Vision-based Process Monitoring for Laser Metal Deposition Processes

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Abstract

Laser Metal deposition is a process with immense scope and promise for becoming a robust manufacturing technology in the near future. Monitoring process variables is very instrumental in process planning and output monitoring. The current work deals with realizing the effect of power modulation on size of the high temperature region during deposition with varying powder feed. A thermal camera was used to visualize and analyze the deposition process. The area of the high temperature region through the deposition was identified and compared to realize the effect of each variable parameter during deposition. The power modulation was fruitful in modulating the area of the high temperature zone. Optimum set of parameters to perform deposition were identified.

Introduction

Free form fabrication of metal by direct metal deposition holds up good promise for complex profile fabrication and high precision repair. Direct metal deposition coined at UIUC, a technology where high power laser is focused to melt injected powder stream to build parts layer by layer. This process gives one the scope for great accuracy, controllable microstructure and the feasibility of manufacturing functionally gradient materials [1]. Direct metal deposition techniques such as LENS have been under development by Sandia National Labs with extensive university, industry and government participation [2-5]. Laser melts the powder completely to form dense parts with a small heat effected zone that results in finer microstructure and good material properties [6]. Several aspects of the parts made by the LMD or DMD processes such as strength, surface finish and tolerances are dependent on the thermal history[7].

Monitoring the thermal history during deposition is instrumental in understanding various phenomenon that occur during deposition thus provide basis and rationale for process planning and model validation. Thermal imaging systems have been integrated into the Selective Laser Sintering systems to monitor the thermal history, correlate the outcomes and plan an optimized approach for part manufacture[7-9]. Evaluating the parameters for accurate temperature acquisition involves complexities leaves scope for error.

The phase transformations in metal powder during deposition, melting and solidification results in drop and rise of emissivity. Oxidation of surface results in further difference of emissivity, hence a single value emissivity temperature evaluation requires post processing. However using an infrared camera makes it possible to collect temperature data over a large area at an acquisition rate enough to capture the phenomena occurring during deposition.

Experimental Setup

The infrared camera used, FLIR A615 is an industry automation camera manufactured by FLIR with a resolution of 640x480. The working spectral range of the camera is 8µm to 14 µm. It is equipped with micro bolometers as sensors for temperature measurement. The camera was placed at a distance of 0.4 m from the substrate plates to record the thermal data in the front view. Deposition of 304 Stainless Steel was monitored and analyzed in the current setup. The deposition system is equipped with two closed loop control feedback systems, one aimed at maintaining the amount of energy in the deposit and the other to ensure the height of the build matches the design. The schematic view of the setup is shown in fig 1,

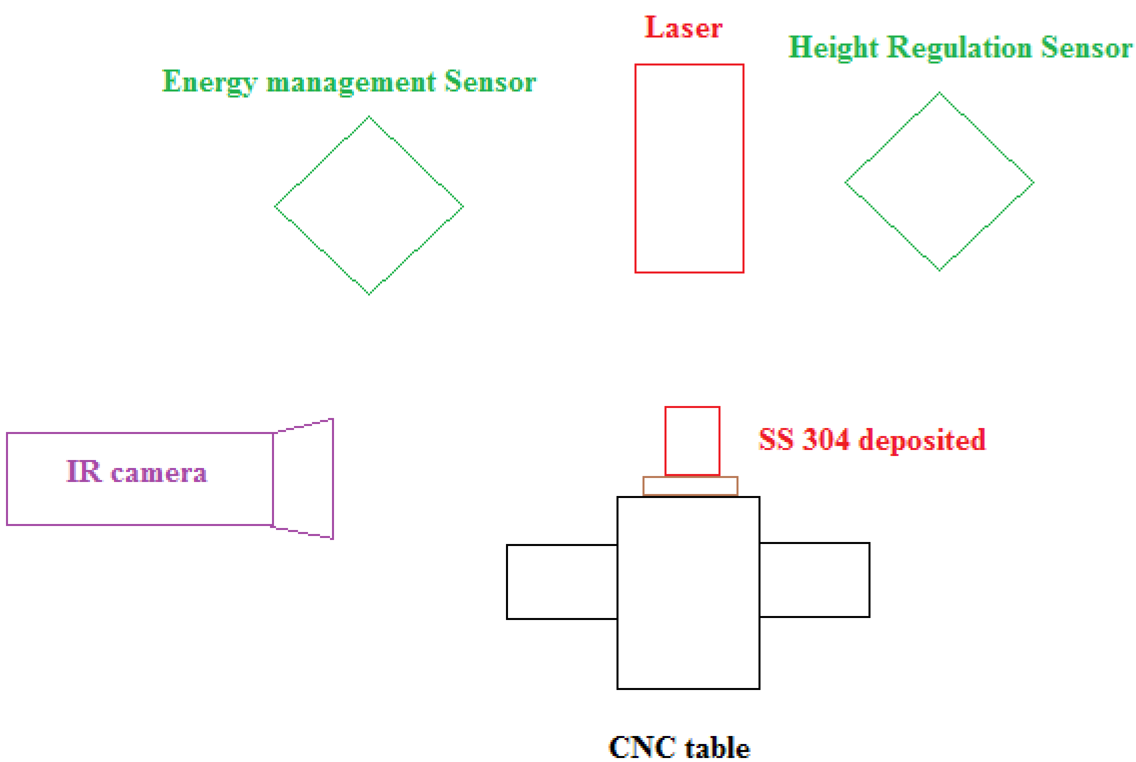

Fig. 1 Schematic side view of experimental setup

Energy management system is incorporated in the setup to ensure homogeneity in the deposit. It is required that all the layers be built in similar environment. In other words establishing a steady state scenario where the heat lost in conduction is replaced by the laser input, in extension maintaining a constant volume melt pool throughout deposition[7-8]. The schematic logic for the control system is shown in fig 2,

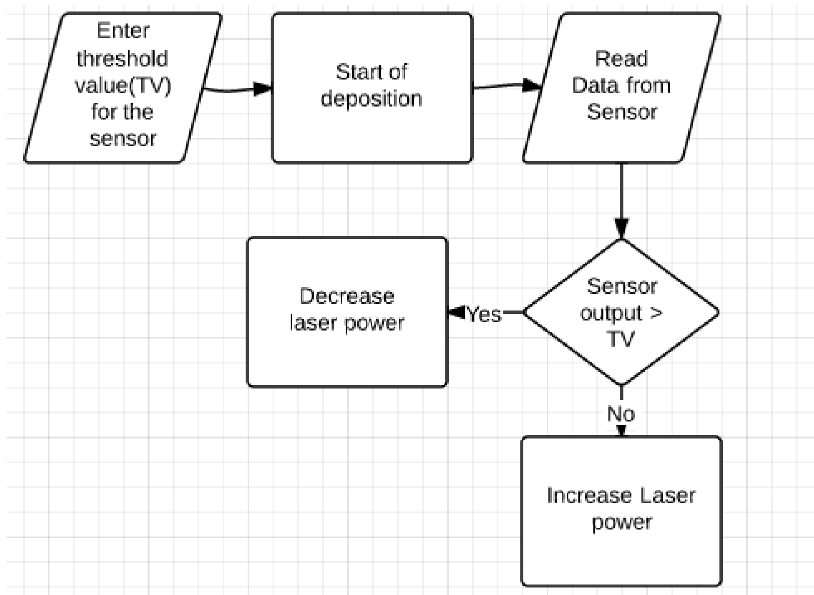

Fig. 2 Flowchart logic diagram for the Energy management system.

Height Regulation System, this system accounts for the height inconsistensies in the build. Thus compensates and skips lag and lead occurences in height. Thereby ensures a perfect build to the prescribed height. The schematic logic for this system is shown in fig 3,

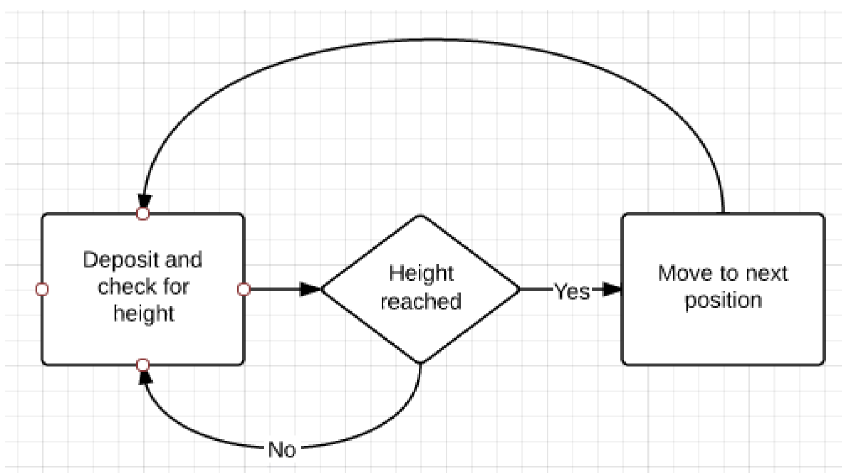

Fig. 3 Flowchart logic diagram for the height regulation system.

IR Camera Integration

The aim of the experiment was to monitor the area of high temperature region in solid state, i.e. the region close to the solidus temperature of SS 304. The liquid metal has a significantly low emissivity compared to solid and hence the apparent temperature (as viewed through the camera) of the melt pool is less than that of the solid region which is the opposite in reality. It is to be understood that if the emissivity value set was equal to that of the meltpool, we would obtain correct range of apparent temperature values for meltpool but the soild portion apparent temperatures would become even larger.

Most oxides have high emissivities, close to that of a blackbody. The deposition by choice was done in an open atmosphere which hence results in extensive surface oxidation. Radiation being a surface phenomenon, the chosen value must pertain to the most available material on the surface. Hence the emissivity must pertain to that of the oxide scale that forms on the deposit. The emissivities of the consituent metal oxides were averaged and applied to the case. The spectral and temperature dependence of emissivity was relaxed for the experiment.

Results

The threshold value for the energy management system was varied and the variation in the area of the high temperature region was visualized. The temperature data was represented by an iron color palatte to visualize the thermal profile of the deposit. An in-situ snapshot of the depostion is as shown in fig 5,

Fig. 5 False colour image of deposit

The temperature data was acquired at a rate of 200 fps. Depositions of the all combinations in parameter domain were acquired and post processed to identify the high temperature region. A temperature cutoff was imposed to shortlist the area that qualifies the criterion. The false color image after post processing at a particular frame during deposition is shown in fig 6,

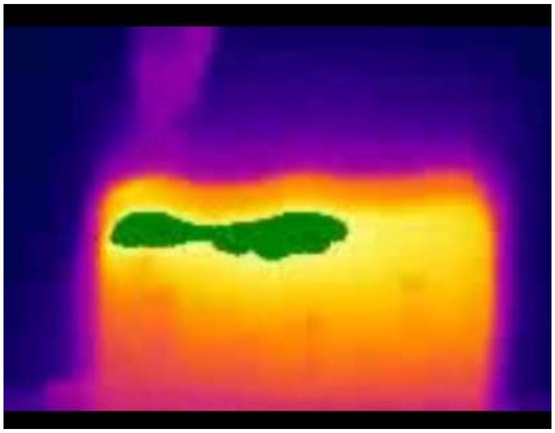

Fig. 6 Green color depicts the high temperature region.

The effect of the energy management system was realized through logging the power modulationfor each of the threshold values. The plot in fig 7 shows power modulation,

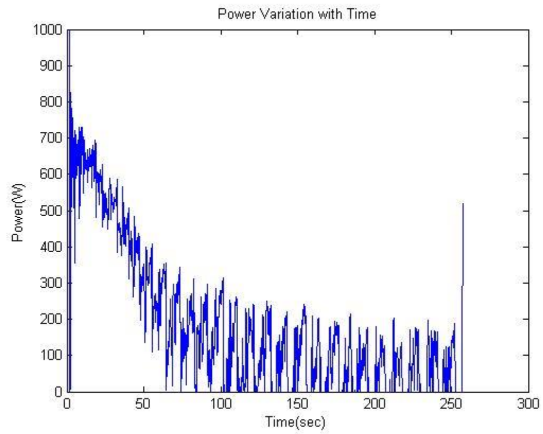

Fig 7. Sample Power log depicting power modulationfor threshold value 1.

The area of the high temperature region vs. time was plotted for settings of 10, 30 and 50 gm/min powder feed rates at each of the threshold values. The obtained results are shown in figures 8-10 as follows,

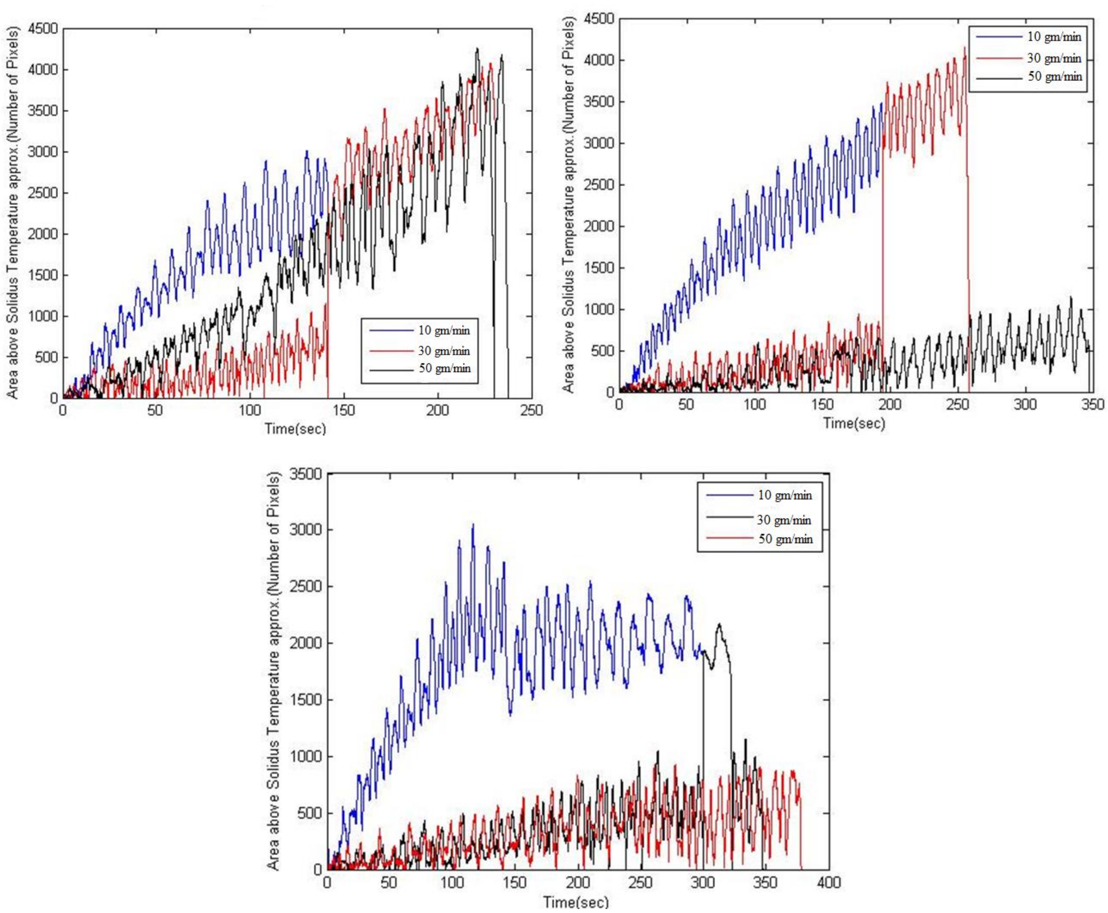

Fig. 8-10. Variation in area of the high temperature region with time.

Discussions

The assumptions on the emissivity compromises the accuracy of the temperature values, hence arriving at a concrete quantitative estimate is not possible. However it is desirable to realize the behavior of the system in a qualitative fashion. The logged power data set with time represents the variation of power with time (fig 7). The area of the deposit above the set temperature has been highlighted green and accounted for each frame (sample, fig 6). This area was then plotted against time (fig 8-10).

The power modulations seem to decay and stabilize around a range for each of the scenario. The decay seems to happen in an exponential fashion. The highest and lowest peaks seem to match the instances when the laser beam is at the extreme ends of the geometry (see fig 7). The peaks in the area graphs also match the positions where the laser is at the extreme ends of the geometry (see fig 8-10). The efficiency of the energy management system is better appreciated from the area of the high temperature region vs. time. Similar to power modulation, the area of the high temperature region also stabilizes around a range of values. The fact that not all set of parameters are optimum is highlighted from the area vs. time plots. The stabilization is different in nature and range for each threshold value. For a chosen threshold value, only a single powder feed rate seems to stabilize with time. In this way for any material system, we can establish an optimum set of parameters or develop a Pareto front with experimental characterization and manufacture good quality deposits. Through consistent control on the high temperature region, we can tailor the material properties and maintain homogeneity.

The non-optimal parameter settings developed a lag in height during deposition. After the point where the lag exceeds the tolerance of the height regulation system, the compensation can be visualized by the sudden peaks in the area vs. time plots (fig 8-10). The height control system causes the depositor to slowdown/ stop at positions of height deficit there by increasing the amount of energy input into a single spot. This in extension translates to increase in the area of high temperature region. The interesting aspect is the absence or minimum involvement of H.R.S. in optimum settings.

Future Work

A more quantitative approach must be developed to understand and control the area of interest. Melt pool visualization and geometry-mapping with respect to time has to be performed. Schemas to achieve precision control on the areas of interest have to be developed and implemented.

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References

1. Jyoti Mazumdar Lijun Song, “Advances in Direct Metal Deposition”, NSF-IUCRC-2010, ppt, University of Michigan.

2. M.L. Griffith et al., “Free Form Fabrication of Metallic Components Using Laser Engineered Net Shaping (LENSTM),”Proc. of the Solid Freeform Fabrication Symp. (Austin, TX: The University of Texas at Austin), p. 125.

3. Dave M. Keicher and John M. Smugeresky, “The Laser Forming of Metallic Components Using Particulate Materials,” JOM, 49 (5) (1997), p. 51.

4. C.L. Atwood et al., “Laser Engineered Net Shaping (LENS™): A Tool for Direct Fabrication of Metal Parts,” Proc. Of ICALEO ’98, (Orlando, Fl: Laser Institute of America, 1999), p. E-1.

5. E. Schlienger et al., “Near Net Shape Production of Metal Components Using LENS™,” Proc. of the Third Pacific Rim International Conference on Advanced Materials and Processing, (Warrendale PA: TMS, 1998), p. 1581

6. Nannan GUO, Ming C. LEU, “Additive manufacturing: technology, applications and research needs”: Front. Mech. Eng. 2013, 8(3): 215–243

7. Diller, T.; Sreenivasan, R.; Beaman, J.; Bourell, D.; LaRocco, J.: Thermal model of the build environment for polyamide powder selective laser sintering, in: Bourell, D. (Editor): Proceedings of the 21st Annual International Solid Freeform Fabrication Symposium (SSF 2010): The University of Texas at Austin 2010, pp. 539-548.

8.Sauer, A.: Optimierung der Bauteileigenschaften beim Selektiven Lasersintern von Thermoplasten, PhD thesis; University of Duisburg-Essen, 2005.

9. Emmanuel Rodriguez, Francisco Medina, David Espalin, Cesar Terrazas, Dan Muse, Chad Henry, Eric MacDonald, and Ryan B. Wicker; “ Integration of a Thermal Imaging Feedback Control System in Electron Beam Melting”, Proceedings of the 23rd Annual International Solid Freeform Fabrication Symposium (SSF 2012): The University of Texas at Austin 2012, pp. 945-961.