A Design of Experiments Approach Defining the Relationships Between Processing and Microstructure for Ti-6Al-4V

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Abstract

A study was conducted to evaluate the relative significance of input parameters on Ti-6Al-4V deposits produced by an electron beam freeform fabrication process under development at the NASA Langley Research Center. Five input parameters where chosen (beam voltage, beam current, translation speed, wire feed rate, and beam focus), and a design of experiments (DOE) approach was used to develop a set of 16 experiments to evaluate the relative importance of these parameters on the resulting deposits. Both single-bead and multi-bead stacks were fabricated using 16 combinations, and the resulting heights and widths of the stack deposits were measured. The resulting microstructures were also characterized to determine the impact of these parameters on the size of the melt pool and heat affected zone. The relative importance of each input parameter on the height and width of the multi-bead stacks will be discussed.

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Introduction

Electron beam freeform fabrication, EBF^3, is a promising new process for direct fabrication of metal components. There is a growing interest in industry for applying this technology for adding details onto simplified preforms, fabricating complex structures, and repairing worn or damaged parts. [1] However, process repeatability is paramount to insertion of this technology from the research environment into industrial applications. A thorough understanding of the process is necessary to develop closed-loop process control to attain consistency in the parts fabricated. [2,3] In this study, a design of experiments (DOE) was conducted [4] as a first step in understanding the EBF^3 process so that full computerized process control may be achieved. DOE is a systematic approach to minimizing the number of experiments required to obtain the breadth of the processing envelope and the influence of the process parameters on the geometry, dimensions, and quality of the deposited part.

The EBF^3 process uses a focused electron beam in a 10^{-5} Torr vacuum environment to create a molten pool on a metallic substrate. The part is translated with respect to the beam while wire is fed into the molten pool to build up the part in a layer-additive fashion. The tool path is controlled by G-code (a commonly used numerically-controlled machining code) that is generated either by directly programming the EBF^3 system or by post-processing a Computer-aided design (CAD) drawing of the part.

Experimental Procedures

Design of Experiments

An experimental test schedule was selected using a DOE approach to examine the role of various process parameters on the resulting EBF^3 deposits. This streamlined approach minimizes the number of experiments required and provides a systematic way to evaluate the influence of individual parameters and their interactions on the output. A two-level design, where each parameter is assigned a high or low value, was used in this study. A set of unique experimental conditions are generated and the appropriate experiments performed by systematically varying the combinations of high and low parameters. A suitably-constructed "factors" array, formed by normalizing the parameter's high and low values to +1 and -1, serves as a basis for statistical analysis of the experimental output. The results of the analysis are used to evaluate the relative importance of the parameters and their interactions and to generate empirical process models that can be used to guide subsequent production runs.

Five input parameters and two outputs were chosen in order to produce a manageable number of experiments. The input parameters chosen were beam voltage (V), beam current (C), translation speed (T), wire feed rate (W), and beam focus (F). Although there are many other input parameters that affect the EBF^3 process, these were selected because they are the most easily adjusted and believed to be the most influential on the process. The high and low values for the focus were interpreted as a defocused and focused beam, respectively. A half-factorial DOE for five parameters at 2 levels results in the 16 experiments described in Table 1. The interaction of beam focus with the remaining four parameters and four-way interactions were not evaluated to simplify the analysis. This allowed evaluation of the five parameters plus all two- and three-way linear interactions among voltage, current, translation speed, and wire feed rate with the16 experiments.

EBF^3 Processing

Experiments in this study were performed using Ti-6Al-4V base plate that was 6 inches wide by 12 inches long by 0.2 inches thick and Ti-6-4 wire that was 0.063 inches diameter. The Ti-6-4 base plate was fixtured to the positioning table in the EBF^3 system. Three type K thermocouples were attached to the back of the base plate for temperature measurements. The thermocouples were evenly-spaced across the width of the plate and located in the center along the length. One panel was produced for each of the processing parameter combinations in the DOE, consisting of three 10-inch long parallel lines deposited on a single base plate. The first pass for each line deposited was performed at the same translation speed as the experiment to be performed, but at half power, to remove oxides and preheat the base plate for improved bonding of the deposit. The first line consisted simply of this preheat pass. The second line was the preheat pass followed by a single bead deposit. The third line was a preheat pass followed by approximately eleven beads deposited in rapid succession, which is termed a stack.

Table 1. Test schedule of EBF[3] process parameters resulting from the DOE approach

Experiment Number	EBF[3] Process Parameters				
	Voltage[1]	Current[1]	Translation Speed[1]	Wire Feed Rate[1]	Focus[2]
1	-1	-1	-1	-1	-1
2	-1	-1	-1	+1	+1
3	-1	-1	+1	-1	+1
4	-1	-1	+1	+1	-1
5	-1	+1	-1	-1	+1
6	-1	+1	-1	+1	-1
7	-1	+1	+1	-1	-1
8	-1	+1	+1	+1	+1
9	+1	-1	-1	-1	+1
10	+1	-1	-1	+1	-1
11	+1	-1	+1	-1	-1
12	+1	-1	+1	+1	+1
13	+1	+1	-1	-1	-1
14	+1	+1	-1	+1	+1
15	+1	+1	+1	-1	+1
16	+1	+1	+1	+1	-1
Notes:	[1] High: +1, Low: -1		[2] Defocused beam: +1, Focused beam: -1		

The widths and heights of the stacks were measured using calipers. Height measurements were determined by measuring the total height and subtracting the average base plate thickness.

Metallurgical specimens were also removed from selected panels and prepared for metallurgical analysis. Samples were prepared using standard metallographic preparation techniques and imaged using bright field in an optical microscope. This allowed verification of the height and width measurements and comparison of the heat affected zone and melt pool depths using scaled micrographs.

Results & Discussion

Experimental Results

The caliper measurements of the stack widths were found to correlate well with selected stacks measurements using metallographic techniques. Height measurements were more problematic. Many of the experimental conditions produced "bulging" on the back side of the base plate which made measurement with calipers difficult. This effect was encountered on all experiments produced with the low translation speed, presumably caused by the increased heating of the panel as the beam takes more time to make its traverse. Selected specimens were mounted and polished, and the height of the bulge was measured from scaled micrographs. To

correct the caliper measurements for this bulge the average value of the bulge height was then subtracted from the caliper measurements for panels which were deformed.

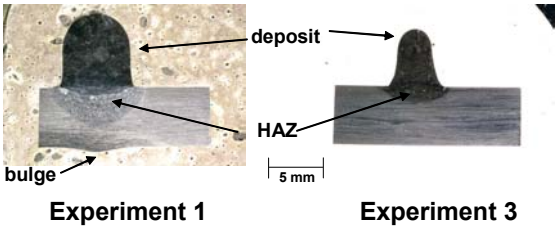
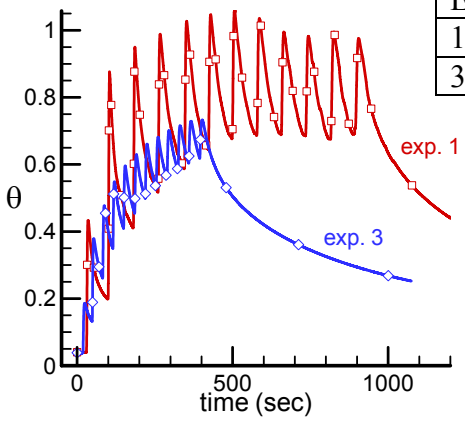


Figure 1. Micrographs of multi-bead stacks produced by experiments 1 and 3.

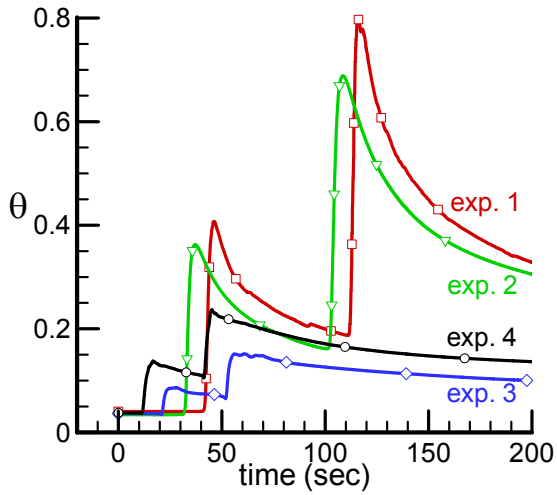


Exp	T	W
1	-1	-1
3	+1	-1

Figure 2. Normalized temperature history on the back side of the plate during the multi-bead stacks produced by experiments 1 and 3

Figure 1 illustrates this bulge as well as some of the variation in width and height that was encountered. This figure compares a multi-bead stack produced by experiment 1 which produced a bulge with experiment 3 which did not. These two deposits were made with the same voltage, current, and wire feed rate, but experiment 1 was produced with the low translation speed and experiment 3 the high. The figure shows that experiment 3 produced a narrow stack with a small heat-affected zone, while experiment 1 produced a wider stack, a heat-affected zone (HAZ) that extends deep through the thickness, and distortion on the backside of the base plate. The increased width of the stack shown produced by experiment 1 is consistent with the low translation speed, as this allows for a greater volume of material to be deposited per length of deposit. Also, a deeper heat affected zone is consistent with higher heating from the low translation speed. The higher heating of the lower translation speed is also evidenced in the thermocouple data (normalized to the maximum measured temperature) presented in Figure 2, showing that experiment 1 produced higher back side temperature compared to temperatures compared to experiment 3.

The normalized data for the thermocouples located directly below the deposit on the back side of the plate for single bead runs are shown in Figure 3. Each line on the graph represents a particular set of processing parameters, in this case those for experiments 1 through 4. For each line, there is an initial peak in temperature that corresponds to the preheat pass at half power followed by a higher peak that corresponds to the deposit of a single bead. These results again show that the low translation speed (experiments 1 and 2) produced a higher back side temperature than the high translation speed (experiments 3 and 4).



exp.	T	W	F
1	-1	-1	-1
2	-1	+1	+1
3	+1	-1	+1
4	+1	+1	-1

Figure 3- Normalized temperature history on the back side of the plate during the single bead runs of experiments 1-4.

Micrographs of the melted region produced by the pre-heating pass in experiments 3 and 4 are shown in Figure 4 to compare the effect of beam focus. These two experiments were performed at the same voltage, current, and translation speed, and since it was the pre-heating pass, the wire feed rate can be ignored. The normalized data from the thermocouple located directly below the beam on the back side of the plate for the heating pass of experiment numbers 3 and 4 is shown in Figure 5. Beam focus is the only processing parameter that differs for these runs. The sharp focused beam results in a higher backside temperature than the defocused beam, but both peak temperatures are low. The micrographs in Figure 4 show the melted region and heat affected zone for these passes to be similar in size and shape. Figure 6 shows higher magnification micrographs for the samples presented in Figure 4. Again, although there is arguably a small difference between these two specimens, the two experimental conditions produced microstructures that are remarkably similar in size and morphology. These results suggest that changing the beam focus produces a negligible effect on the width of the melted pool and can, therefore, be discounted as an important parameter.

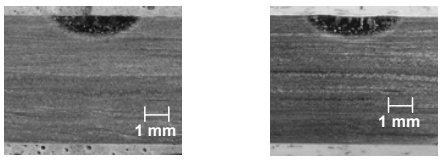


Figure 4 – Micrographs of results produced by the pre-heating pass of experiments 3 and 4.

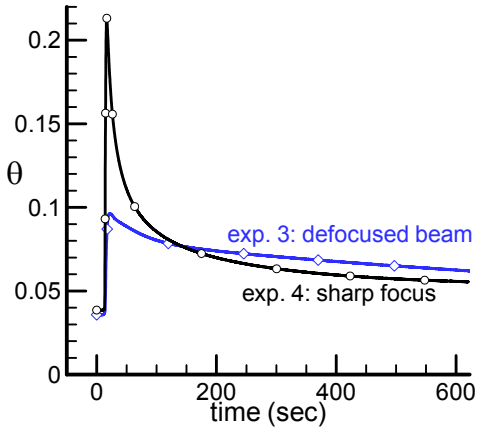


Figure 5 – Micrographs of results produced by the pre-heating

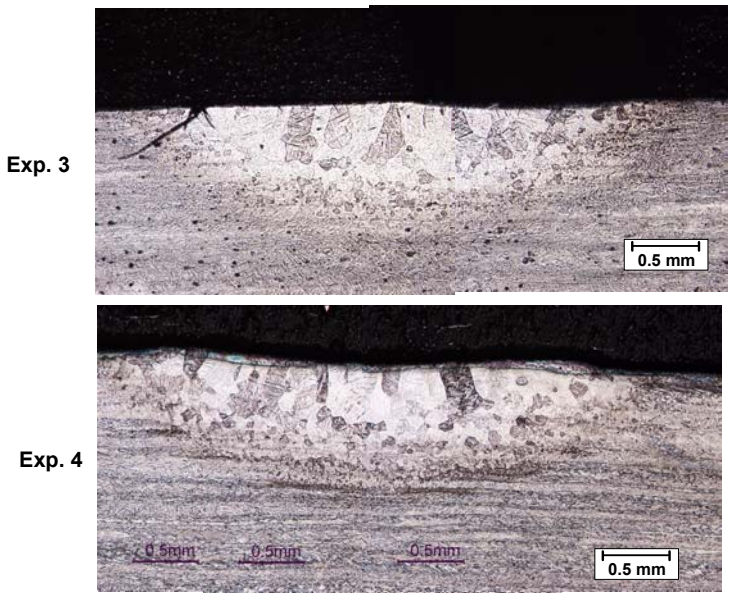
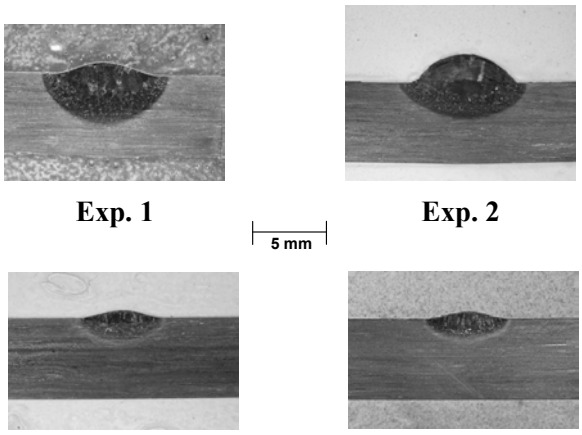


Figure 6. Higher magnification micrographs of pre-heating passes performed for experiments 3 and 4.

Figure 7 compares micrographs of the microstructure produced by the single-bead stack produced by experiments 1 through 4 (See Figure 3 for corresponding thermocouple data.) All four were produced at the same voltage and current setting, and if the focus can be discounted by the previous argument, then these micrographs show the differences produced by varying translation speed and wire feed rate. For instance, comparing experiments 1 and 3, and similarly experiments 2 and 4, shows the differences produced by translation speed. Experiments 1 and 3 were both produced with the low wire feed rate, and experiments 2 and 4 with the high wire feed rate, but with differing translation speeds. Both of the comparisons show that the faster translation speed produces a bead with smaller width, height, and depth of heat affected zone. Comparing experiments 1 and 2, and similarly experiments 3 and 4, shows the differences produced by varying wire feed rate. Experiments 1 and 2 were both produced with the low translation speed, and experiments 3 and 4 with the high translation speed, but with differing wire feed rates. Comparison of the micrographs show that increasing the wire feed rate leads to an increase in deposit height but no measurable change in width. The change in height is less noticeable for the fast translation speed (experiments 3 and 4), but this would be expected due to the smaller volume of material being deposited.



exp.	T	W
1	-1	-1
2	-1	+1
3	+1	-1
4	+1	+1

Figure 7. Micrographs of single bead passes produced by experiments 1 through 4.

DOE Analysis Results

One panel per condition has been completed to date, and the resulting stack height and widths were measured. This lack of replication does not allow for a full analysis of the data and generation of a meaningful process model. However, the results were sufficient to examine the relative importance of the parameters by way of marginal mean plots and Pareto diagrams of the half effect values. [4]

These analyses start with averages of appropriate sets of the output of interest, in this case height or width. For each input parameter, j, and therefore each column of Table 1, there are two marginal means: an average of the output corresponding to a high parameter value (+1), denoted by m_j^+, and an average of the output corresponding to a low parameter value (-1), denoted by m_j^-. The more significant the impact of the parameter on the final output, the bigger the difference between these two averages $| m_j^+ - m_j^- |$. The marginal mean plots provide a visual way to evaluate the relative significance of the parameters, and are generated by plotting the marginal mean values for each parameter. For a 2-level DOE, the half effect is simply one half of the difference between the two marginal means for the parameter, $| m_j^+ - m_j^- |/2$. Again, the magnitude of the half-effect for a parameter indicates the significance of its impact on the output.

The marginal mean plots for stack widths are shown in Figure 8 for the input parameters (V = voltage, C = current, T = translation speed, W = wire feed rate, and F =focus), and the corresponding half effect chart is shown in Figure 9. These results suggest that the most significant parameter affecting the width of the deposit is translation speed, with decreasing effect for voltage, current, and wire feed rate. Focus appears to have the smallest effects on the stack width. The marginal mean plot also shows how the stack width varies with each parameter; increasing voltage or current produces an increase in stack width, while increasing translation speed or wire feed rate produces a decrease in stack width. The result of extending the half effects analysis to include interactions between the parameters is shown in Figure 10. These

results show that none of the interactions between parameters appear to have a significant impact on the resulting stack width. However, interactions between current, translation speed, and wire feed rate; translation speed and wire feed rate; and voltage and wire feed rate are more significant than beam focus.

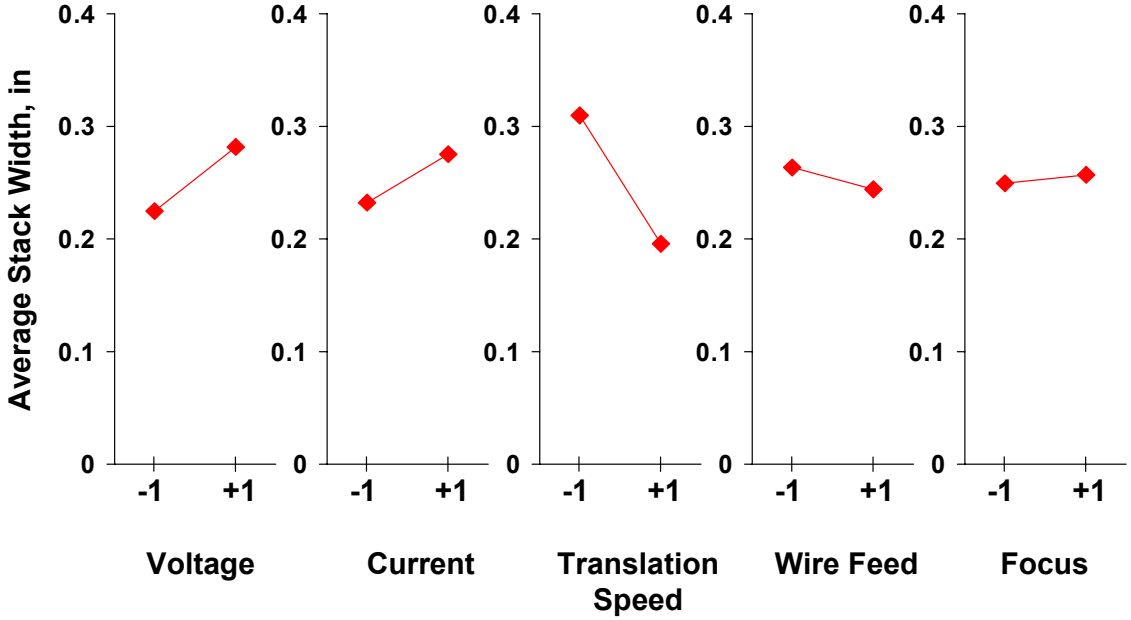


Figure 8. Marginal mean plots for average stack widths

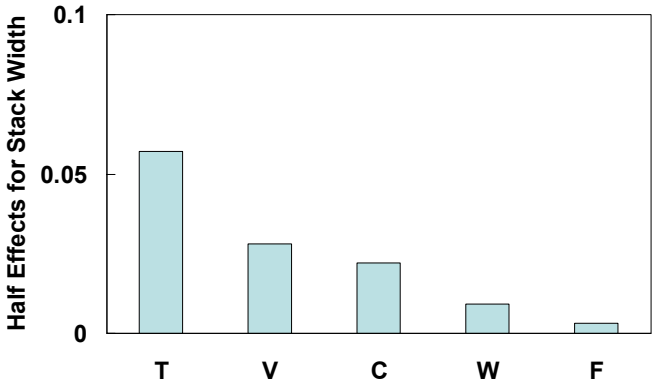


Figure 9. Stack width half-effects for input parameters with no interactions.

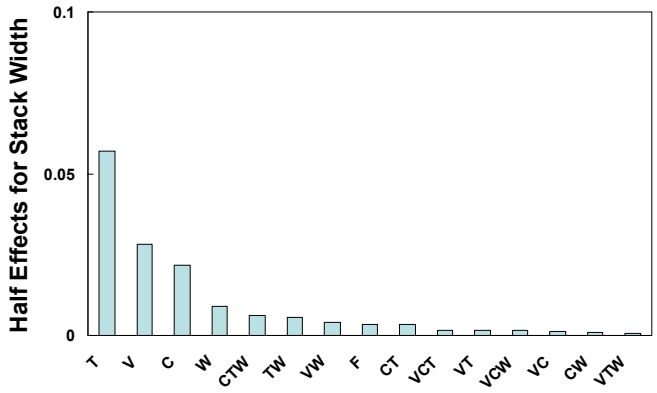


Figure 10. Stack width half-effects for the input parameters with some interactions.

The marginal mean and half effects analysis results for the stack height of 11 beads are shown in Figures 11 and 12. The data for stack height is not as complete as the data for stack width for two reasons. First, the panels produced at a low translation speed bulged at the back side of the multi-bead stacks making accurate height measurements difficult; the present analysis used the heights after correction for this bulge (See earlier discussion.) Second, due to processing difficulties, several of the stacks were produced with fewer beads, and the height measurements could, therefore, not be included in this analysis. Further work will be necessary to conduct a more thorough analysis; however, the results in Figures 11 and 12 still show some useful general trends. As in the analysis of stack width; translation speed, voltage and current are all significant parameters. In this case, however; increasing the translation speed, voltage, or current will cause a decrease in the stack height. The wire feed rate is the parameter with the most impact on the resulting stack height. Focus still has a small effect, but the results suggest that it has a larger effect on the height than it has on the width.

The results of the DOE analysis are all intuitively consistent with the EBF^3 process. Several experimental parameters considered in this study would influence the deposit width by controlling the amount of input energy. Anything that would increase the input energy would be expected to increase the size of the melt pool, thus increasing the width of the deposit. Current and voltage would have an obvious impact on the input energy, and increasing either parameter would be expected to increase the deposit width. However, the translation speed of the beam would also influence the total input energy. Decreasing this speed would increase the amount of time the beam spends over a particular location, increasing the energy input and thus increasing the deposit width. These arguments are consistent with the DOE analysis of stack width (Figure 8) that showed width increased with increased current or voltage or decreased translation speed.

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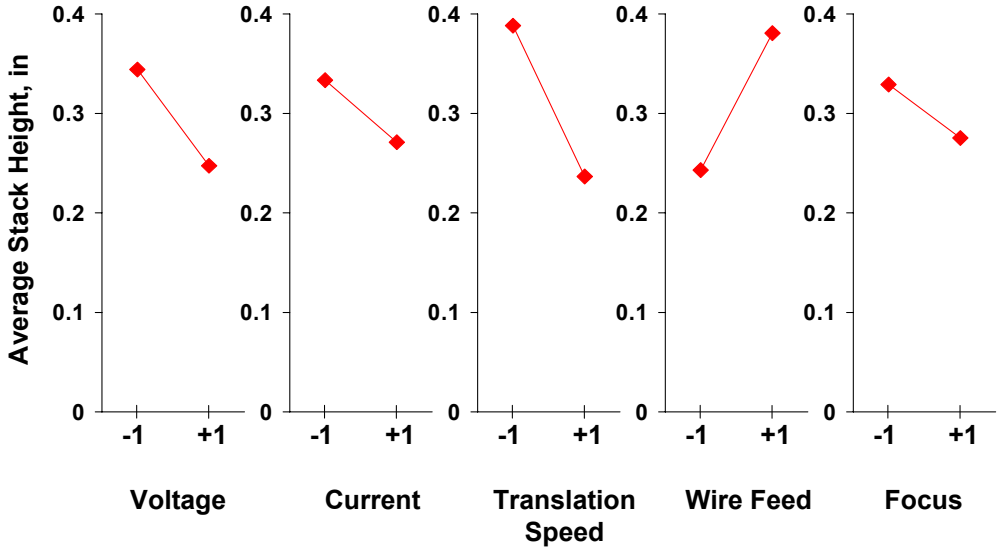

Figure 11. Marginal mean plots for average stack heights

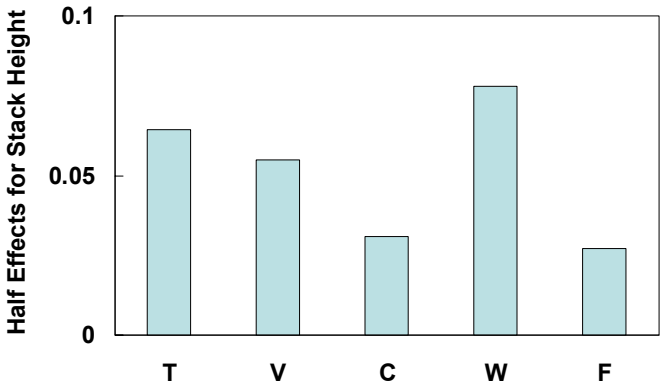

Figure 12. Stack height half-effects for input parameters with no interactions.

Stack height would also be expected to vary with voltage, current, or translation speed by the same argument. As the deposit width increases with voltage or current, the resulting height of the deposit must decrease as the total volume of material being deposited stays constant. Translation speed would have this same effect, but in this case the volume of material being deposited also changes. Reducing the translation speed increases the volume of material, countering the decrease in height produced by the higher energy. The DOE analysis results shown in Figure 11 show that decreasing the translation speed increases the deposit height, indicating that for these experimental conditions, the increase in volume is high enough to overcome the decrease in height due to increased energy input. Further study of this output would be useful, including examination of the parameter inputs.

The effect of wire feed rate is a little more difficult to understand. Clearly, increasing the wire feed rate would be expected to increase the volume of material deposited and, therefore, would be expected to increase height, which is consistent with the results presented in Figure 11. However, this higher volume of input material will require more input energy to melt and less energy will be available to sustain the molten pool. Thus the molten pool diameter will be reduced resulting in a decreased deposit width. Therefore, at a constant heat input (voltage, current, and translation speed held constant), the width of the deposit would be expected to decrease with an increase in wire feed rate. This is consistent with the DOE results shown in Figure 8, and is also consistent with observations of EBF^3 deposited Al [6].

Future Work

More data must be generated in order to conduct a more complete DOE analysis, and generate a meaningful process model. This includes producing replicate deposits for each set of experimental parameters. Extension of the analysis to include other output parameters, such as melt pool depths and heat affected zones, would also be useful. In addition, further work is required to determine the effect of the deposit parameters on the resulting microstructure of the Ti-6Al-4V deposits.

Concluding Remarks

A study was conducted to evaluate the relative significance of input parameters on deposits produced by an electron beam freeform fabrication process under development at the NASA Langley Research Center. Five parameters where chosen for study (beam voltage, beam current, translation speed, wire feed rate, and beam focus), and a DOE approach was used to develop a set of 16 experiments to evaluate how these parameters influence the output. To date only one experiment was conducted for each set of parameters, so a full statistical analysis and generation of an empirical process model was not possible. However, there was enough data for the generation of plots of the marginal means and half-effects in order to evaluate the relative importance of each input parameter on the height and width of the multi-bead stacks.

The results of this analysis showed that translation speed is important to both the height and width of the resulting deposit. This is partly because changing the speed at which the beam is moving changes the total volume of material that is deposited per unit length. In addition, changing the translation speed changes the amount of heat input during the process. The direct effect of this change of heat on the height and width is not fully known at this time, but metallurgical analysis shows that the samples with higher heating had a bigger melted zone. This larger melt pool is expected to cause the increase in width and decrease in height measured in the resulting multi-bead stacks.

The current and voltage were also found to be important parameters to both the stack height and width, though they were second in importance to translation speed. Increasing either the voltage or the current was found to cause an increase in the width and decrease in the height of the stack. An increase of either parameter enlarges the size of the melt pool, thereby spreading out the deposited material over a larger area and decreasing the height.

The wire feed rate was found to strongly influence the stack height but only produced a minimal change in stack width. Increasing the wire feed rate produced an increase in the stack height, which is consistent with the larger amount of material being introduced into the melt pool. However, further analysis is required to understand the interaction between wire feed rate and stack width.

The least important parameter was found to be beam focus for both stack height and width. Varying beam focus produced no measurable change in the stack width. In fact, metallurgical analysis confirmed that changing the beam focus produced no measurable change in the size of the melted or heat affected zones. Changing beam focus was found to produce a small change in stack height, but it had the smallest relative importance of the five parameters examined.

References

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