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# Application of a Diagnostic Tool in Laser Aided Manufacturing Processes

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## Abstract

Lasers play a vital role in producing parts with high dimensional accuracy, strength and quality in today's rapid prototyping industry. In the process of Laser Metal Deposition, many problems are encountered where the part quality does not meet the required standards. This could be due to the nonconformity of control parameters or unnecessary interactions between the control factors. This paper discusses the implementation of Dr. Genichi Taguchi's optimization techniques using Design of Experiments (DOE) where a series of fractional factorial experiments are performed on the laser deposition process. The results from these experiments are evaluated with respect to the rate of deposition alongside the part quality and the optimized level setting of control parameters are determined efficiently. This tool can be used to detect and diagnose flaws and discrepancies in the Laser Metal Deposition process and optimize it accordingly.

## Introduction

Laser Metal Deposition (LMD) is a process where metal powder is focused on a substrate and a laser beam melts the powder and deposits it. It is possible to convert any part into a series of slices and each slice can be deposited by the above method accurately (layered deposition) and the whole part can be fabricated. The advantage of this process is that complex geometries can be constructed with high degrees of accuracy to achieve near net shape with a solid model of the part. The Laser Aided Material Processing system (LAMP, shown in figure 1) at the University of Missouri Rolla is primarily comprised of a 2.5 KW Nd: YAG Rofin Sinar laser (at $TEM_{00}$) with integrated 5-Axis FADAL CNC with a maximum spindle speed of 7500 RPM.

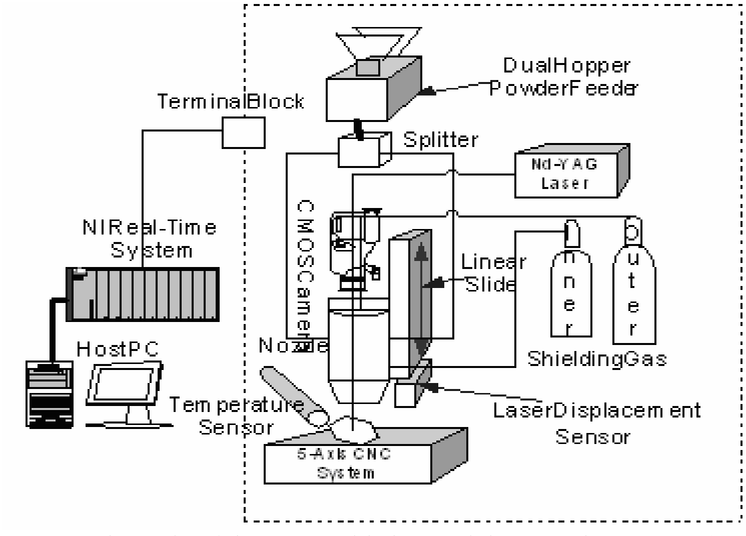


Figure 1. A Schematic of the Laser Aided Material Processing system (LAMP).

There is a coaxial screw feed dual powder delivery system that is capable of delivering two types of powder for Functionally Gradient Material parts. The 5-axis CNC ensures high part finish quality and can be used to remove any unwanted deposit. A schematic of the factor interrelationship is shown in figure 2.

This process has the capability of producing overhang parts and does not use support material because additional use of support increases the build time of the part and requires a time consuming post-processing. With a five-axis deposition integrated with five-axis machining, these obstacles are removed [1]. This paper deals with the testing of H13 powder deposited on H13 substrates and optimized for maximum build rate and at the same time, for having a good part quality. The hardness and the porosity will be used to evaluate part quality in this case study. There is a large range of layer thickness as well as deposition rates that can be achieved using laser deposition. The deposit rate can be increased by increasing the laser power, powder flowrate and the traverse speed. However, the requirement of a good part quality puts a limit on optimal deposition speeds. Both the layer thickness and the volume deposition rates are affected predominately by the specific energy and powder mass flow rate.

Here, specific energy (SE) is defined as:

$$SE = P/(Dv), \tag{1}$$

Where "P" is the laser beam power, "D" is the laser beam diameter and "$v$" is the process traverse speed. Also it is well known that actual laser power absorbed in the melt pool is not the same as nominal laser power measured from a laser power monitor due to absorptivity and other plasma related factors depending on the materials [2]. The use of adjusted specific energy is thus preferable. Considering the factors, it has been reported that there is a positive linear relationship between the layer thickness and adjusted specific energy for each powder mass flow rate [3].

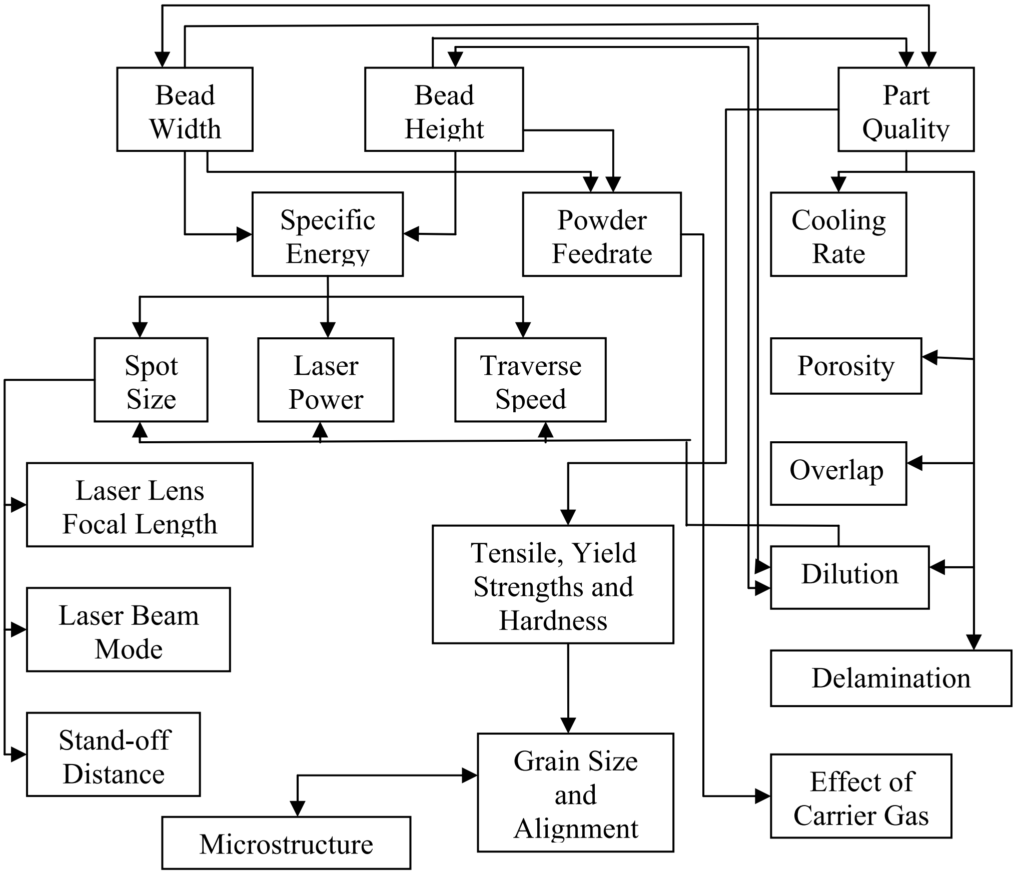


Figure 2. Schematic showing the basic laser deposition factor interrelations.

## Design of Experiments - Taguchi Methods of Optimization

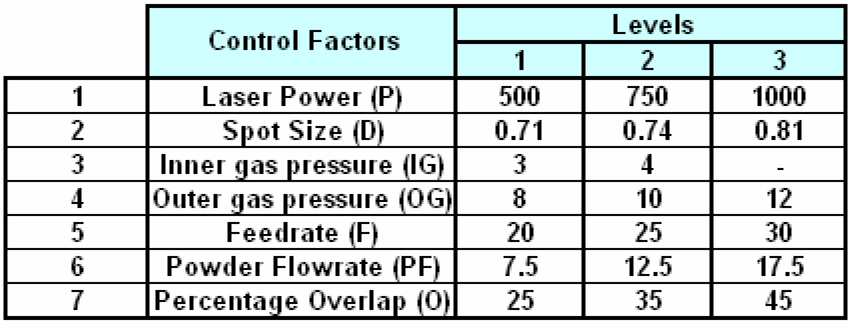
The Taguchi system of quality engineering is aimed at improving the robustness of a product and reducing the sensitivity to external variation. In other words, the part or product should perform as per customer expectations in the presence of various operational conditions. A special set of arrays called Orthogonal Arrays (also known as fractional factorial experiments) is used to optimize the processes. Not all the combinations of parameter levels are used to find out the best setting for a particular result, but a well defined combination that spans the whole set evenly is used. The main advantage is that an optimized result can be achieved in the least possible time.

## Experimental Approach

The steps that were used in the implementation of the Taguchi methods are:

- Identifying the factors and interactions: A total of 7 factors were chosen in this process as shown in table 1.
- Identifying the levels of each factor: It was found that 3 factors were necessary to check the linearity in the variation. Moreover, there is a good chance of getting closer to the best values more quickly.
- Selecting an appropriate orthogonal array (OA): An orthogonal array "A" is defined as an "N * k" array with entries from the set "S" with a number of levels "s", strength "t" and index "λ"[4]. The arrays must be chosen according to the number of control parameters, their respective levels and the factors which interact with each other. The L18 was chosen for this experiment.
- Assigning the factors and interactions to columns of the OA: One column was allocated to measure the factor interactions and any other factors and errors that were not taken into consideration.
- Conducting the experiments: Three samples were used for each experiment for repeatability. Analyzing the data and determining the optimal levels – this is an important part of the whole process and helps in obtaining the optimized values depending on the output we choose to measure. In the analysis of data, Signal to Noise ratios (S/N) are used in controlling the target as well as reducing the variation about the target. The three types of Signal to Noise Ratio approaches are Nominal the Best, Smaller the Better and Larger the Better. Analysis of Variance (ANOVA) is used in this process is to calculate the percentage contribution of the control factors associated with the conclusions.
- Conducting the confirmation experiment: This is done to validate the accuracy of the experiment. If the predicted values that we obtain after optimization match the results from the confirmation experiment, then the experiment is valid.

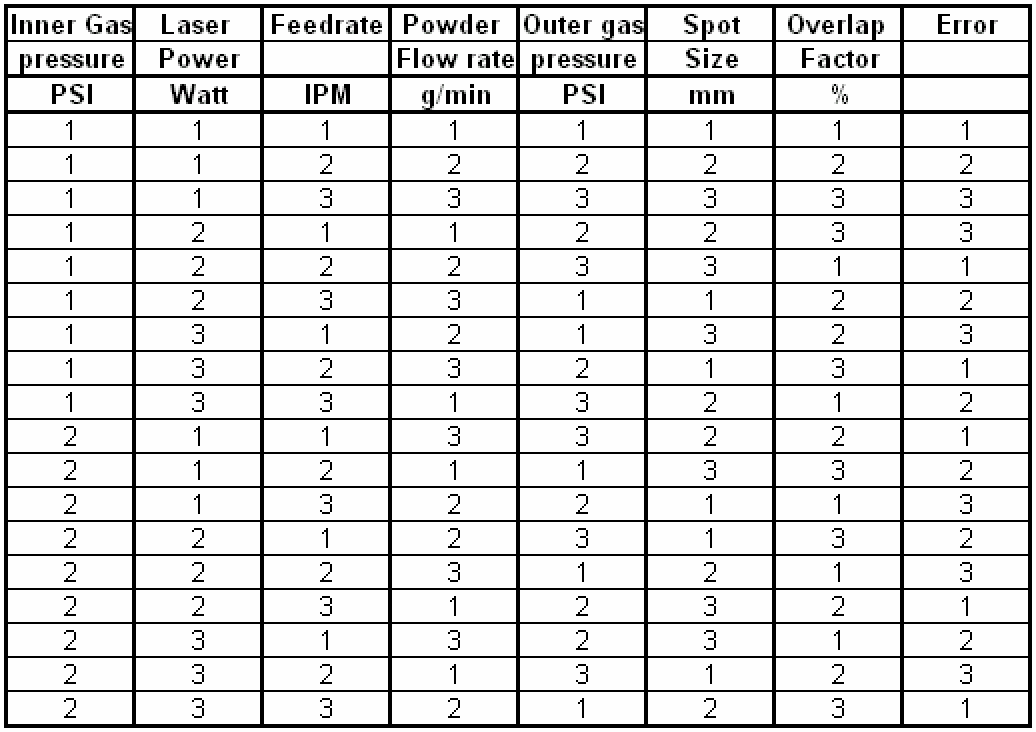
## Factor Level Selection



|  | Control Factors | Levels |  |  |
|---|---|---|---|---|
|  |  | 1 | 2 | 3 |
| 1 | Laser Power (P) | 500 | 750 | 1000 |
| 2 | Spot Size (D) | 0.71 | 0.74 | 0.81 |
| 3 | Inner gas pressure (IG) | 3 | 4 | - |
| 4 | Outer gas pressure (OG) | 8 | 10 | 12 |
| 5 | Feedrate (F) | 20 | 25 | 30 |
| 6 | Powder Flowrate (PF) | 7.5 | 12.5 | 17.5 |
| 7 | Percentage Overlap (O) | 25 | 35 | 45 |

Table 1. Control factor levels and their values chosen for this experiment.

In order to determine the levels of the factors in the experiment, a series of experiments was conducted and it was ensured that there was a deposition and good bonding with the substrate. It can be noted that the inner gas pressure has only 2 levels and the other factors have 3 levels (table 1). The Degrees of Freedom (DOF) that we need to conduct for this experiment is 13. So it is appropriate to use the L18 orthogonal array for the experiment as shown in figure 4. Three samples were made for each experiment for repeatability hence the overall DOF for the control factors changes to 39. The main goal is to improve the deposit build rate and also maximize hardness (maximum of 120 in the Rockwell B scale) and minimize the porosity. These characteristics are combined into a single yardstick known as an Overall Evaluation Criterion (OEC) which is to be used to weight the output of the various combinations of the factors. The different values are first normalized and a weight is allotted to each characteristic to ensure a single standard is followed throughout the experiment. It is important to note that the deposits were four layers and had a square area with zigzag deposition pattern for subsequent layers.



| Inner Gas pressure PSI | Laser Power Watt | Feedrate IPM | Powder Flow rate g/min | Outer gas pressure PSI | Spot Size mm | Overlap Factor % | Error |
|---|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 |
| 1 | 1 | 3 | 3 | 3 | 3 | 3 | 3 |
| 1 | 2 | 1 | 1 | 2 | 2 | 3 | 3 |
| 1 | 2 | 2 | 2 | 3 | 3 | 1 | 1 |
| 1 | 2 | 3 | 3 | 1 | 1 | 2 | 2 |
| 1 | 3 | 1 | 2 | 1 | 3 | 2 | 3 |
| 1 | 3 | 2 | 3 | 2 | 1 | 3 | 1 |
| 1 | 3 | 3 | 1 | 3 | 2 | 1 | 2 |
| 2 | 1 | 1 | 3 | 3 | 2 | 2 | 1 |
| 2 | 1 | 2 | 1 | 1 | 3 | 3 | 2 |
| 2 | 1 | 3 | 2 | 2 | 1 | 1 | 3 |
| 2 | 2 | 1 | 2 | 3 | 1 | 3 | 2 |
| 2 | 2 | 2 | 3 | 1 | 2 | 1 | 3 |
| 2 | 2 | 3 | 1 | 2 | 3 | 2 | 1 |
| 2 | 3 | 1 | 3 | 2 | 3 | 1 | 2 |
| 2 | 3 | 2 | 1 | 3 | 1 | 2 | 3 |
| 2 | 3 | 3 | 2 | 1 | 2 | 3 | 1 |

Table 2. The actual experimental layout of the L18 array.

The above setup (table 2) is a typical L18 array. It should be noted that there is a separate column attributed to the errors. This error column was added mainly to take into account the interactions and unaccountable noise factor effects that would affect the performance of the system. The main emphasis was to reduce the effect of the errors or variations and make the system more robust to these error variations and produce the expected result even in the presence of these errors. The array was set up and quality characteristics for the various combinations of control factors and their various levels were calculated and then the mean, standard deviation, and signal to noise ratios for the noise as well as the control factors were computed. The signal to noise ratio for the "Larger the Better" case was considered for the build rate and the hardness. The three quality characteristics were then combined to form a single Overall Evaluation Criterion (OEC) and used for comparison and further calculations.

### Formulation of the Overall Evaluation Criterion

It is quite common to encounter a situation where there is more than one Quality Characteristic (QC). It is possible to analyze the QCs separately, but it cannot be guaranteed that a single common optimized result will be achieved. It would more often be different and contradicting. This emphasizes the use of what is called an Overall Evaluation Criterion. In this case a certain relative weight percentage must be allocated to each QC subjectively during the experiment planning session. The different QCs are adjusted in such a way that they give rise to a QC that is either Smaller the Better (STB) or Larger the Better (LTB). To combine the different QCs into a single OEC, they must be normalized first and then weighted. The Nominal the Best (NTB) QC must be modified to represent the deviation from the nominal value which would become STB [5]. In this case the build rate, hardness and the porosity were given a weight percentage of 40, 40 and 20 respectively. To simplify the experimental array, the individual sample readings have not been shown in the experiment table (table 3). There were three readings taken for each quality characteristic on each sample. Only their mean values are shown in the table. The OEC is formulated as a LTB case for all three characteristics. The hardness was measured in the Rockwell B scale, the build height and width were measured in an optical microscope and the time was calculated from the NC code for the deposition. The build rate was calculated as build volume per unit time in mm$^3$/s. The porosity was viewed at 500X resolution and measured by a ranking system from a scale of 1 to 10.

Here the OEC was formulated as follows [5]:

$$OEC = \left\{ \frac{QC_a - QC_{\min(a)}}{QC_{\max(a)} - QC_{\min(a)}} * W_a\% \right\} + \left\{ \frac{QC_b - QC_{\min(b)}}{QC_{\max(b)} - QC_{\min(b)}} * W_b\% \right\} \ldots.. \qquad (2)$$

The above equation is for a larger the better case where QC$_a$ is the performance value of "a", QC$_b$ is the performance value of "b", QC$_{max}$ & QC$_{min}$ are the best and the worst performance values of the respective QCs and W$_x$ is the weight percentage allotted to the QC "x". For a smaller the better case, we can modify the above equation to suit a larger the better case as shown below [5]:

$$OEC = \left\{ \frac{QC_a - QC_{\min(a)}}{QC_{\max(a)} - QC_{\min(a)}} * W_a\% \right\} + \left\{ \left( 1 - \frac{QC_{\max(b)} - QC_{(b)}}{QC_{\max(b)} - QC_{\min(b)}} \right) * W_b\% \right\} + \ldots \qquad (3)$$

In equation 3, characteristic "b" is smaller the better whereas the OEC is formulated for larger the better approach. For NTB approaches, it must be noted that the OEC will be evaluated based on the magnitude of deviation from the nominal value. This magnitude must be made to be smaller the better. This can be easily reformulated to fit larger the better as shown above [5].

## Experiment

| Trial | IG | P | F | PF | OG | D | O | INT | Avg. | Avg. | Avg. | OEC 1 - 40:40:20 | | OEC 2 - 33:34:33 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No. | PSI | Watt | IPM | g/min | PSI | mm | % | | Build rate | Hardness | Porosity | Mean | S/N Ratio | Mean | S/N Ratio |
| 1 | 3 | 500 | 20 | 7.5 | 8 | 0.71 | 25 | 1 | 2.99 | 95.80 | 6.33 | 12.58 | 26.76 | 16.03 | 28.87 |
| 2 | 3 | 500 | 25 | 12.5 | 10 | 0.74 | 35 | 2 | 5.21 | 99.30 | 7.33 | 38.15 | 36.40 | 45.60 | 37.95 |
| 3 | 3 | 500 | 30 | 17.5 | 12 | 0.81 | 45 | 3 | 6.73 | 117.70 | 5.67 | 60.30 | 40.38 | 50.29 | 38.80 |
| 4 | 3 | 750 | 20 | 7.5 | 10 | 0.74 | 45 | 3 | 3.39 | 116.40 | 6.67 | 53.90 | 39.40 | 52.91 | 39.24 |
| 5 | 3 | 750 | 25 | 12.5 | 12 | 0.81 | 25 | 1 | 5.98 | 106.80 | 7.33 | 54.61 | 39.52 | 59.27 | 40.23 |
| 6 | 3 | 750 | 30 | 17.5 | 8 | 0.71 | 35 | 2 | 11.05 | 116.00 | 6.67 | 85.59 | 43.42 | 79.87 | 42.82 |
| 7 | 3 | 1000 | 20 | 12.5 | 8 | 0.81 | 35 | 3 | 7.80 | 111.20 | 7.67 | 73.38 | 42.08 | 77.69 | 42.58 |
| 8 | 3 | 1000 | 25 | 17.5 | 10 | 0.71 | 45 | 1 | 9.68 | 118.40 | 7.67 | 94.03 | 44.24 | 94.93 | 44.32 |
| 9 | 3 | 1000 | 30 | 7.5 | 12 | 0.74 | 25 | 2 | 3.49 | 116.40 | 6.00 | 47.67 | 38.34 | 42.27 | 37.29 |
| 10 | 4 | 500 | 20 | 17.5 | 12 | 0.74 | 35 | 1 | 4.21 | 115.20 | 7.33 | 61.93 | 40.61 | 65.12 | 41.05 |
| 11 | 4 | 500 | 25 | 7.5 | 8 | 0.81 | 45 | 2 | 1.59 | 111.30 | 6.67 | 37.32 | 36.21 | 39.04 | 36.60 |
| 12 | 4 | 500 | 30 | 12.5 | 10 | 0.71 | 25 | 3 | 5.04 | 108.40 | 6.67 | 46.76 | 38.17 | 47.19 | 38.25 |
| 13 | 4 | 750 | 20 | 12.5 | 12 | 0.71 | 45 | 2 | 3.10 | 115.80 | 7.33 | 58.28 | 40.08 | 61.99 | 40.62 |
| 14 | 4 | 750 | 25 | 17.5 | 8 | 0.74 | 25 | 3 | 6.69 | 117.80 | 6.67 | 70.32 | 41.71 | 66.80 | 41.27 |
| 15 | 4 | 750 | 30 | 7.5 | 10 | 0.81 | 35 | 1 | 1.59 | 111.70 | 6.67 | 38.02 | 36.37 | 39.61 | 36.73 |
| 16 | 4 | 1000 | 20 | 17.5 | 10 | 0.81 | 25 | 2 | 7.30 | 106.20 | 7.00 | 55.80 | 39.70 | 57.64 | 39.99 |
| 17 | 4 | 1000 | 25 | 7.5 | 12 | 0.71 | 35 | 3 | 2.45 | 115.70 | 7.33 | 55.38 | 39.64 | 59.53 | 40.27 |
| 18 | 4 | 1000 | 30 | 12.5 | 8 | 0.74 | 45 | 1 | 7.26 | 118.50 | 6.33 | 70.66 | 41.75 | 64.39 | 40.95 |
| | | | | | | | | | | | **Total** | **1014.7** | **704.79** | **1020.2** | **707.80** |
| | | | | | | | | | | | **Mean** | **56.37** | **39.15** | **56.68** | **39.32** |

Table 3. The experimental array with the measured performance statistics and S/N ratio.

From table 3, we can see that there is an attempt made to evaluate another OEC with 33:34:33 weightage. This was done to study the change in the optimal values when all QCs are given equal importance. The OEC 2 can be used only if the part quality is of primary importance. It is also important to note that the optimal level settings may not be the same for different QCs. The optimal combination for hardness may differ from that of porosity. When both are used, there would be a trade-off in the result obtained.

## Analysis of the Means (ANOM)

The Analysis of the Means (ANOM) is conducted basically to do a two step optimization. This is done by first reducing the variation in the process (using the S/N ratio and maximizing the slope) and then shifting the mean or target performance to get the best output. The ANOM was conducted next and the factor level plots were constructed. The levels of the control factors with the highest S/N ratio were used in verification of the predicted values for the confirmation experiment [6]. The ANOM tables for the mean and the Signal to Noise ratio are shown below (tables 4 and 5).

| | Inner Gas pressure | Laser Power | Feedrate | Powder Flow rate | Outer gas pressure | Spot Diameter | Overlap Factor |
|---|---|---|---|---|---|---|---|
| Mean | PSI | Watt | IPM | g/min | PSI | mm | % |
| 1 | **57.80** | 42.84 | 52.64 | 40.81 | **58.31** | **58.77** | 47.96 |
| 2 | 54.94 | 60.12 | **58.30** | 56.97 | 54.44 | 57.10 | 58.74 |
| 3 | - | **66.15** | 58.17 | **71.33** | 56.36 | 53.24 | **62.41** |

Table 4. ANOM for the Means.

|  | Inner Gas | Laser | Feedrate | Powder | Outer gas | Spot | Overlap |
|---|---|---|---|---|---|---|---|
|  | **pressure** | **Power** |  | **Flow rate** | **pressure** | **Diameter** | **Factor** |
| **S/N** | **PSI** | **Watt** | **IPM** | **g/min** | **PSI** | **mm** | **%** |
| **1** | 38.95 | 36.42 | 38.11 | 36.12 | 38.66 | 38.72 | 37.37 |
| **2** | **39.36** | 40.08 | 39.62 | 39.67 | 39.05 | **39.70** | 39.75 |
| **3** | - | **40.96** | **39.74** | **41.68** | **39.76** | 39.04 | **40.34** |

Table 5. ANOM for the Signal to Noise Ratios.

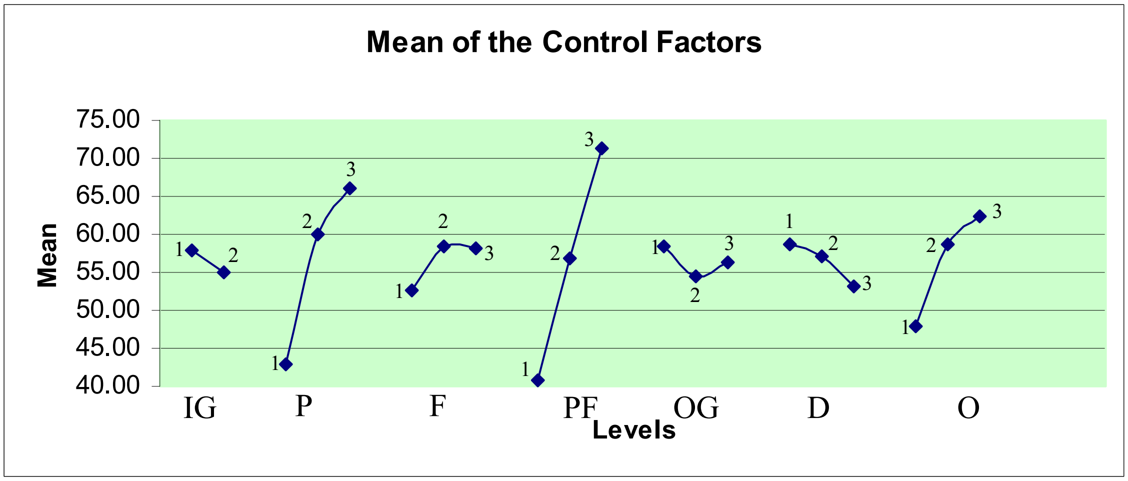


Figure 3. Factor Effect Plots for the Means.

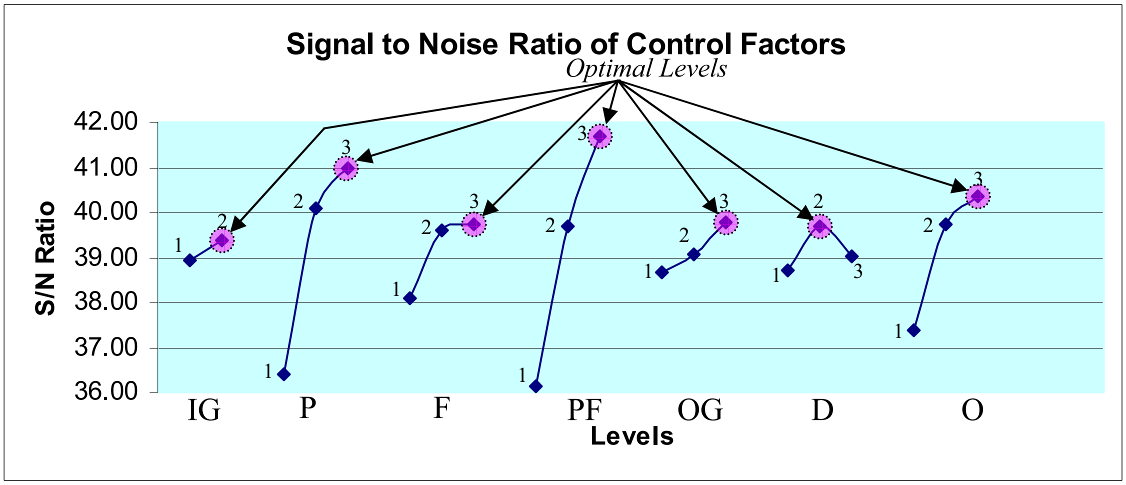


Figure 4. Factor effect Plots for the Signal to Noise Ratios.

In the above figures (3 and 4), IG / OG are Inner Gas / Outer Gas (PSI), P is Laser Power (W), F is the Feedrate (IPM), PF is the Powder Flowrate (g/min), D is the Spot Diameter (mm), O is the Overlap (%) and INT denotes the Interactions and Noises (their effects and percentage contributions would be calculated for further evaluation).

### Optimal Levels

From the plots and the Analysis of the Means, it was found that the optimal levels that are required to produce the given OEC 1 are $IG_2$= **4 PSI**, $P_3$ = **1000W**, $F_3$ = **30 IPM**, $PF_3$ = **17.5 g/min**, $OG_3$ = **12 PSI**, $D_2$ = **0.74mm** and $O_3$ = **45%**. With these optimal levels the expected performance should be predicted and the confirmation experiment should be carried out to verify the validity of the results.

From OEC 2, the study of the ANOM shows that the optimal levels remain the same except for the Feed rate and the Overlap factor. It must also be noted that there are only slight differences in the S/N ratio values of those control factors.

### Predictive Model

The predictive model is constructed from the ANOM results and is formed by considering the optimum level contribution of each factor to the deviation from the overall mean value for the experiment. The general formula for a predictive value is given below: [6]

$$y(A,B,C,D) = \overline{y} + (\overline{y_A} - \overline{y}) + (\overline{y_B} - \overline{y}) + (\overline{y_C} - \overline{y}) + \ldots \tag{4}$$

Where, y is a Quality Characteristic and A, B, C, etc. are the control factors.

In this experiment the predicted value for the S/N ratio was calculated to be **45.6** and the results of the confirmation experiment showed an S/N ratio of **45.2** which showed that the experiment was valid.

### Analysis of Variance (ANOVA)

ANOVA is a statistically based decision making tool used for detecting any discrepancies in the average performances of the groups of data tested. ANOVA breaks down total variation into comprehendible sources. In other words it enables us to quantitatively estimate the relative contribution each control factor makes to the overall performance. This contribution is expressed as a percentage. The importance of each control factor is measured by comparing the variance between the control factor effects with that of the experimental data. Here a mathematical technique known as the Sum of Squares (SS) is used to measure the deviation of the control factor effects on the average response quantitatively, from the overall experimental mean response. The effects of random experimental error can also be determined in this process. The basic steps involved in ANOVA are firstly determining the Grand Total Sum of Squares (GTSS). The GTSS is comprised of the overall experimental mean (or) the Sum of Squares due to the mean which is given by [6]:

$$GTSS = \sum_{i=1}^{N} (S/N)_i^2 \tag{5}$$

And the Sum of Squares due to the variation about the mean (or) the total Sum of Squares is given by [6]:

$$Total\ SS = \sum_{i=1}^{N} (S/N_i - \overline{S/N})^2 \tag{6}$$

It is important to note that GTSS = Total SS + SS due to the mean (See table 6).

| | $(dB)^2$ |
|---|---|
| **Grand Total Sum of Squares** | **27845.98** |
| **Total Sum of Squares** | **250.27** |
| **Sum of Squares due to the Mean** | **27595.71** |

Table 6. The Sum of Square values obtained from the experiment.

The Sum of Squares due to variation about the mean for a Factor A can be given as [6]:

$$\mathrm{SS_A} = \left( \begin{array}{l} (\text{Number of experiments at } \mathrm{A_{Level\ 1}}) * (\overline{S/N}_{\text{Level 1}} - \overline{S/N})^2 + \\ (\text{Number of experiments at } \mathrm{A_{Level\ 2}}) * (\overline{S/N}_{\text{Level 2}} - \overline{S/N})^2 + \\ \ldots + (\text{Number of experiments at } \mathrm{A_{Level\ N}}) * (\overline{S/N}_{\text{Level N}} - \overline{S/N})^2 \end{array} \right) \tag{7}$$

### Percentage Contribution of Parameters

The percentage contribution is the portion of the total variation that was observed in an experiment and is attributed to each significant factor and/or interaction. It is a function of the sums of squares of each factor. If the factor and/or interaction levels were controlled precisely, then the total variation would reduce by the amount indicated by the percentage contribution. The percentage contribution due to error provides an estimate of the adequacy of the experiment. It is given by [6]:

$$Percentage\ Contribution = (SS_{factor} / Total\ SS) * 100 \tag{8}$$

| **SS for Factors** | | **Percentage Contribution** |
|---|---|---|
| $\mathbf{SS_{IG}}$ | **0.77** | **0.31** |
| $\mathbf{SS_{P}}$ | **69.52** | **27.78** |
| $\mathbf{SS_{F}}$ | **9.92** | **3.96** |
| $\mathbf{SS_{PF}}$ | **95.00** | **37.96** |
| $\mathbf{SS_{OG}}$ | **3.75** | **1.50** |
| $\mathbf{SS_{D}}$ | **3.02** | **1.21** |
| $\mathbf{SS_{O}}$ | **29.81** | **11.91** |
| $\mathbf{SS_{INT}}$ | **12.42** | **4.96** |
| $\mathbf{SS_{Error}}$ | **26.08** | **10.42** |

Table 7. Sum of Squares due to each factor and their Percentage Contribution.

From the Percentage Contributions (table 7 and figure 5) we may note that there are more unaccountable errors contributing around 10.4% to the overall variation along with the 4.96% of assumed interactions and uncontrolled noises. This is attributed to three main causes:

- Uncontrollable noise factors.
- Factors which are not included in the experiment and
- Experimental error [5] [7].

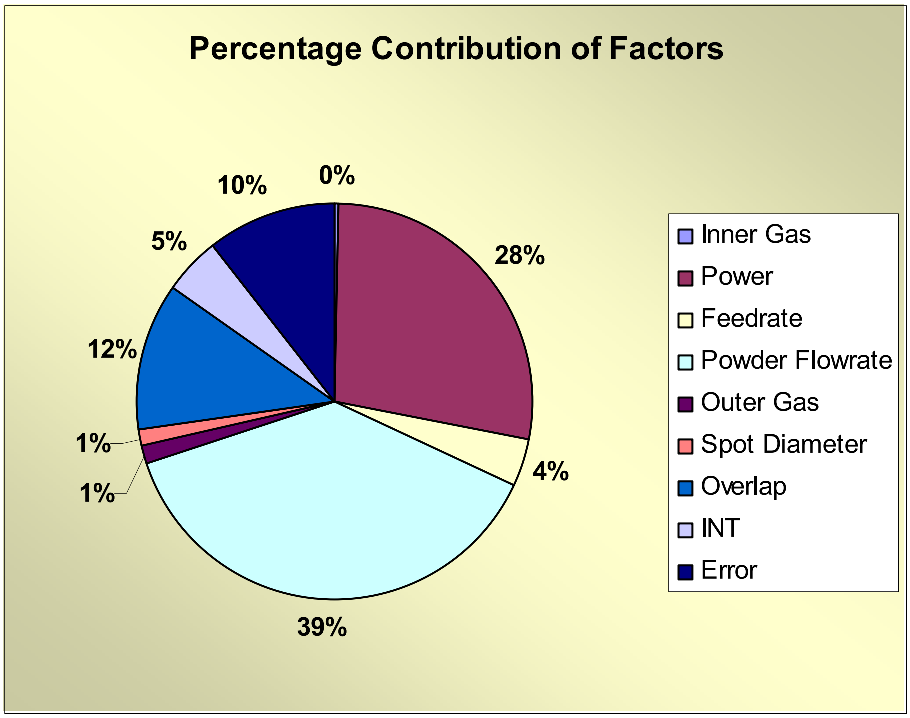


Figure 5. Pie chart showing the Percentage Contributions.

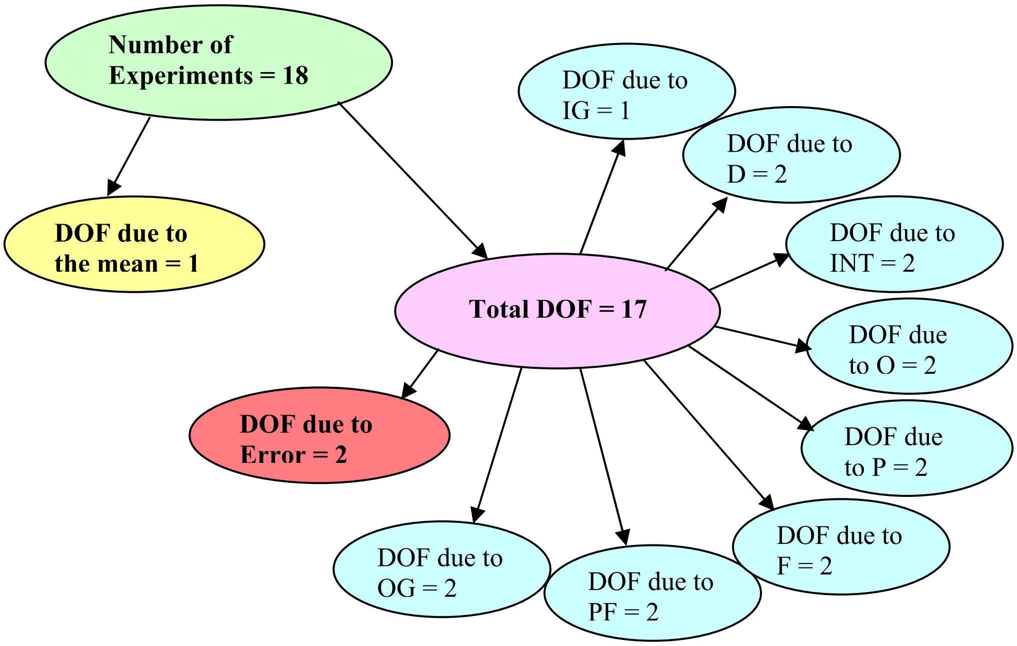


Figure 6. Schematic of the Degree of Freedom decomposition [6].

From figure 6, it is found that the DOFs due to all the factors taken into consideration are two less than the total DOF. This means that there are experimental errors and unknown or uncontrollable factor contributions worth two DOFs [7]. In this situation, it is necessary to do an F-Test to validate the importance of the control factors and prove that they can still control the process in the presence of these errors and variations.

## F- Test

The F-Test or F-Ratio, also known as the variance ratio, is used to test the significance of the factor effects. It is given by [6]:

$$F = \frac{MS}{S_e^2} = \frac{\textit{mean square due to a control factor}}{\textit{mean square due to experimental error}} \tag{9}$$

Where, $MS = \frac{\textit{factor effect sum of squares}}{\textit{factor degrees of freedom}}$ (9.1) & $S_e^2 = \frac{\textit{error sum of squares}}{\textit{error degrees of freedom}}$ (9.2)

When the value of F is more than 1, then the effect of the control factor is more than the variance due to experimental error and the interaction effects. Some general guidelines for the F-Ratio are [6]:

- $F<1$, then the experimental error outweighs the effect of the control factors. The control factors will be trivial and indistinguishable from the experimental error.
- $F \approx 2$, the control factor only has a reasonable effect compared to the experimental error.
- $F>4$, the control factor is strong compared to the experimental error and is obviously significant.

It is recommended to pool the insignificant control factors with the error. This makes it possible to calculate the contribution of the significant control factors more effectively [6] [7]. In this experiment, laser power, powder flow rate and overlap will be counted as significant factors and the remaining factors will be pooled together as the error as shown in table 8.

| Factor | Mean Square |
|---|---|
| $S_e^2$ | 5.08609 |
| $MS_P$ | 34.75925 |
| $MS_{PF}$ | 47.49824 |
| $MS_O$ | 14.90408 |

Table 8. Mean Square values for the significant factors and the error.

The F ratios that are calculated from the above values ($F_P = 6.8$, $F_{PF} = 9.3$& $F_O = 2.9$) show that Laser Power and Powder Flowrate are clearly significant when compared to the errors and Overlap factor has only a reasonably significant effect on the errors.

## Conclusion

The LAMP process at UMR was optimized using the Design of Experiments approach based on Taguchi's methods for maximum build rate, hardness and minimum porosity within the level settings that were decided for this experiment. The control factor interactions were studied and it was shown that the contribution of some control factors namely the laser power, the overlap factor and the powder flowrate are significant and the optimal levels for this experiment were determined. The contribution of the errors which include the experimental error, error due to interactions between factors and error due to uncontrollable noises were also studied and the system was made robust to these variations. A comparative study was also done with equal weightage for all the Quality Characteristics and the optimal values were not found to vary by much.

It is required that this process be further improved. This can be done by using the results of this experiment and conducting iterative experiments to hone in on the best possible level values of the control parameters that are least sensitive to the variations and are more improved and repeatable.

## References

1. Liou, F. W., Choi, J., Landers. R. G., *et al.,* "Research and Development of a Hybrid Rapid Manufacturing Process", *Twelfth Annual Solid Freeform Fabrication Symposium*, Austin, Texas, August 6–8, 2001, pp. 138–145.
2. Duley W. W., "Laser Processing and Analysis of Materials", Plenum Press, New York, 1983, pp. 69-78.
3. Mazumder J., Choi J., Nagarathnam K., Koch J., and Hetzner D., "The Direct Metal Deposition of H13 Tool Steel for 3-D Components", JOM, 49(5), 1997, pp. 55-60.
4. Hedayat, A. S.; Sloane, N. J. A.; and Stufken, J. "Orthogonal Arrays: Theory and Applications". New York: Springer-Verlag, 1999.
5. Ranjit, K. Roy, "Design of Experiments using the Taguchi Approach – 16 Steps to Product and Process Improvement", John Wiley & Sons, Inc., 2001.
6. William Y. Fowlkes, Clyde M. Creveling, "Engineering Methods for Robust Product Design Using Taguchi Methods in Technology and Product Development", Addison Wesley Publishing Company, Massachussets, 1998.
7. Ross, R. J. "Taguchi Techniques for Quality Engineering", McGraw-Hill, New York, 1989.

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