PROCESS VARIABLE EFFECTS ON LASER DEPOSITED Ti-6Al-4V

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Abstract

An initial study of the processing parameters affecting deposition quality of Ti-6Al-4V was conducted using the LENS™ direct laser deposition system. The significant number of process variables presents a problem in determining relative effects. A few of the easily identifiable variables were isolated and the deposits were characterized qualitatively by comparison of layer adhesion, porosity, and dimensional accuracy. These characteristics were compared for each deposit while processing variables such as laser power, travel speed, and hatch spacing were varied. The results led to the development of a set of optimum processing conditions that produce a quality deposit.

Introduction

Direct laser manufacturing technology has developed rapidly in the recent past [1-4]. Though it has been shown to be a potentially useful manufacturing technique, there are aspects of the process that remain to be fully understood. Various systems exist with different heat sources, fixturing, and materials delivery. Although the setup of each system is unique, there exist certain process variables that are common to all. These process variables need to be interrelated to determine the optimum conditions needed to achieve a successful deposit. By studying these process interactions, a "recipe" can eventually be determined that will yield a fully dense, near-net shape part in the shortest time possible, thus making laser direct fabrication feasible in large scale manufacturing. The purpose of the present study is to develop a basic understanding of how these process parameters interrelate and also will lay the groundwork for future, more comprehensive studies.

Experimental Procedure

The experiment was planned so that appropriate data could be analyzed by statistical methods. This was done using MINITAB statistical analysis software. The following six process variables, or factors, were chosen for this analysis: travel speed, laser power, stand-off distance, hatch width, layer thickness and powder flowrate. These factors and their ranges were selected based on previous experience and process knowledge. For each factor two levels, high and low, were selected, a common strategy in a screening analysis. The optimum performance is assumed to be within these levels. The factors and their different levels are shown in Table 1.

The method of design chosen for the experiment was a 2^k factorial design, where k is the number of factors. With six factors the experiment has $2^6 = 64$ combinations (runs) to obtain a full factorial

Variables	Low	Zero	High
Laser Power (W)	300	350	400
Travel Speed (in/min)	10	15	20
Powder Flowrate (g/min)	1.30	1.95	2.60
Hatch Spacing (in)	0.010	0.015	0.020
Layer Thickness (in)	0.010	0.015	0.020
Stand-off Distance (in)	6.000	5.980	5.960

Table 1: *Process variables and experimental low, zero, and high values.*

design with full resolution. Performing 16 runs, 2^{6-2} factorial offers a ˘ factorial design with a resolution IV, which is sufficient for a screening design of experiments [5]. Two replicates were taken, which is important for significance testing and to obtain an error, for a total of 32 experiments. Three center points, median values between high and low, were included bringing the total number of runs to 35. These center points give additional information about the array of factors spanned. Since the sequence of experiments was randomized, every experiment was re-setup and rerun, involving complete rebuilding of the experimental trial from ground up. After designing the experiment as described above, the program created a randomized data matrix. This matrix outlines the level (high or low) for all six factors of each run. The order of the runs was randomized to account for the unknown influence between factors.

The 35 samples were deposited on four separate 0.040" thick pieces of Ti-6Al-4V sheet. Consecutive samples were placed on different substrates to minimize heat buildup. There was, however, considerable warping of the substrates due to unavoidable thermal stresses. The heat source was a 750 watt Nd:YAG laser delivered via fixed optics. Calibration of the laser power was done by pulsing the laser for a set time and reading the absorbed power on a calorimeter. 300 watts is approximately the minimum heat input needed to yield a fully remelted deposit, thus it was chosen as the lower limit and 400 watts was chosen as the high limit. The stand-off distance was determined based on the six inch focal length of the lens. Previous work had shown that working slightly overfocused produced desirable results. Thus, the low value was made to be 0.040" overfocus and the high value at sharp focus. The geometry of the deposits was 1 cm by 1 cm square by 10 layers high. Each layer alternated travel direction by 90°. Figure 1 shows the buildup geometry of the deposits. The hatch width was calculated based on a hatch overlap of about 60%. Thus, with an approximate laser spot size of 0.050", the optimum spacing is 0.015" between each pass. This was assigned the zero value and high and low values were assigned at ± 0.005". Layer height values were determined by the maximum

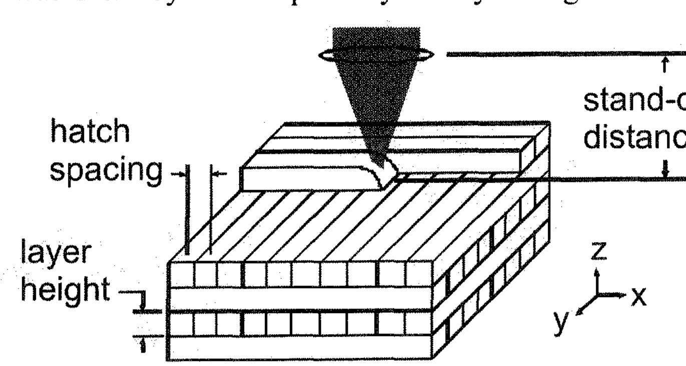

Figure 1: *Schematic of test sample showing geometrically dependent process variables.*

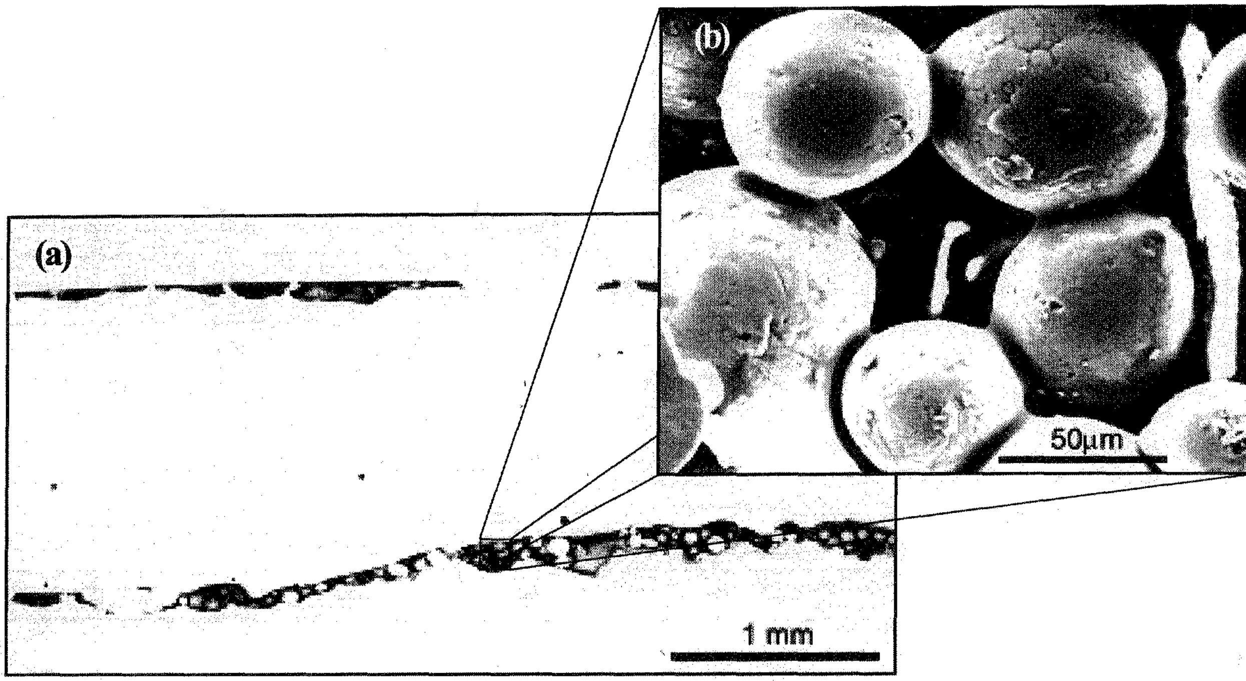

Figure 2: (a) Scanning electron micrographs of a sample showing large amounts of porosity between layers, (b) close-up of porous area showing unmelted powder.

height that could be built up by a single laser pass. Based on this, the upper limit was set at 0.020" and the lower bound was set at half this value, 0.010". Powder mass flowrate values were assigned arbitrarily since no prior calibration had been done. To calibrate the flowrate, the powder delivery motor speed was adjusted and powder was collected from the nozzles for a given time. The powder was then weighed and an approximate flowrate was assigned to each value on the motor speed dial. Travel speed values were assigned based on previous work showing that 20 inches per minute was the maximum speed that produced an acceptable deposit.

Two response variables were selected for this screening analysis; the final build height and the density. Since the expected build height varied from sample to sample (10 layers at 0.010", 0.015" or

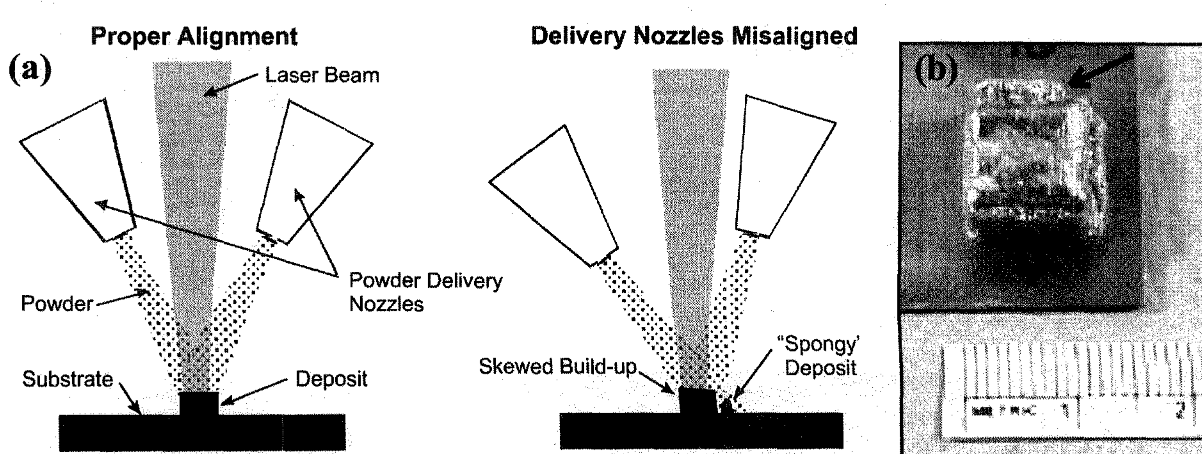

Figure 3: (a) Schematic showing how nozzle mis-alignment can affect the quality of the deposit (b) Photo of a sample showing "spongy" deposit on side of cube.

0.020" per layer) the measured response was assigned a percentage of the expected value. A transverse section was taken through each deposit and the buildup height was measured in the center of the section using calipers. Half of each sample was then mounted and examined for porosity using both optical metallography and scanning electron microscopy (utilizing a FEI/Philips XL-30 FEG). The porosity measurements were taken from top to bottom in the middle of the cross-section. This was done to reduce error since the porosity was highly localized at the layer interfaces instead of evenly distributed. This method is valid only as a comparison for samples within this study. Figure 2 depicts the localized porosity at the layer interfaces. Moreover, the close-up shows unmelted powder in the macro pores.

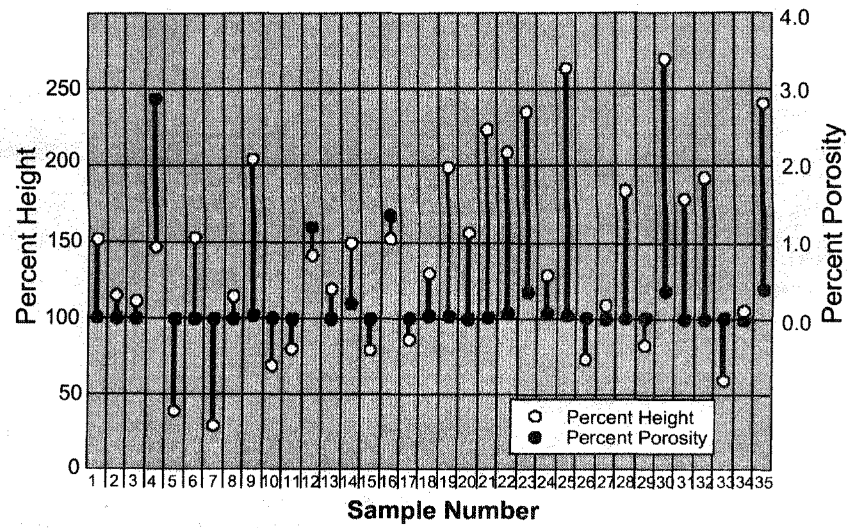

Figure 4: Graph showing the build height and density results for each sample.

Results and Discussion

Visual inspection of the finished samples showed varied results. Some deposits showed good dimensional accuracy while others were quite misshaped. Some of the thicker deposits showed an unusual spongy deposit on two sides of the cube. After breakdown and inspection of the machine, it was apparent that the four powder delivery nozzles were not aligned properly. Figure 3 shows an exaggerated schematic of the delivery head and how the spongy deposit is formed and the resultant buildup is not uniform. Some powder from the left nozzle flows through the laser focus but does not end up in the weld pool but slightly

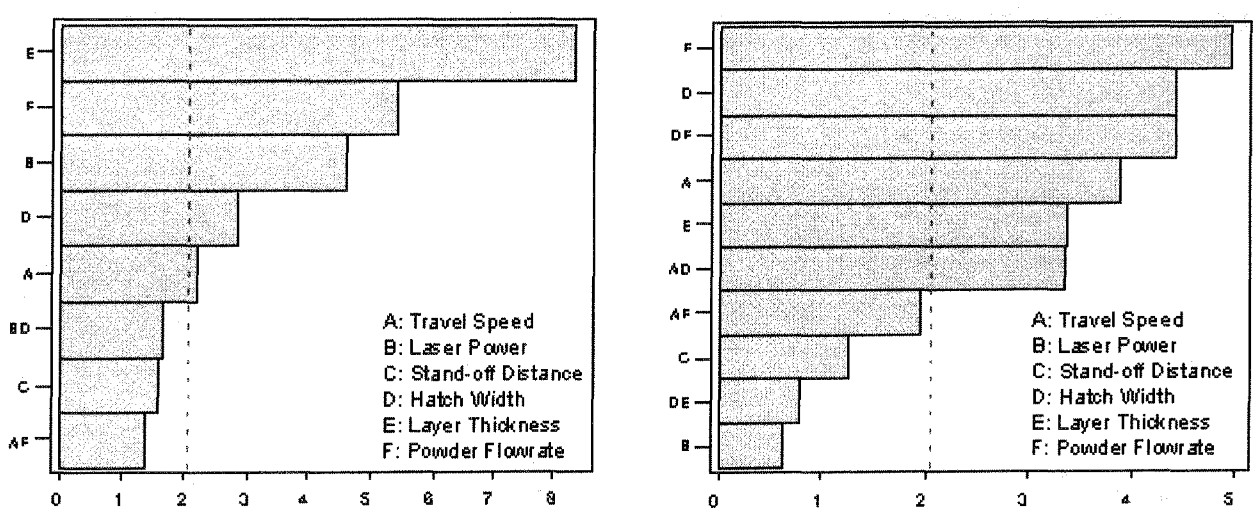

***Figure 5:** Pareto charts showing significance of variables. Chart on left shows response to layer height and the chart on the right shows the respose of porosity.*

Coefficient	Height	Porosity
Travel Speed	-10.91	-0.2086
Laser Power	22.68	-0.0295
Stand-off Distance	7.72	insignificant
Hatch Width	-14.06	-0.2381
Layer Thickness	-41.32	0.1815
Powder Flowrate	27.03	0.2651
Constant	142.62	0.2547

Table 2: *Coefficients of the linear-fit model for each response.*

to the side of it. This results in an overshoot of molten powder and a distorted buildup.

Subsequently, the samples were examined using microscopy and the raw data from the response variables is shown graphically in Fig. 4. From this chart, it can be seen that very few of the samples obtained both dimensional accuracy and low porosity. Finally the responses were statistically analyzed using MINITAB®. Plots of main effects versus responses were obtained. From this analysis, a model was created and the results are depicted in the Pareto charts shown in Fig. 5. The Pareto chart ranks the factors according to their importance for achieving the desired response for the process. The dashed line serves as a standardized threshold. Only factors extending to the right of that line are of statistical significance. Thus, with respect to sample height, the two most important variables are layer thickness and powder flowrate. For porosity, the two most important variables are powder flowrate and hatch width *plus* their interaction. There were no 3-factor or higher interactions of statistical significance. Some 2-factor interactions were not significant and were thus taken out of the model. The equations representing the linear model for the two responses are shown in the Table 2. These coefficients represent an equation of the form:

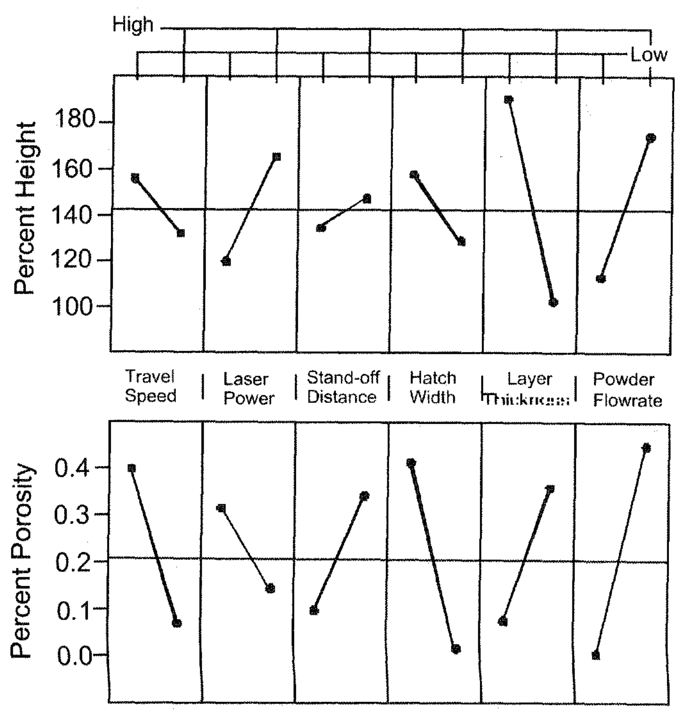

Figure 6: *Graphs showing the main effects of the process variables on the given response. For these graphs, the slope determines the level of significance.*

$$\text{Percent Height} = -10.91\bullet\text{Travel Speed} + 22.68\bullet\text{Laser Power} + 7.72\bullet\text{Stand-off Distance} - 14.06\bullet\text{Hatch Width} - 41.32\bullet\text{Layer Thickness} + 27.03\bullet\text{Powder Flowrate} + 142.62$$

The results from the model equations and the Pareto charts are different for the two responses. Eighty percent of the significant contributions in the model for height come from single factors, only 2% come from 2-factor interactions. Whereas in the model for porosity only 44% of the contribution come from single factors, but 36% from 2-factor interactions. Therefore 2-factor interactions are negligible in the first case, whereas in the latter they are of importance. Powder flow, layer thickness, hatch width and travel speed are among the most influential factors in both models. Focus does not seem to be of importance in either case, as was assumed after performing the experiment. This factor can be excluded in future analysis.

Figure 6 shows the main effects of the process parameters for both measured responses. The slope of each line is directly proportional to the importance of each variable; i.e. the steeper the slope, the more importance the variable has on the given response. Negative slopes have negative effects and positive slopes have positive effects. A comparison between the graphs of the main effects shows that travel speed and hatch width have negative effects; meaning running these parameters at a high level would produce a desirable response. Powder flow has a positive effect in both cases. To obtain a good response powder flow has to be at a low level. This can also be implied from the raw data by noting that 26 of 35 samples (74%) have higher than expected final heights. This indicates that lower powder flowrates should be examined. The effect of the laser power as well as thickness is opposite for the different cases. Comparing the responses of similar runs for the two replicates shows that the reproducibility of the experiments is not very good. The experimental error is 9% for the height and 13% for the porosity data.

Conclusions

Six process variables were chosen and their influence on the deposited samples was analyzed by means of a screening factorial design of experiments. From these experiments, it was concluded that stand-off distance could be ignored as a process variable. Also, the powder flowrate is crucial in obtaining an acceptable deposit. Unfortunately, this is the one variable that currently cannot be monitored during the process. Calibration of the flowrate must be done prior to deposition and the assumption is made that it remains constant. This issue must be addressed before further studies are conducted. Future tests must include more replicates to help reduce the error and increase the reproducibility.

References

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