A GUIDELINE FOR USING EXPERIMENTAL DESIGN MATHEMATICAL MODELING IN WELDING OF COIL LEAD FRAMES

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Abstract: A current general need within industry is to utilize statistical methods including experimental design in the development of new processes and their parameters. This need is even more evident in microjoining (small scale resistance welding) due to the number process variables. This paper outlines an application in which statistical methods are applied to a microjoining process. The paper documents the methodology used to establish optimized process parameters for in microjoining of an electrical lead frame design. The methodology includes utilizing experimental design to develop a linear mathematical model of the process. A preliminary (screening) as well as final design of experiment is performed using a HF inverter and capacitive discharge welding equipment. The validity of the model and its linear assumption are evaluated and a transformation is performed to ensure linearity. Once the regression model has been verified, an optimization is performed to maximize the response variable and determine the optimum process parameters

Keywords: microjoining, welding, small-scale resistance welding, linear mathematical modeling, transformation, design of experiments, DOE

I. INTRODUCTION

A current general need within industry is to utilize statistical methods including experimental design in the development of new processes and their parameters. In many cases, the current mode of operation is for a manufacturing engineer to simply select process parameters that accomplish their goals with respect to a specific result / response through trial and error. The results obtained from the parameters that are selected are usually not optimized and in many cases, do not reflect a robust process. In addition, there are often parameters that are not even controlled that should be, because they are not thought of as having a significant effect on the desired response. These issues lead to manufacturing problems such as downtime and defects that cost organizations a significant amount of money every year.

One of these processes that would potentially benefit from statistical methods is a micro joining (small-scale resistance welding) operation on an electrical lead frame terminal design which, will serve as the scope of this paper. This process has been targeted as a replacement process to existing soldering operations. Microjoining offers many advantages of soldering in this particular application. Problems with the soldering process have included excessive solder, insufficient solder, solder ball contamination, cold solder joints, etc.

In microjoining there are many critical process parameters and minimal documented studies to provide statistical evidence as to the significance of the parameters in predicting the desired response variable results. This paper deals with developing a detailed statistical analysis to determine the process parameters. This analysis includes developing a valid linear mathematical model of the process and determining the specific process parameters that provide the optimum solution.

The purpose of this paper is to outline and document the methodology used to perform the analysis more than to outline actual results that are unique. The methodology outlined may be applied to many different microjoining applications in addressing the industry issue of utilizing statistical methods in developing new processes.

II. DISCUSSION

A. Experimental Design

The first step in applying statistical methods to develop a microjoining operation on an electrical lead frame terminal is to perform a design of experiments to develop a linear model of the process. In the analysis the following steps were taken;

- Develop the experimental design
- Collect the data
- Statistically analyze the data
- Validate the analysis and the assumptions (residual analysis)
- Draw conclusions regarding the significance of the predictors in having an effect on the response
- Build a linear regression model
- Review the assumption of linearity in the model and make transformations if required
- Optimize the model to determine the optimum predictor levels
- Verify results

Minitab®, a commercially available statistical software was used throughout the analysis.

B. Equipment

Initial testing was completed on a Unitek Equipment 2kHz HF (high frequency) inverter welding controller. The HF inverter welder offers flexibility in the ability to control many different potential factors. Subsequent testing was completed on a Unitek Equipment 875 dual pulse (capacitive discharge - CD) stored energy power supply. The CD welder offers the ability to quickly dissipate energy into the samples. Both welders used a Unitek Series 180 Thin-Line weld head. For pull testing results an Ametek EZ250 tensile test machine was used.

C. Materials

The electrical lead frame design constituted of two 0.8mm thick tin plated brass (C2680R-1/2H – MBCu2-Sn5 plated material) leads adjacent to each other to form a lap weld arrangement. Lead frame products were readily available with and without stamping oil and plating.

D. Experimental Design Variables

From preliminary studies on the HF (high frequency) inverter welder it was determined that the primary response variable was pull strength of the weld and the predictors were weld power, weld time, weld force, oil present on the part, plating on the part, squeeze time and hold time. It was determined that the initial (preliminary) experimental design on the HF inverter welder, used to determine the significance of the predictors (factors), will be run at the following two levels, outlined below in Figure 1.

Figure 1. Preliminary DOE Factors Levels

	Factor	*Lower Level (-1)*	*Higher Level (+1)*
A	Weld Power	4.8	8.3
B	Weld Time	28 ms	33 ms
C	Weld Force	2	9
D	Oil	Not Present	Present
E	Plating	Not Present	Present
F	Squeeze Time	0 ms	300 ms
G	Hold Time	0 ms	300 ms

The values for weld power and force are relative values associated with the specific equipment used.

E. Preliminary Fractional Factorial DOE

The initial analysis that was performed was a preliminary fractional factorial design. As stated above, the purpose of the preliminary design was to determine which factors were statistically significant in effecting pull strength of a weld. With the seven factors, a design was developed such that confounding of main effects and two-way interaction effects did not occur. It was decided to perform a 2^{7-3} experiment (1/8 fractional factorial – 16 runs) in order to reduce the number of runs while still minimizing any confounding effects. This design represented a resolution IV design meaning that main effects were confounded with three-way interaction effects and higher. For the purpose of this analysis three-way interaction effects and higher were assumed to have negligible effects on the pull strength (effect consisting of experimental noise only). This assumption allowed for any statistically significant effects involving main effects to be assigned to the main effects only.

With the resolution IV design, two-way interaction effects are confounded with other two-way interaction effects. It was impossible to determine which interaction was significant in any effects involving two-way interactions when the effect was determined to be statistically significant. For that reason in this analysis it was assumed that both two-way interaction effects were significant if their combined effect was determined to be statistically significant, until proven otherwise. In addition, the 2^{7-3} experiment (1/8 fractional factorial – 16 runs) was not replicated nor were center points used (two level).

The data matrix from the preliminary design was randomized to establish the run order. The experiment was set-up to operate the welding process with the specified parameters outlined for each treatment. Each treatment was then evaluated by pull testing each sample. The pull strength samples were evaluated using the tensile test machine by gripping each end of the lead frame specimen and pulling at a rate of 150 mm/min, while monitoring the force, until the specimen broke. The force required to break the weld was recorded and the data were entered into Minitab®. The factorial design was analyzed to draw conclusions.

A significant level of 5% (alpha=0.05) was used throughout the analysis to determine statistical significance. Statistical significant was interpreted throughout the analysis as being important in being able to predict the weld strength. The analysis of variation (ANOVA) table from the analysis outlined that the main effects and two-way interaction effects were not statistically significant (p=0.352 for main effects and p=0.548 for 2-way interaction effects which are both >0.05).

An interpretation of the results was that none of the predictors are statistically significant in predicting weld strength of the lead frame. From an understanding of the process and knowing that this conclusion was not likely, other interpretations were developed. It was thought that the experimental noise may have been significant enough in magnitude to drown out the predictor effects. Building on this assumption the causes for experimental noise were reviewed.

A potential source of experimental noise (error) was hypothesized to be the evaluation method. The evaluation method was reviewed for potential experimental error effects. It was thought that experimental error could enter through the tensile test itself. The primary areas for error were thought to be in the method / location the specimen was gripped and the rate the specimen was pulled. Since it was very difficult to perform a measurement system analysis (gage R&R) because it is a destructive test, it was determined that a test for equal variances and a two-sample t-test would be performed.

F. Equal Variance and Two Sample t-Test Results

An equal variance test and a two sample t-tests were performed to determine if the variance and the mean of two sample populations of different test methods were the same [1]. The first population was developed by operating the process at eight different treatments and evaluating the pull strength with the same test procedure used in the initial, fractional factorial preliminary experiment. The second sample population, thought to be an improvement, was developed by operating the process at the same eight treatments and evaluating the pull strength with a modified test procedure. The modified test procedure gripped the specimen closer to the actual weld joint and pulled the specimen at a slower rate of 50mm/min.

The test for equal variance tested the null hypothesis that the two population variances were equal with a 95% confidence. The critical p-value for the test was alpha/2 or .025. The test results highlighted a p-value of .75. Since the p-value (.75) was greater than the critical p-value (.025) the null hypothesis failed to be rejected and it was concluded that the variances of the two populations were equal.

A two-sample t-Test was performed to verify the difference between the means of the two population were not statistically significant. The two-sample t-test tested the null hypothesis that the difference in the two population means was equal to zero with a 95% confidence. The critical p-value for the test was alpha/2 or .025. The test results highlighted a p-value of .47 Since the p-value (0.475) was greater than the critical p-value (0.025) the null hypothesis failed to be rejected and it was concluded that the difference between the two population means were essentially equal to zero.

The interpretation of the two above studies indicated that the two test methodologies did not produce results that were statistically different. With this conclusion made, a further investigation into the source of the error.

It was thought that the noise effects probably were not coming from the accuracy of the HF inverter welder. The predictor level accuracy on the welder were not suspected because the process parameters were computer controlled with the weld controller and the part parameters were attribute (go/no go) leaving minimal room in either case, for error. Knowing that the noise more than likely was not coming from the actual accuracy of the welder, the data was analyzed further including an investigation of the factors selected and their particular levels.

Each factor and their chosen levels were analyzed and after further review, changes were made to the preliminary experimental design to address the issue of no factors being statistically significant.

G. Modified Preliminary Fractional Factorial DOE

The first review of the factors led to the consideration of the stamping oil on the part. Upon further investigation it was determined that the introduction of the stamping, especially in the method that it was applied in the experimental process, was not representative of the production process. The original thought was that in the production process the lead frame parts might have residual stamping oil on the parts when they are presented to the welding process and that the stamping oil may affect the welding process. To simulate this phenomenon in experimentation parts were staged at a low level (-1) having no stamping oil and at a high level (+1) dipped stamping oil. After further investigation it was determined that the parts would essentially have no stamping on them at the welding process and the inclusion of this factor was not representative of the production process. Based on this finding a decision was made to eliminate the stamping oil as a potential factor in the modified fractional factorial experimental design.

Another review of the factors led to the consideration of the specific high and low levels selected for the power factor. At the initial power factor levels (4.8 and 8.3) a number of the response variables (weld strength) resulted in a value of zero. This 'missing data' was attributed to the fact that at some treatment combinations the end result was a no weld condition. In the initial 16 run experiment, 6 treatments resulted in a condition where there was no weld (response weld strength equal to zero). It was hypothesized that this missing data was a primary cause for the insignificant effects. It was decided to modify the levels for power to significantly reduce the occurrence of missing data.

A third review of the factors led to the consideration of the high level used for hold time and squeeze time.

Through experimentation it was determined that the relationship between weld strength and hold and squeeze time was not linear. It was determined that from 0 to 150 ms, weld strength increased and from 150 to 300 ms weld strength decreased.

Based on the above review a modified preliminary fractional factorial experimental design was developed. The modified design was a 2^{6-1} experiment (1/2 fractional factorial – 32 runs) in order to reduce the number of runs while still minimizing any confounding effects. This design eliminated stamping oil as a factor, changed the power low level to 6.0 to eliminate the missing data occurrences and changed the hold and squeeze time high level to 150 ms. The power high level could not be increased without introducing weld expulsion. This narrow difference between power low and high levels posed a concern in being enough of a difference to demonstrate a significant change in the process. In addition, the number of runs was increased to further minimize any confounding effects. By further minimizing the confounding any noise effects introduced would be able to be isolated. See Figure 2 for the factors and levels included.

Figure 2. DOE Factors Levels

	Factor	*Lower Level (-1)*	*Higher Level (+1)*
A	Weld Power	6.0	8.3
B	Weld Time	28 ms	33 ms
C	Squeeze Time	0 ms	150 ms
D	Hold Time	0 ms	150 ms
E	Weld Force	2	9
F	Plating	Not Present	Present

This design was a resolution VI design meaning that main effects are confounded with five-way interaction effects and higher. For the purpose of this analysis again three-way interaction effects and higher were assumed to have negligible effects on the pull strength (effect consisting of experimental noise only). In addition, the 2^{6-1} experiment (1/2 fractional factorial – 32 runs) was not replicated at nor were center points (two level). The standard order was again randomized to determine the run order in the same manner as the preliminary design.

The experiment was set-up to operate the welding process with the specified parameters outlined in the design matrix for each treatment. Each treatment was then evaluated by pull testing each sample. The pull strength from each sample was evaluated using the tensile test machine by gripping each end of the lead frame specimen and pulling at a rate of 150 mm/min, while monitoring the force, until the specimen broke. The force required to break the weld was recorded and the data were entered into Minitab®. The factorial design was analyzed to draw conclusions.

A significant level of 5% (alpha=0.05) was used again to determine statistical significance. Statistical significant was interpreted as important in being able to predict the weld strength. The analysis of variation (ANOVA) table outlined that the main effects were statistically significant and two-way interaction effects were not ($p=0.001$ for main effects <0.05 and $p=0.804$ for 2-way interaction effects which is >0.05).

The specific main effects that were found to be statistically significant in predicting weld strength are listed with their corresponding p-value; weld time (0.015), force (0.004) and plating (0.000). An unexpected result was that power was not determined to be statistically significant. It was hypothesized that the levels chosen did not represent a large enough difference to be reflected and characterized in the weld strength. This posed a problem in that the levels could not be expanded without introducing missing data on the low end or expulsion on the high end. The end result was that the HF inverter welder was not capable of providing a process model with a wide enough band of power.

Focus was then directed at identifying a welder that was able to widen that band of power required to weld the lead frame. A capacitive discharge welder was identified as a potential replacement to the HF inverter welder. Due to the construction of the capacitive discharge welder a much wider band of power was able to be implemented in the process.

H. CD DOE

The next testing on the capacitive discharge welder allowed the use of a different machine that had the capability to induce the power in the part at a faster rate (which expanded the power band) while still being able to accomplish the process goals. It was decided that the primary response variable would still be pull strength of the weld and the predictors were weld power, weld pulse, weld force and plating on the part. It was determined that the next experimental design on the capacitive discharge welder, used to determine the significance of the predictors (factors), would be run at the following two levels, outlined in Figure 3.

Figure 3. CD Factor Levels

	Factor	*Lower Level (-1)*	*Higher Level (+1)*
A	Weld Power I	30	45
B	Weld Power II	30	45
C	Weld Pulse	Short	Long
D	Weld Force	2	7
E	Plating	Not Present	Present

The reduced number of factors in the next analysis allowed the possibility of a full factorial design to be performed. With the five factors and a full factorial, a design was developed such that no confounding effects were present. This design was a 2^5 experiment (full factorial – 32 runs). This design was a full resolution design meaning that there are no effects that are confounded. In addition, the 2^5 experiment (full factorial – 32 runs) was not replicated at this time nor were center points used (two level) and the design was free from aliasing.

The data matrix from the design was randomized to establish the run order. The experiment was set-up to operate the welding process with the specified parameters outlined in the design matrix for each treatment. Each treatment was then again evaluated by pull testing each sample. The force required to break the weld was recorded and the data were entered into Minitab®. The factorial design was analyzed to draw conclusions.

A significant level of 5% (alpha=0.05) was again used in the analysis to determine statistical significance. The analysis of variation (ANOVA) table from the analysis outlined that the main effects and two-way interaction effects were statistically significant (p=0.000 for main effects and p=0.030 for 2-way interaction effects which are both <0.05).

The specific main effects that were found to be statistically significant in predicting weld strength are listed with their corresponding p-value; power (0.000), pulse (0.006), force (0.000) and plating (0.000). The only two-way interaction effect that was determined to be statistically significant was pulse * plating (0.001).

I. Linear Regression Mathematical Model

Based on the results from the above experimental design a linear regression analysis was performed with the predictors that were found to be statistically significant against weld strength. The purpose of this analysis was to develop a linear mathematical model to be optimized and establish a coefficient of determination to judge the fit of the linear model developed. With this analysis conclusions could be drawn regarding the accuracy and improvements of the model.

The regression provided reasonable results by providing a model with a coefficient of determination, R^2 of 85.5% and a R^2 adjusted of 82.7%. The small difference between R^2 and R^2 adjusted indicated that the model probably was not over specified. The model also was statistically significant as demonstrated by the regression p-value of 0.000.

To substantiate these results a complete residual analysis was performed. To verify the constant variance assumption a plot of the residuals versus the fitted values and each of the regressors was performed. The plot of the residuals versus the fitted values showed signs of non-constant variance. As the fitted values increased the magnitude of the residuals increased. This caused a megaphone (funnel) type shape in the plot shown below.

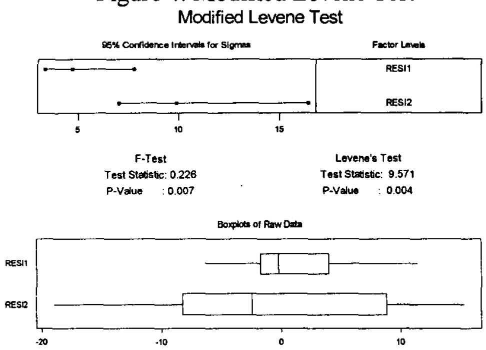
The majority of the plots of the residuals versus each of the regressors showed no definite signs of any particular pattern existing. The plot of the plating did however show signs of a pattern, in particular the data demonstrated a funnel pattern indicating that the variance may be increasing. In the rest of the plots the data were well dispersed indicating that no systematic effects had occurred. Since the increasing variance funnel shape plots showed up in the plot of the residuals versus the fitted values and the plating it was hypothesized that the constant variance assumption was violated by the inclusion of plating in the model.

To verify the independence assumption a plot of the residuals versus the order of the data and was performed. The plot of the residuals versus the order of the data showed no signs of a particular pattern existing and was well dispersed. The data was not trending in a specific direction nor did it have any systematic effects. This plot substantiated the independence assumption.

To verify the residuals followed a well-behaved distribution a normal probability plot and a histogram of the residuals were performed. The normal probability plot of the residual further confirmed that the residuals follow a normal distribution by representing a straight line. The histogram plot shows that the residuals are approximately normally distributed (bell-shaped slightly skewed right). These two plots together illustrate that the residuals followed a well-behaved distribution.

In order to determine if the non-constancy of the error was statistically significant a formal statistical test was performed. A Modified Levene Test was performed by analyzing the plots of the fitted values versus the residuals [2]. A data matrix was created by ordering the residuals by increasing fitted values. This matrix was then divided into two distinct population samples. Since there were 32 runs the residuals for the first 16 fitted values were placed in the first population then the residuals for the last 16 fitted values were placed in the second population. These two populations were then analyzed to determine if the differences in their variances were statistical different. A 5% significance level (alpha=0.05) was again chosen to determine statistical significance. The p-value for the Modified Levene Test was 0.004 that is less than the critical p-value of 0.05 indicating that the error variance was not constant. The Figure 4 shows graphically the differences in the error variance through box plots.

Figure 4. Modified Levene Test



Since the error variance was determined to be statistically significant and a linear model was desired it was decided to attempt to apply a transformation of the response variable (strength of the weld) [2]. The purpose of the transformation was to alleviate any non-constancy of error issues while maintaining a good fit (high coefficient of determination) without compromising the other model assumptions (well-behaved distribution and independence). Three transformations to the response variable of weld strength were attempted with one being successful. Transformations of taking the $\log_{10}$ and inverse of weld strength violated the above assumptions and deteriorated the model coefficient of determination. The transformation of taking the square root of the weld strength (raising to the power of 0.5) provided positive results.. The transformed regression provides an improved model with a coefficient of determination, R^2 of 87.0% and a R^2 adjusted of 84.5%. The small difference between R^2 and R^2 adjusted indicated that the model probably was not over specified. The model also was statistically significant as demonstrated by the regression p-value of 0.000.

To substantiate the above results a complete residual analysis was performed. To verify the constant variance assumption a plot of the residuals versus the fitted values and each of the regressors was performed. The plot of the residuals versus the fitted values showed no signs of non-constant variance. The points in the plot were well dispersed and showed no signs of any particular pattern or shape. The plots of the residuals versus each of the regressors also showed no definite signs of any particular pattern existing. The points on the plots between each level did not show any signs of a particular pattern existing. These plots verified the constant variance assumption.

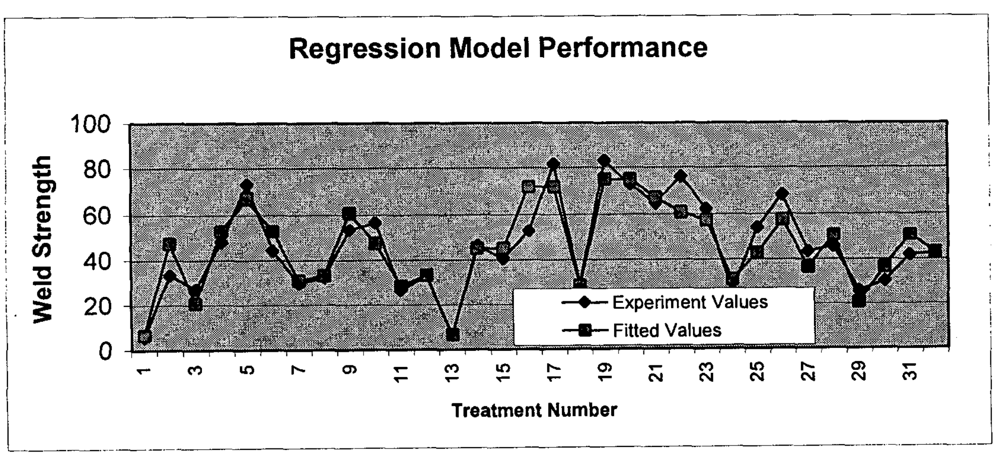
To verify the independence assumption a plot of the residuals versus the order of the data and was performed. The plot of the residuals versus the order of the data showed no signs of a particular pattern existing. The data was not trending in a specific direction nor did it have any systematic effects. This plot substantiated the independence assumption.

To verify the residuals followed a well-behaved distribution a normal probability plot and a histogram of the residuals was performed. The normal probability plot of the residual further confirmed that the residuals follow a normal distribution by representing a straight line. The histogram plot shows that the residuals are approximately normally distributed (bell-shaped – slightly skewed right). These two plots together illustrate that the residuals followed a well-behaved distribution.

The linear model developed in the transformed regression was:

$$\text{Weld Strength}^{.5} = 6.55 + 0.946 * \text{Power} - 0.434 * \text{Pulse} - 0.598 * \text{Force} + 0.706 * \text{Plating} + 0.547 * \text{Pulse} * \text{Plating}$$

Figure 5. Regression Model Performance



The performance of the model is displayed in Figure 5 with the actual experiment data and the fitted values versus the treatment number. As can be witnessed the model follows the experimental data closely. With the model developed and assumptions verified a linear programming optimization was performed using the linear solver in Microsoft Excel®.

J. Linear Programming Optimization

The optimization was performed by setting the linear regression model developed as the objective function. The optimization performed was a maximization of the objective function. The initial constraints used in the optimization are listed in Figure 6 below and are the same factor levels used in the experimental design.

Figure 6. Linear Optimization of Regression Model

Factor	Coefficient	Regressor	Constraint Coded		Constraint Uncoded	
		Value	Minimum	Maximum	Minimum	Maximum
Coefficient	6.55	1	-	-	-	-
Power	0.946	1.0	-1	1	30	45
Pulse	-0.434	1	-1	1	1	2
Force	-0.598	-1.0	-1	1	2	7
Plating	0.706	1	1	1	1	1
Pulse*Plating	0.547	1				
Objective Function	Strength^.5	8.91				
	Strength	79.4416				

Pulse was treated as an integer variable since it is attribute (either short or long). The plating was set equal to 1 in coded units or 'plating present' in uncoded units since it cannot be controlled in the process. However, since the plating was determined to be statistically significant it is recommended that plating be controlled. One possible control item is as an incoming inspection item.

The initial optimization provided a trivial solution in that the optimum setting for the process parameters were at their maximum or minimum level values. The process settings established through this optimization in coded and uncoded units per the above results are listed in Figure 7.

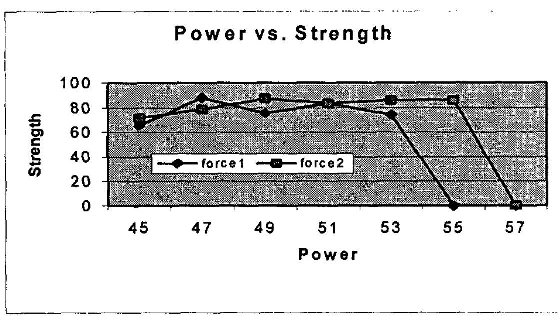
Figure 7. Optimized Factor Coding

Factor	Coded Units	Uncoded Units
Power	1	45
Pulse	1	Long
Force	-1	2
Plating	1	1

The actual value achieved through experimental at the optimized settings (factor level) was 83.1 which is very close to the predicted optimized value of 79. These results are confirmed by the fact that the treatment that produced the maximum strength value had the same factor levels.

Since the solution to the initial optimization with the given constraints was trivial it was decided to attempt to extend the constraint limits to determine if another combination of constraints could achieve a higher optimized weld strength. From the model it was decided to attempt to increase the maximum constraint for power and decrease the minimum constraint for force since the model recommended that the process be set at the lowest force and the highest power levels. The highest power setting performed in the original experiment was 45. Additional trials were then performed and analyzed at 45, 47, 49, 51, 53 and 55 to determine the impact they would have on the strength of the weld while maintaining cosmetic appearance. Figure 8 shows the relationship between power and strength.

Figure 8. Power vs. Strength



The phenomenon of strength decreasing at higher powers is explained by the fact that at higher power values the welding process has significant expulsion and does not provide as robust of a joint. The points that this phenomenon occurs differ according to which force setting is used. At a force setting of 1 (approximately 5 lbs), the joint began to expulse at around 55 power while at a force setting of 2 (approximately 10 lbs) the joint began to expulse at 57 power (the maximum attempted in this experiment). These points can be seen on Figure 8 above represented by zero strength. It was also attempted to minimize the force to aid in obtaining a stronger weld. The minimum level used in the original experiment was set at 2. The model then predicted that our strongest weld would occur at that minimum setting. A study was performed to attempt to operate the welder with a force of 1.

Operating the welder with a force of 1 introduced a significant more amount of variation in the weld strength. This increase in variation is explained by the change in contact resistance. Contact resistance is the electrical resistance between the electrode and the specimen. When the force was changed from 2 to 1 the contact resistance changes substantially. At a value of 1 the force was not high enough to compensate for the resistances due to the imperfections in the mating surface areas and material finishes.

The range of weld strengths varies much more when the force setting is equal to 1 than when the force setting is equal to 2 increasing the process control. As a result the optimization was re-run with the power maximum constraint increased to 55 (a point prior to expulsion) and the force minimum constraint held at 2. The coded value for a force of 55 is 1.7. All other values remained the same as used in Figure 6.

The second optimization provided a solution with the optimum setting for force at the 55 maximum constraint. All other factor remained that the same recommended setting. The process settings established through this optimization, in coded and uncoded units per the above results, are listed in Figure 9.

Figure 9. Optimized Factor Coding

Factor	*Coded Units*	*Uncoded Units*
Power	1.7	55
Pulse	1	Long
Force	-1	2
Plating	1	1

The optimized model established the recommended setting to achieve a weld strength of 91 lbs.

III. CONCLUSIONS

The above analysis served as an exercise outlining the statistical process using design of experiments to develop a linear regression model of a welding process. A linear model was established that served as a good representation of the actual process. This linear model was optimized and verified to provide the process parameters required to obtain a weld strength of 91lbs. This micro joining process provides a reliable alternative process to conventional soldering of 0.8mm thick tin plated brass lead frame terminal designs.

While the results are trivial the value in the work is in outlining the methodology used to arrive at the results. The methodology can be applied to many different microjoining processes.

IV. REFERENCES

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