deposition in a relatively efficient way, such that there is little waste or reduction of materials [1,2]. Almost more than three decades old, now laser stepped in the arena of additive manufacturing with the expectations to take the manufacturing industry to a whole new level. LAM process is layer-by-layer material addition technique which is used for manufacturing of complex 3D parts by selective deposition of consecutive layers of powder material on top of each other and the structure of the part is achieved by thermal energy supplied by focused and computer guided laser beam as a heating source. Thus the process produces almost ready to use parts which do not need any other post-processing than surface finishing [1]. The characteristics of built up parts using LAM process are very different from the components made by conventional processes where it mainly depends on the material properties. A number of process parameters are involved that governs the properties of components fabricated by LAM process [3]. The important process parameters are laser power, material flow rate,



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scanning speed, laser beam size while powder beam size, powder particle size, shielding gas and substrate temperature are secondary important during the process. Thus a small change in any of these parameters (e.g. substrate temperature) during the operation may vary the melt pool size, temperature distribution, cooling rate and subsequently the geometry as well as properties of the components. Thus it is necessary to monitor and optimize all process parameters continuously in real time to obtain components with desired properties and shapes. Many critical applications e.g. graded material components also require successful deployment for LAM process with real time monitoring. Hence, the complete control of feature and geometry of LAM fabricated structures needs monitoring of many in-process signals and subsequent simultaneous control of processing parameters. The thermal behaviour of the molten pool is one of the critical factors that affect laser deposition indices such as geometrical accuracy, material properties and residual stresses. The aim of this process monitoring is to gather all the relevant information on the process and to improve the occurring phenomena, and to use the gathered data to create quality control methods and closed loop control of the process. As the manufacturing of a product may take several of hours, lack of information on the progress and uncertainty of the quality of the final product may prevent the process from spreading in industry more widely. So the process monitoring and control are important to reduce the amount of rejects, improve the process reproducibility and save cost. Different approaches with newer or alternative strategies are being investigated for better process insight and better understanding of LAM process. The closed loop control system may efficiently improve various studies and hence relevant process management of LAM fabricated structures. Wang et al. presented an approach for estimating the track height and width at medium powder feed rate [4]. Kumar et al. developed a finer approach for estimating the temperature distribution and prediction of the single track geometry during LRM [5, 6]. This approach uses temperature distribution for the prediction LAM fabricated structures. This temperature distribution is also used an important parameter in the present work for the feedback in automated closed loop system to achieve greater geometrical accuracy of the built part. In this paper, we deal with the optimization of LAM process with closed loop control using lumasense thermal imager (MCS 640) as sensing device. The MCS640 is planned to be incorporated with the appropriate application specific imaging components for use in non-destructive testing, process control, and diagnostic applications [7]. For real time sensing and control of the melt pool size, architecture for closed loop control through lab view is developed. Lab view (laboratory virtual instrumentation engineering workbench) is a platform and development environment for a visual programming language from national instruments [8]. Closed loop controlled LAM process can overcome the effect of the thermal variation, This is used to manipulate the laser power via a closed-loop controlled processing in which the laser power is controlled to achieve an improvement in geometrical accuracy of the built part.

II. DATA ACQUISITION AND METHODOLOGY FOR LASER POWER VARIATION

A. Monitoring

For measuring the temperature distribution during LAM, infrared camera i.e. MCS 640 lumasense camera is to be focused in heat affected zone. The camera captures top view of the melt pool in the coloured format with a 640×480 pixels resolution at a constant frame rate. The images produced by infrared camera are used for analysing the length, width and shape or stability of the melt pool [9]. The grabbed image of the melt pool by the camera includes two main regions, the dark region which represents the background or the surrounding of the melt pool and the bright or coloured area, which represents various temperature zones of the melt pool. However, it is essential to separate the area which accurately presents the melt pool from its surrounding. For this Image thresholding and Boundary tracing is to be used [10]. Thresholding often provides a simple and convenient way to perform this segmentation on the basis of the different intensities or colours in the foreground and background regions of an image. The threshold is set to a value, where the frame fits exactly to the bright area of the melt pool (fig.1). The calculated frame is adapted automatically by the analysis software for every single image so the length, width and area size of the melt pool is measured for each image.

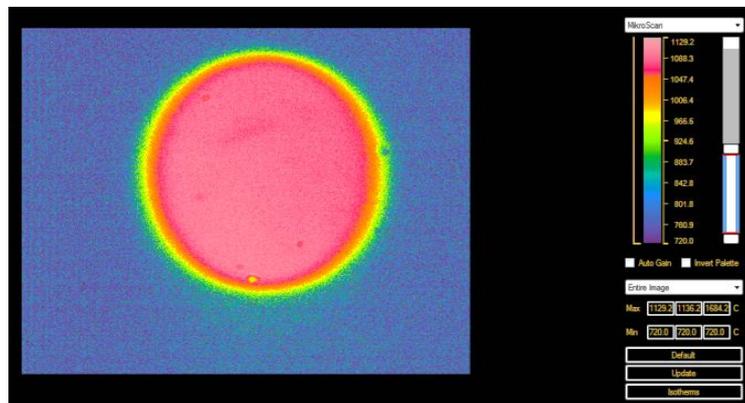


Fig.1 Lumasense image of the heat affected zone during LAM

The threshold level is kept static throughout the image; however, it is adapted from frame-to-frame during LAM process. In LAM process the physical size of the melt pool will grow or shrink as more or less energy is transferred to the melt pool. These effects may prominently observe at the Edges of the melt pool. So to obtain the varying geometrical features of molten pool, a constant width nearby the molten pool area is selected. This can be done by taking edge stripes of maximum sensitive zone on both sides of melt pool after thresholding from the foreground pixels or boundary tracing as shown in fig 2.

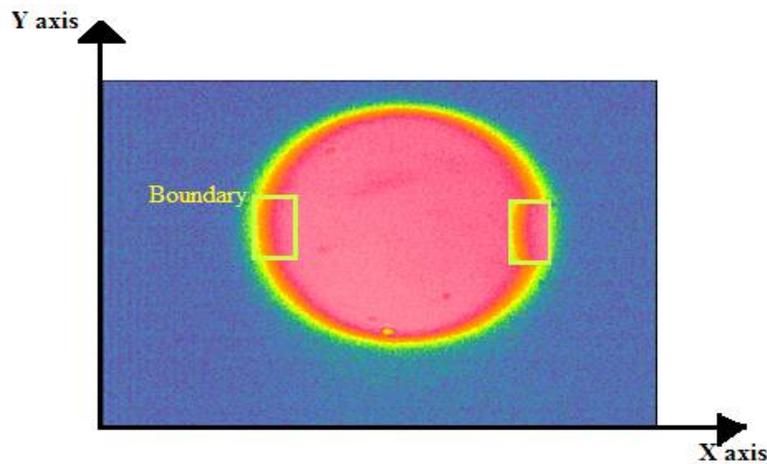


Fig. 2 Shows melt pool boundary tracing with edge stripes on both side of the melt pool image



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The height of the edge strip can be calculated as shown in table at different frames shown in table 1.

Table 1. Height calculation of edge strip

Melt pool edge strip of % height (at boundary)	Temperature range in melt pool edge strip	Melt pool edge strip of % height (at 10 th column from boundary)	Temperature range in melt pool edge strip	Melt pool edge strip of % height (at 20 th column from boundary)	Temperature range in melt pool edge strip
5%	900.7-924	5%	976.6-994.1	5%	1028.9-1040.3
10%	903.2-922	10%	977.8-995.2	10%	1028.5-1039.4
15%	901.6-923	15%	975.4-993.8	15%	1026.5-1039.2
20%	897-922.0	20%	972.9-990.4	20%	1025.2-1037.3
25%	893.9-921.1	25%	969.8-987.8	25%	1022.4-1034.8

From the table 1, it is clear that 10% of the total data in y direction represent the representative maximum change in temperature occurs with respect to laser power compared to others. So in the present project work 10% is considered as optimum data required for melt pool length at the melt pool edge strip. Similarly, for the same purpose as of length calculation the width of the edge strip has been calculated. The width can be calculated at different frames shown in table 2.

Table 2. Width calculation of edge stripes

Width(pixels)	Average temperature range w.r.t boundary of the melt pool	Width(pixels)	Average temperature range w.r.t boundary of the melt pool
0-10	920.5-995.20	0-10	907.3-978.90
0-20	920.5-1039.4	0-20	907.3-1030.9
0-30	920.5-1073.4	0-30	907.3-1065.5
0-40	920.5-1088.1	0-40	907.3-1085.4
0-50	920.5-1095.1	0-50	907.3-1088.5
0-60	920.5-1098.6	0-60	907.3-1091.8
0-70	920.5-1100.0	0-70	907.3-1089.7
0-80	920.5-1098.1	0-80	907.3-1090.7
0-90	920.5-1097.4	0-90	907.3-1088.2
0-(-10)	920.5-851.30	0-(-10)	907.3-843.00
0-(-20)	920.5-794.40	0-(-20)	907.3-789.70
0-(-30)	920.5-771.50	0-(-30)	907.3-781.10
0-(-40)	920.5-777.80	0-(-40)	907.3-763.10
0-(-50)	920.5-764.30	0-(-50)	907.3-762.80
Frame 11 th		Frame 16 th	
0-10	922.8-991.30	0-10	909.1-977.80
0-20	922.8-1038.4	0-20	909.1-1028.5
0-30	922.8-1068.6	0-30	909.1-1062.9
0-40	922.8-1085.8	0-40	909.1-1081.7
0-50	922.8-1089.9	0-50	909.1-1088.5
0-60	922.8-1093.7	0-60	909.1-1091.5
0-70	922.8-1093.3	0-70	909.1-1091.8
0-80	922.8-1094.1	0-80	909.1-1091.2
0-90	922.8-1091.7	0-90	909.1-1089.2
0-(-10)	922.8-856.30	0-(-10)	909.1-845.30



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0-(-20)	922.8-786.90	0-(-20)	909.1-792.50
0-(-30)	922.8-767.80	0-(-30)	909.1-774.10
0-(-40)	922.8-770.70	0-(-40)	909.1-773.50
0-(-50)	922.8-764.00	0-(-50)	909.1-775.90

From the above table it is clear that in between 0-70 pixel shows maximum sensitivity at different frames. So 0-70 pixel has been considered as optimum pixel range in this project work. After calculating we are selecting some of the pixels from large number of pixels which are used in closed loop controlling of laser power for the quick response time. The selection of some of the pixels can be done by selecting a particular data sets pattern after examining various data set patterns. These different patterns are shown in fig.3 (a),(b),(c),(d).

1036	1025.9	1036	1039	1040.5
1024.1	1025.9	1037.5	1034.5	1055.3
1003.5	1043.4	1022.2	1047.9	1014.7
1034.5	1016.6	1040.5	1058.3	1029.7
1001.6	1022.2	1029.7	1043.4	1022.2

(a) X-pattern

1003.5	1043.4	1022.2	1047.9	1014.7
1034.5	1016.6	1040.5	1058.3	1029.7
1001.6	1022.2	1029.7	1043.4	1022.2
1031.5	1031.5	1046.4	1037.5	1044.9
1033	1043.4	1049.4	1040.5	1031.5

(b) Octal pattern

1036	1025.9	1036	1039	1040.5
1024.1	1025.9	1037.5	1034.5	1055.3
1003.5	1043.4	1022.2	1047.9	1014.7
1034.5	1016.6	1040.5	1058.3	1029.7
1001.6	1022.2	1029.7	1043.4	1022.2
1031.5	1031.5	1046.4	1037.5	1044.9
1033	1043.4	1049.4	1040.5	1031.5

(c) Wavy pattern

1036	1025.9	1036	1039	1040.5
1024.1	1025.9	1037.5	1034.5	1055.3
1003.5	1043.4	1022.2	1047.9	1014.7
1034.5	1016.6	1040.5	1058.3	1029.7
1001.6	1022.2	1029.7	1043.4	1022.2
1031.5	1031.5	1046.4	1037.5	1044.9
1033	1043.4	1049.4	1040.5	1031.5

(d) Alternate pattern

Fig. 3 Schematic patterns (a) X-pattern (b) Octal pattern (c) Wavy pattern (d) Alternate pattern

To obtain representative average temperature for the logic to get feedback to input laser power, Standard deviation is used for different patterns of temperature distributions and then comparing with the real temperature distribution curve [11]. The standard deviation is given by

$$\sigma_N = \sqrt{\frac{1}{N} \sum_{i=1}^N (x_i - \bar{x})^2}$$

σ_N = Standard deviation

\sum = Summation

x_i = Each value in the data set

\bar{x} = Mean of all values in the data set



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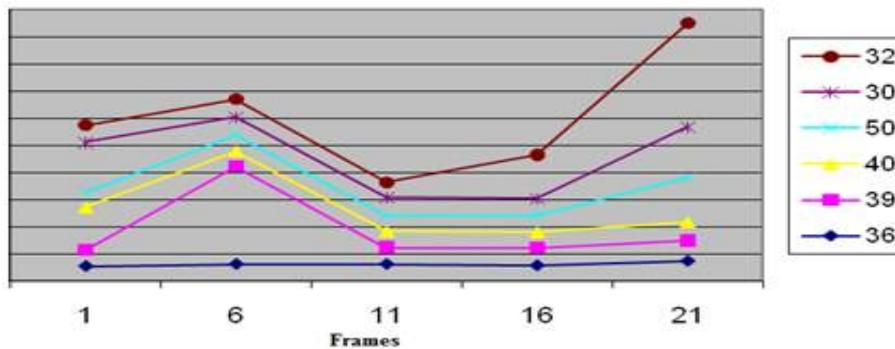
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N= Total number of data values in the data set

After examining number of patterns for getting the average temperature distribution it has been found that the wavy pattern is most suitable pattern for finding the average temperature distribution.

Table 3 Standard deviation

Number of selected data in pattern	Frame Number				
	1st	6th	11th	16th	21th
36	53.6	61	61	56.07	72.3
39	60.5	359	61.9	65.6	75.7
40	158.08	58.3	60.8	58.8	69.9
50	53.2	59.2	57.2	61.6	161.4
30	184.3	65.4	65.9	60.7	187.8
32	64.7	67	58.2	163	381.8



Graph1 Depicting standard deviation at different frames

B. Developing architecture of open and closed loop control through LABVIEW

The architecture of open and close loop control begins with getting the average temperature values of a selected pattern through lab view to reduce the error values and hence to reduce the response time. Fig.4 shows architecture of the average temperature distribution of wavy selected pattern performed in lab view.

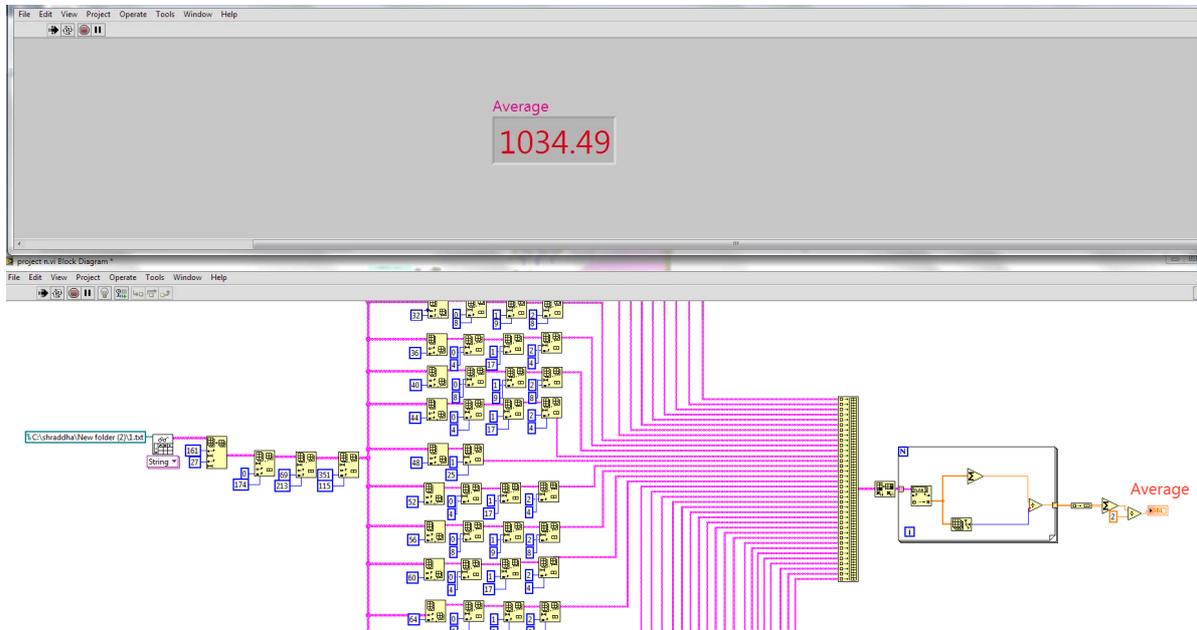


Fig.4 Depicting average temperature distribution of wavy selected pattern

C. Open loop control

Irregularities in surface of substrate the temperature intensity will vary at each and every point on the substrate surface. This open loop error has been calculated using Labview by which defects on the substrate surface can be noticed. The theoretical open loop error originated using the software is shown in fig 5.

$$\frac{T - T_{\infty}}{T_i - T_{\infty}} = \exp\left(\frac{-hAt}{\rho cV}\right)$$

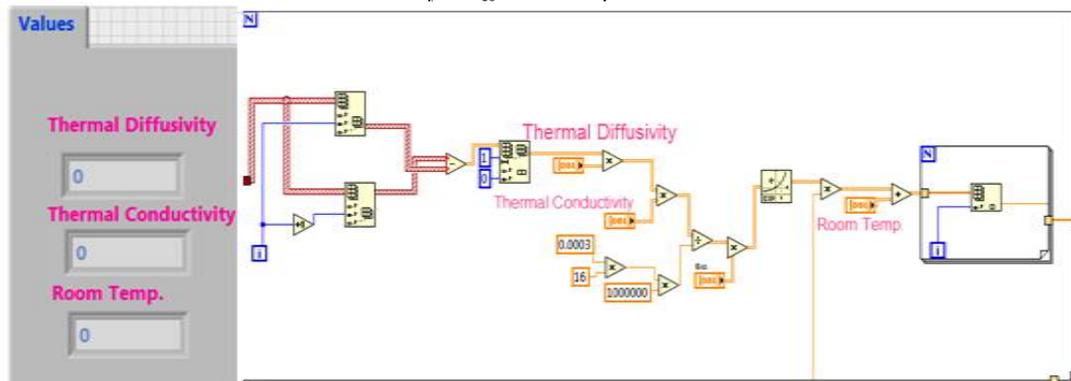


Fig.5: Depicting Open loop error calculation through lab view

D. Closed loop control

For quality and process reliability assurance purposes the interest towards closed loop manufacturing systems has increased in recent years. The closed loop control is typically achieved by optically monitoring either the back reflected laser radiation. In closed loop control during experimentation the different values of experimental laser power is obtained using energy balance equation.

$$q = \dot{m} C_p \Delta T$$

$$= \rho A V C_p \Delta T$$

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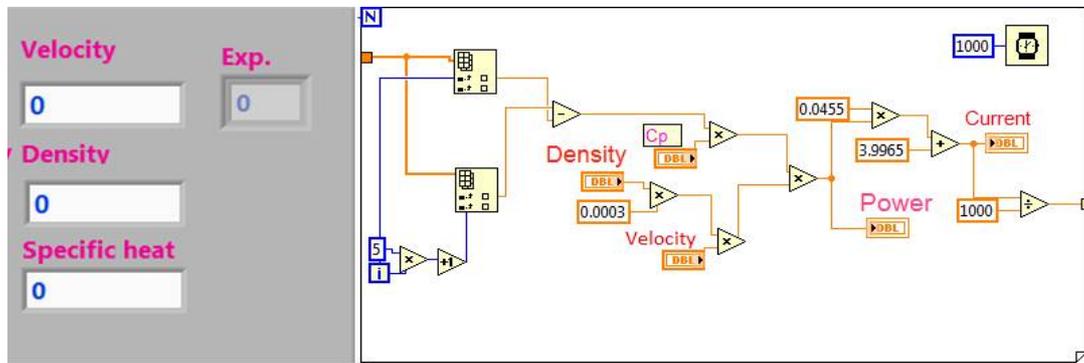
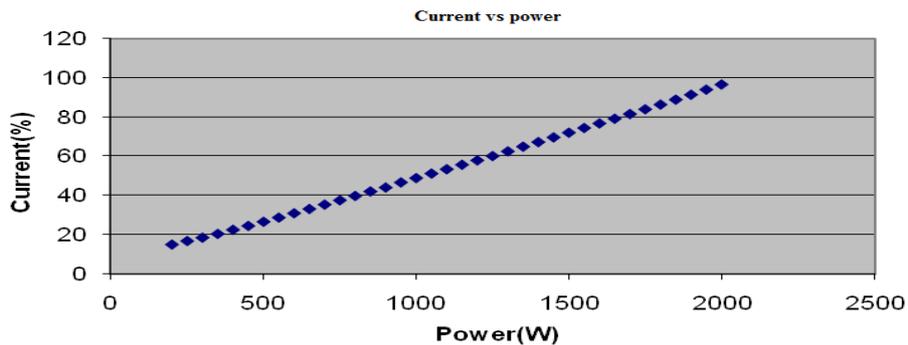


Fig.6 Calculation of power and current using Lab view

After calculating the different current values at corresponding power, a curve fitting is obtained which is a equation of st. line shown in fig . The equation of obtained curve fitting is $Y=0.0455X+3.9965$ where X and Y are the values of experimental laser power and current respectively. From this curve fitting equation at different values of experimental current the different calculated power has been obtained and finally errors were estimated by comparing experimental power and calculated power.



Graph 2 Depicting current vs. power

E. DAQ VI

To provide correcting signal to the LAM, is done by using daq card which generate analog output at the output channel. Also output can be chaked by using multimeter.

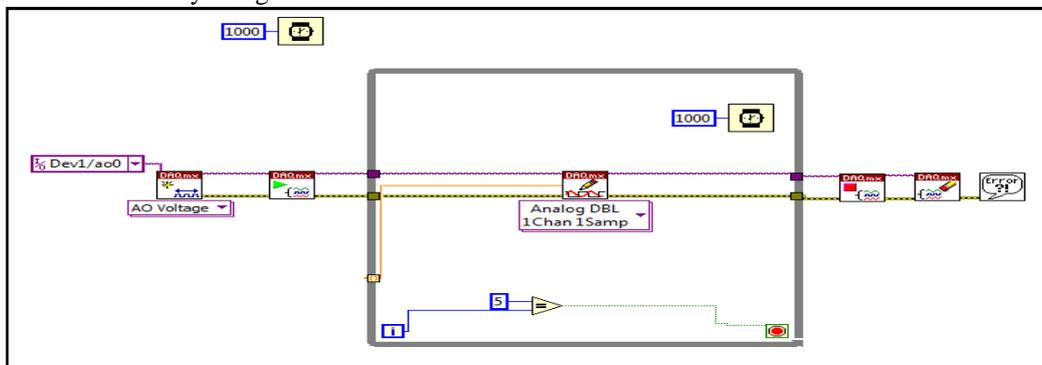


Fig.7 DAQ VI

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III.RESULT AND DISCUSSION

A methodology will be developed for closed loop control of LAM. We captured temperature distribution in a dynamic fashion throughout the process domain during laser additive manufacturing and the architecture for close loop control with laser power as main parameter is developed as shown in below Fig. Here two types of architecture present

1. Online mode
2. Offline mode

In online mode we work on the real world, continually we extracting file from the thermal imager. As shown in fig

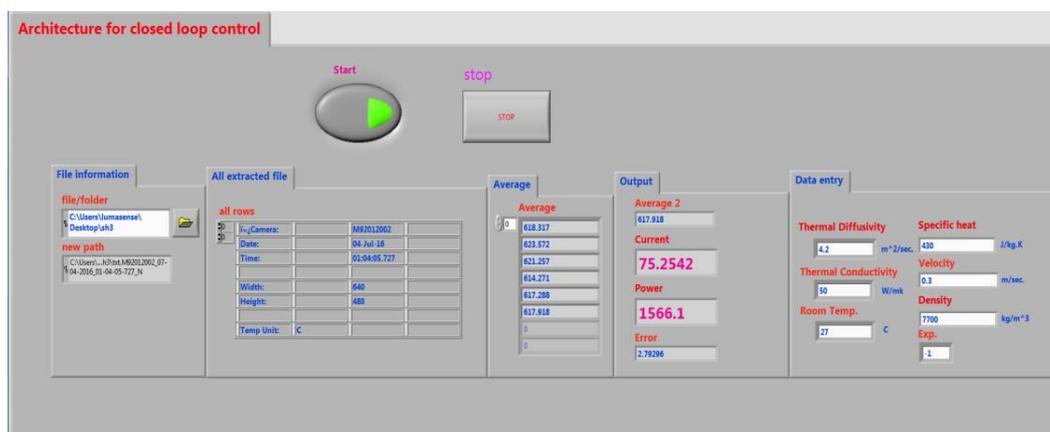


Fig.8 Architecture for closed loop control (online)

In case of offline mode we use already saved file. As shown in fig 9.

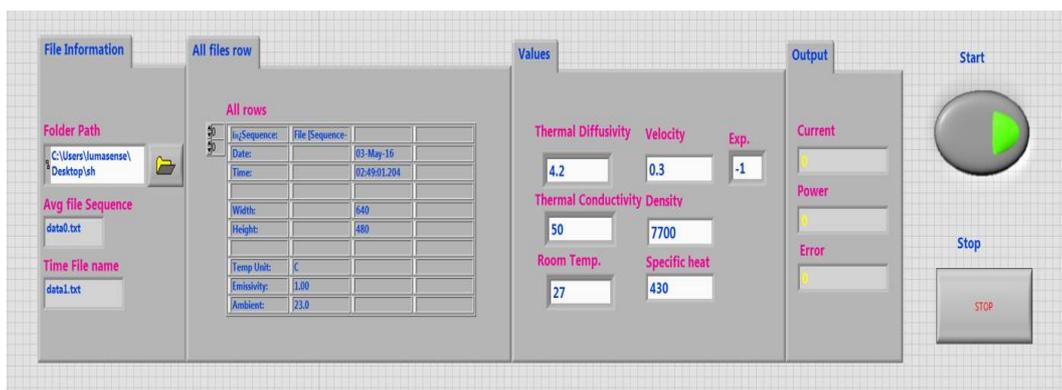


Fig.9. Architecture for closed loop control (offline)

From this architecture we increase or decrease power as per the requirement.

IV.CONCLUSION

This study examines chances of real time monitoring technique attached to LAM. During the deposition, monitoring equipment (MCS640) has been installed inside the LAM chamber. This has captured the temperature distribution in dynamic fashion and also recorded the high temperature values of melt pool and surrounding areas simultaneously. During the LAM process this can be utilized for rapid monitoring of the thermal stability which in turn can be used for controlling laser power. The captured image has also help to recognize, how the defects form and progress during the LAM process. One of the critical factors that affect laser deposition indices such as geometrical accuracy, material



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properties and residual stresses is thermal behaviour of the molten pool. So for on-line quality control during LAM process and to obtain components with desired properties and shapes, architecture for closed loop control through lab view is developed. This is used to manipulate the laser power via a closed-loop controlled processing in which the laser power is controlled to keep the shape (i.e. length and width) of the molten pool constant. The closed-loop controlled LAM process can overcome the effect of the thermal variation and, thus it is important for the consistency in the layered deposition during the process.

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