Effect of Structured Laser Pulses on Grain Growth in H13 Tool Steel

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Abstract

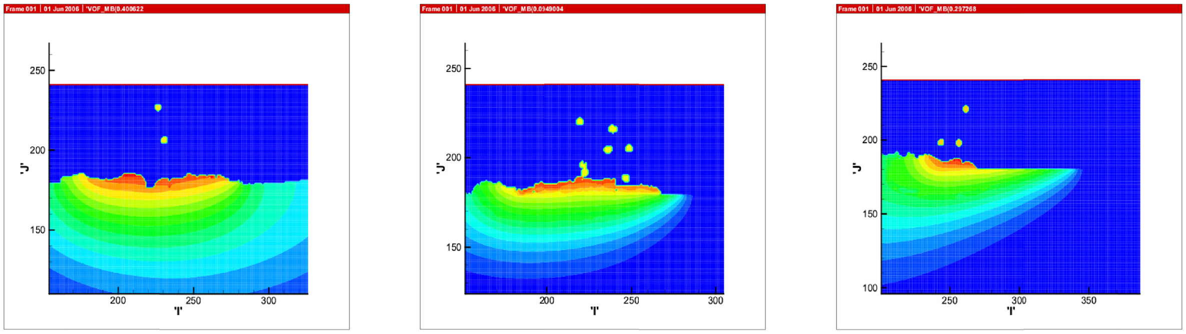
In metal solidification, the cooling rate is an important factor in determining the resultant grain structure of the material. The paper discusses the results of a feasibility study done to determine whether a laser pulse scheme can be designed to affect, and eventually control, the resultant microstructure of the deposited material. A factorial experimental approach is applied to determine the significant parameters affecting grain size and orientation. Parameters investigated include maximum pulse power, pulse frequency, pulse shape, and material feed rate. Particular attention is given to parameter combinations that can cause grain growth through the layer boundaries of the deposited metal.

Introduction

Microstructural characteristics are a major factor in determining the performance of a material. The microstructure of a material is determined by its processing. Thus, there is a significant link between material processing and material performance. Laser metal deposition is typically characterized by high cooling rates, producing a fine grain structure with columnar growth in the direction of the laser's travel [Gao03, Wu04]. However, by using a controlled pulse schedule, it is possible to dictate the cooling rates to affect the solidification microstructure.

The ability to control the solidification microstructure presents two exciting possibilities: location dependent material properties and a reduction in heat treatment time. Location dependent material properties would allow a part to be optimized for high hardness in one location, and high fatigue strength in another, all within the same material. This eliminates material compatibility issues occurring in functionally graded material to achieve similar performance. Also, by tuning the solidification microstructure, it is possible to reduce heat treatment times, or even eliminate the need to heat treat altogether. Heat treatment is a costly and time consuming process, so any reduction in it would be appreciated by industry. Laser processes, such as laser shock peening (LSP) can be used to alter surface properties [Nalla03, Bozdana05]. However, laser additive processes present an opportunity to modify the microstructure of the entire part as it is being constructed.

Numerical simulations conducted by the Laser Aided Manufacturing Processes (LAMP) Lab at the University of Missouri – Rolla (UMR) suggest that laser power determines melt pool depth, as shown below in Figure 1. This suggests that by reducing the laser power at some rate can cause the melt pool to solidify from the bottom to the top at a some controllable rate, as illustrated in Figure 2. Nucleation rates are related to undercooling and the geometry of the liquid/solid interface [Smallman99]. By controlling the rate that the melt pool shrinks, it is possible to promote or retard the rate at which new grains nucleate. This leads to the possibility of selectively producing a wide range grain structures, as suggested in Figure 3.



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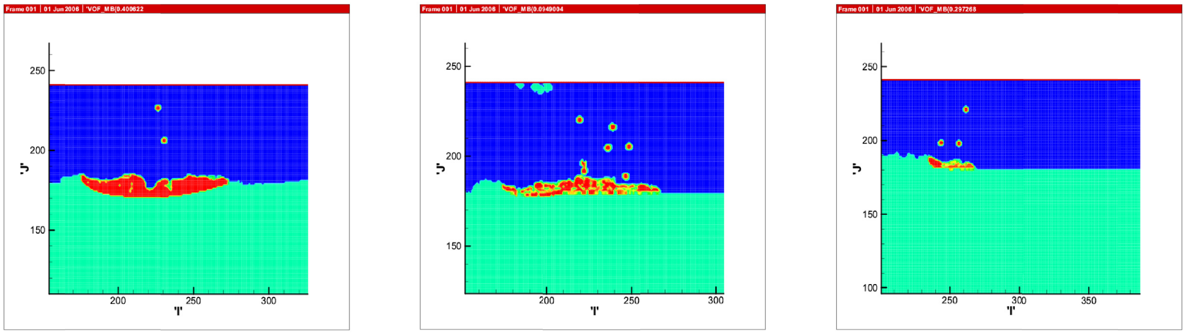

1.0kW, Fluid Field 750W, Fluid Field 550W, Fluid Field

Figure 1 – Parameter Dependence of the LAMP Deposition Process
Temperature Field: The gradient shows temperature difference
Fluid Field: red=liquid, green=solid, blue=gas
(grid size = 20mm, identical mass flow and travel speed for each)

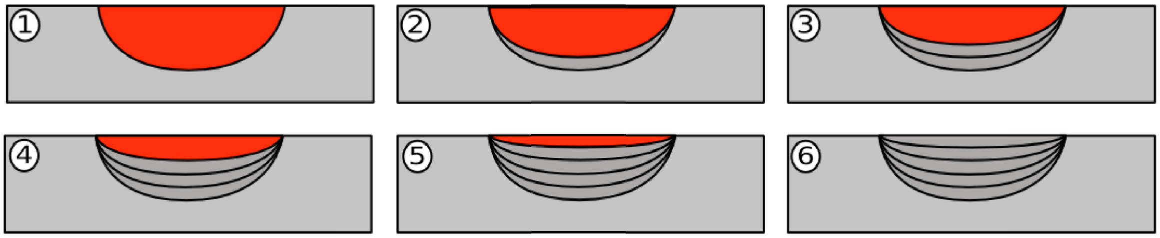

Figure 2 – Melt Pool Solidification

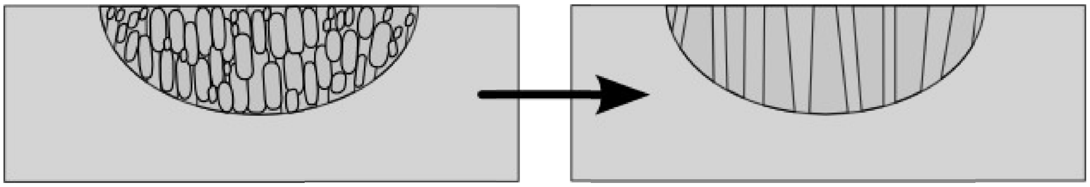

Figure 3 – Range of Possible Grain Structures Created by Controlling Nucleation Rate

This paper summarizes the results of an initial experiment in microstructural control. A factorial experiment was conducted on using a laser pulse to effect the solidification microstructure. A single period of the laser pulse structure used is shown below in Figure 4. The parameters P_{max}, T_{max}, T_{solid}, and T_{cool} are used as factors in the factorial experiment, as well as the powder mass flow rate. The experimental procedures and results are described below.

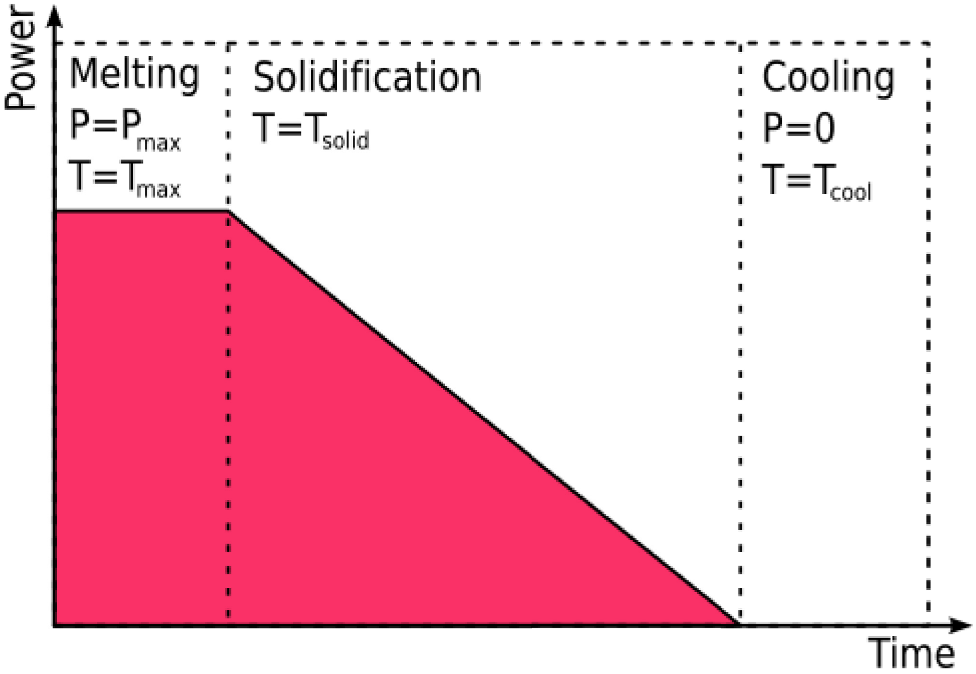

Figure 4 – Laser Pulse Structure

Experiment Setup and Procedure

The experiment was conducted at the LAMP Lab at the UMR. A National Instruments real time controller was used to control the Nuvonyx diode laser to generate the desired pulse shapes. A Bay State thermal spray powder feeder was used to provide a steady state mass flow rate for each run of the experiment.

Figure 5 – Bay State Technologies Model 1200 Powder Feeder

Figure 6 – Precitec YC50 Cladding Head

Figure 7 – 1kW Nuvonyx Diode laser

Figure 8 – National Instruments PXI-8195-RT Real Time Controller

The material used for this experiment is H13 tool steel. Ten substrates, each 0.75" x 0.5" x 0.375" in size, were cut from a single H13 bar. The powder used is a -100+325 mesh, gas atomized H13 powder. A simple jig was constructed to locate the substrates in the LAMP system so that the deposition location will be consistent from run to run. This ensures similar heat transfer conditions for each run.

The experiment, detailed below in Table 1, is a five factor, two level, quarter fraction factorial experiment with two center points. After deposition, the specimens were sectioned via wire EDM, mounted polished, and finally etched with a 2% Nital solution. Optical microscopy was used to measure the grain size, distribution, and preferred growth directions. The results of this analysis are detailed below.

Table 1 – 2^{5-2} Factorial Experiment

Run Order	Std Order	P_{MAX} (W)	T_{MAX} (ms)	T_{SOLID} (ms)	T_{DWELL} (ms)	Powder Flow Rate (grams/min)
1	-	750	600	550	2750	6
2	17	1000	200	100	500	4
3	8	500	200	1000	5000	8
4	32	1000	1000	1000	5000	8
5	29	1000	1000	1000	500	4
6	5	500	200	1000	500	4
7	9	500	1000	100	500	4
8	20	1000	200	100	5000	8
9	12	500	1000	100	5000	8
10	-	750	600	550	2750	6

Experimental Results

At the time of this writing, two of the ten samples, runs 1 and 4, have been observed. Both specimens exhibit similar microstructural characteristics. The center and dilution regions have a fine grain structure with an occasional dendritic structure. The sides of both specimens are characterized by columnar grains with a very high length/width ratio. The conditions used in run 4 produced a significantly longer grain at the edge of the specimen than those produced by the conditions in run 1. In all regions, the preferred growth direction of grains was in towards the source of the laser beam. Figures 9 and 10, below, illustrate the microstructures observed in the two samples.

The tops of both specimens have amorphous structures surrounded by fine grained structures typical of laser deposition with a high cooling rate. These amorphous structures could be partially melted powder particles that fell into the melt pool during the solidification phase of the laser pulse. Synchronizing the powder feeder to the cycle of laser pulses used in this experiment is not yet implemented in the LAMP system, so anomalies such as this are unavoidable.

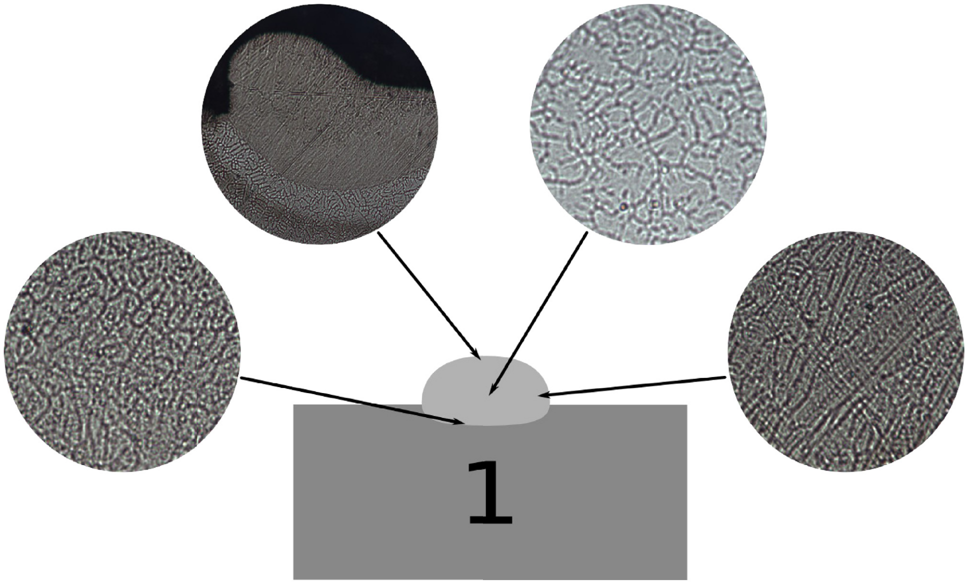

Figure 9 – Microstructure Map of Specimen 1

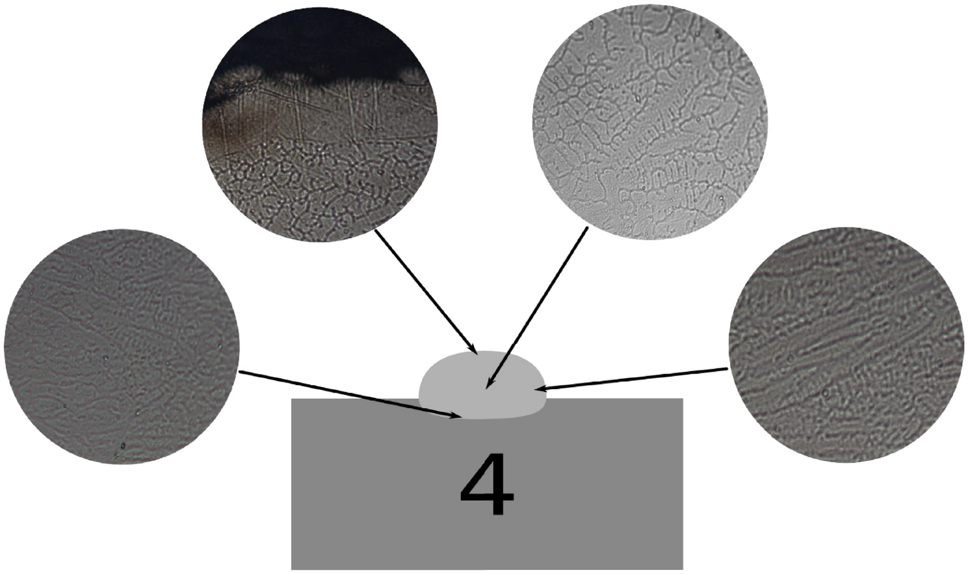

Figure 10 – Microstructure Map of Specimen 4

Table 2 – Grain Size Measurements

		Width (micron)	Length (micron)	L/W ratio
S1 Middle	mean	9.63	21.89	2.38
	stdev	4.4	14.37	1.09
S1 Top	mean	5.24	14.36	3.45
	stdev	2.87	4.18	1.69
S1 Edge	mean	4.43	30.65	7.47
	stdev	1.31	19.78	5.43
S4 Middle	mean	9.77	22.54	2.42
	stdev	4.84	16.63	0.97
S4 Top	mean	13.63	31.34	2.39
	stdev	5.42	18.38	1.49
S4 Edge	mean	13.18	62.51	4.88
	stdev	5.7	43.25	3.06

Analysis and Conclusions

With the limited data available, the only conclusion that can be drawn is that the parameters used by run 4 produces a longer columnar structure at the edge of the deposit than the parameters used by run 1. Since the factorial is incomplete, it is impossible to statistically determine which factor has what effect.

The goal of this project is to find which factors affect grain growth. The two data points presented above represent only a small part of the original experiment. Once complete, a regression model will be used to determine the next course of action in this line of research. A melt pool temperature sensor is already planned for the next phase.

One interested result observed thus far is that the deposit is more difficult to etch than the substrate. After etching with the 2% Nital solution, the deposit remains as shiny as it was before polishing while the substrate has noticeably dulled, as shown below in Figure 11. This behavior was observed in both samples prepared thus far. Since the powder used for deposition and the substrate material are both H13 tool steel, the corrosion resistance must be a microstructural characteristic.

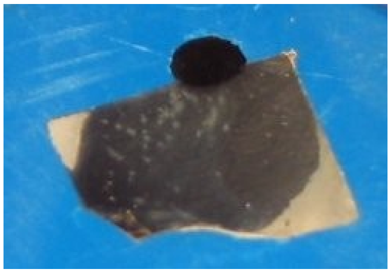

Figure 11 – Specimen 4 post etching

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