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Robert A. Hafley and Stephen J. Hales
Analytical Services & Materials, Inc.
Hampton, Virginia

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THE APPLICATION OF STATISTICALLY DESIGNED EXPERIMENTS TO RESISTANCE SPOT WELDING

Robert A. Hafley and Stephen J. Hales *

Analytical Services & Materials Inc.
107 Research Drive
Hampton, VA 23666

ABSTRACT

State-of-the-art Resistance Spot Welding (RSW) equipment has the potential to permit real-time monitoring of operations through advances in computerized process control. In order to realize adaptive feedback capabilities, it is necessary to establish correlations between process variables, welder outputs and weldment properties. The initial step toward achieving this goal must involve assessment of the effect of specific process inputs and the interactions between these variables on spot weld characteristics. This investigation evaluated these effects through the application of a statistically designed experiment to the RSW process. A half-factorial, Taguchi L_{16} design was used to understand and refine a RSW schedule developed for welding dissimilar aluminum-lithium alloys of different thickness. The baseline schedule had been established previously by traditional trial-and-error methods based on engineering judgement and one-factor-at-a-time studies. A hierarchy of inputs with respect to each other was established, and the significance of these inputs with respect to experimental noise was determined. Useful insight was gained into the effect of interactions between process variables, particularly with respect to weldment defects. The effects of equipment-related changes associated with disassembly and recalibration were also identified. In spite of an apparent decrease in equipment performance, a significant improvement in the maximum strength for defect-free welds compared to the baseline schedule was achieved.

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* Mr. R. A. HAFLEY and Dr. S. J. HALES are Research Scientists working in the Materials Division at NASA Langley Research Center in support of the National Launch System Program.

1. INTRODUCTION

A critical aspect of the successful application of Resistance Spot Welding (RSW) to joining in large aerospace structures will be the development of effective non-destructive evaluation (NDE) techniques. Quantitative assessment of spot weld quality tends to be based on overlap shear strength and defect population of weldments [1]. Typical Mil-Spec requirements for aluminum alloys specify levels of weld strength and the absence of any weldment defects [2]. Currently, determination of weldment properties relies heavily on extensive off-line destructive evaluation which is impractical during actual manufacturing operations [3]. However, state-of-the-art RSW equipment offers the potential for on-line quality control (QC) with the advent of digital data acquisition and process control [4]. Figure 1 illustrates one way in which the information generated by the modern RSW equipment used in this study can be presented. For each spot weld, the values for the important process variables, with respect to cycle time, are output as current and force profiles. Indicated on the figure are the locations on the various data outputs from which quantitative information concerning the amount of weld and forge force in conjunction with the levels of pre-heat and weld heat can be obtained. The main on-line output for monitoring weld quality is the plot of nugget expansion as a function of weld time. Nugget expansion is measured directly by the equipment in terms of electrode separation as a function of cycle time. The peak height can be correlated with weld strength and the overall shape of the peak can be related to the presence of defects.

The potential for on-line QC will only be realized if the precise relationship between process variables and weld quality can be established. A thorough understanding of the process will require correlation of inputs with each other, outputs with each other, inputs with outputs and all with weld quality and strength. In order to resolve these issues through one-factor-at-a-time (OFAT) experiments would require a great many experiments. An optimum weld schedule would undoubtedly result, but it would be difficult or impossible to quantify the effect of individual equipment settings on each other. In order to fully define the process the level and type of interaction between the process variables must be established. Statistically designed experiments are an effective method for providing such information. The application of experimental matrices consisting of orthogonal arrays is also an efficient means for optimizing a process. The factorial designed experiments pioneered by Taguchi represent a sub-category of statistical experimentation and consist of tabulated versions of latin square or fractional factorial designs [5]. This tabulation simplifies the design and analysis of the experiment, making the technique a powerful tool for non-statisticians.

The ability to optimize equipment settings and produce a robust schedule is often cited as the major advantage connected with Taguchi-type experimentation [7]. In contrast, it is difficult to design a statistical experiment which will be meaningful in cases where the expertise is not available. A substantial level of knowledge is required to both define the significant inputs and assign appropriate ranges for the process variables considered important. Therefore, the approach must be considered as a complement to, rather than a replacement for, traditional experiments. Full factorial designs are the simplest to implement, but the number of tests required can still be large if numerous factors at many levels are to be evaluated. Fractional factorial designs can greatly decrease the necessary number of tests, without drastically reducing the information provided [6]. However, limitations are introduced with respect to the ability to evaluate the effects of interactions between factors as the matrix size, relative to a full factorial design, is reduced. This can lead to a confounding of the statistical data concerning factors and interactions and the inability to determine the specific effect of certain inputs on the outputs. These problems can be circumvented through sufficient brainstorming and careful evaluation of the variables and ranges for inputs to be included in the experiment.

Currently, the RSW process is being considered as a candidate joining technique for the fabrication of large, built-up sheet metal structures for future launch systems. The skin-stiffened structures being considered for incorporation in cryogenic propellant tanks are likely to consist of dissimilar aluminum-lithium (Al-Li) alloy components of different nominal thicknesses. The particular combination of commercially available Al-Li alloys being addressed in this experiment is 0.050" 8090-T6 stiffener material joined to 0.125" 2090-T8E50 skin material. Although Al-Li alloys have been demonstrated to be very weldable, the database available for reference is very limited due to their relatively recent introduction into the commercial arena. Therefore, the baseline schedule selected for the experiment consisted of equipment settings established using engineering judgement. The objective of the study was to determine the suitability of statistically designed experiments for optimizing schedules for RSW of Al-Li alloys. Assessment was based primarily on the ability of the technique to enhance the understanding of the process and lead to improvements in the baseline schedule. This involved determination of the relative contribution of the various inputs to specific weldment properties by establishing hierarchies for both factors and interactions. The predicted and measured responses provided by statistical analysis of the data were compared as a measure of the ability of the design selected to simulate the RSW process. Identification of both equipment- and process-related variables not included in the matrix which affected weldment characteristics were considered an integral part of the study. In addition, the merit of the experimental approach was assessed based on the ability to correlate welder outputs with weld quality for on-line QC capability.

2. EXPERIMENTAL APPROACH

2.1 Experimental Design

A "brainstorming" session was conducted to establish an effective experimental design [8]. The primary aim was to select the most important process-related variables to be incorporated in an experimental matrix. Initially, the factors which can determine the quality of a resistance spot weld were identified on a broad basis. These were then classified into those related to material and environmental conditions and those which can be employed to control the process itself. The pertinent controllable and uncontrollable process inputs are summarized in Figures 2 and 3, as a result of this exercise. Figure 2 represents a summary of the physical variables which were selected to be assigned fixed values for the purposes of the experiment. Deviations in the composition and heat treatment condition of the commercially-produced batches of material were assumed to be within acceptable limits. Appropriate pre-RSW material preparation procedures, along with a suitable electrode dressing schedule, had been established prior to this study. Consequently, it was not considered necessary to include variations in part and electrode cleanliness in the experiment. The radii and diameters for the upper and lower electrodes had been established in previous trial-and-error screening studies [4]. Further, changes in room temperature and humidity could not be accounted for effectively and it was surmised that environmental variations would become an integral part of experimental noise. It is important that the optimized weld schedule derived through the experiment will be robust to uncontrolled process inputs.

In Figure 3, the process variables and responses considered most important are categorized as inputs and outputs, respectively. In broad terms, the input factors govern the amount and time that heat and force are applied during a weld cycle. The outputs encompass the data compiled in order to characterize a spot weld. The selection of appropriate ranges for the inputs was based on knowledge of the equipment and limited prior experience with the materials being welded. The choice of range widths is critical in an experimental design involving only two factor levels. The whole region where a good schedule might exist needs to be covered, but if the width is too great most of the welds would be defective. The latter event would jeopardize the ability of the experiment to model the process and provide useful simulations. The outputs were classified in terms of quantitative and qualitative responses. The quantitative responses are continuous in nature and are frequently used as an engineering measure of weld quality. Weld strength is measured in pounds per spot with nugget expansion and nugget diameter being measured in mils (in. x 10^{-3}). The qualitative responses are associated with commonly occurring defects in RSW. Although difficult to quantify, the presence of any defects can be cause for rejection of a weld. Thus, these responses were considered to be categorical in nature and were assigned values of "zero", in the absence of, or "one", with the existence of defects.

A Taguchi L_{16} design, shown in Table I, was selected as the most appropriate experimental matrix for this investigation [6]. The size of the matrix was based primarily on manageability for an exploratory study. It was also considered to be of sufficient size to assess the merits of applying this novel experimental technique to the development of a refined RSW schedule. The matrix usually consists of a full-factorial orthogonal array for evaluating four factors. As applied in this experiment, the matrix became a half-factorial due to the replacement of a four-way interaction (-ABCD) with another factor (E) [6]. Consequently, it was hoped that the effects of five factors plus all two- and three-way linear interactions could be evaluated from just 16 different weld schedules. Concerning the design of this factorial experiment, it was deemed important to use the actual machine control settings where possible. Consequently, the air pressure on the upper and lower side of the diaphragm was considered, rather than weld force and forge force per se. These inputs, included as "high" and "low" pressure, respectively, generate the forces between the electrodes during the RSW process. The high pressure (designated as P_1) determines the level of forge force. The differential between the low pressure (P_2) and high pressure (designated as P_1-P_2) determines the level of weld force. In order to achieve an electrode force, high pressure must be greater than low pressure. In experiments involving orthogonal arrays this fact translates into the ranges selected for low and high pressure being mutually exclusive.

Table I. Taguchi L_{16} (2^{15-1}) Half-factorial Design

Run #	Input Factors and Interactions															Responses	
	A	**B**	-AB	**C**	-AC	-BC	ABC	**D**	-AD	-BD	ABD	-CD	ACD	BCD	**E**	Quant.	Qual.
1	**-1**	**-1**	-1	**-1**	-1	-1	-1	**-1**	-1	-1	-1	-1	-1	-1	**-1**		
2	**-1**	**-1**	-1	**-1**	-1	-1	-1	**+1**	+1	+1	+1	+1	+1	+1	**+1**		
3	**-1**	**-1**	-1	**+1**	+1	+1	+1	**-1**	-1	-1	-1	+1	+1	+1	**+1**		
4	**-1**	**-1**	-1	**+1**	+1	+1	+1	**+1**	+1	+1	+1	-1	-1	-1	**-1**		
5	**-1**	**+1**	+1	**-1**	-1	+1	+1	**-1**	-1	+1	+1	-1	-1	+1	**+1**		
6	**-1**	**+1**	+1	**-1**	-1	+1	+1	**+1**	+1	-1	-1	+1	+1	-1	**-1**		
7	**-1**	**+1**	+1	**+1**	+1	-1	-1	**-1**	-1	+1	+1	+1	+1	-1	**-1**		
8	**-1**	**+1**	+1	**+1**	+1	-1	-1	**+1**	+1	-1	-1	-1	-1	+1	**+1**		
9	**+1**	**-1**	+1	**-1**	+1	-1	+1	**-1**	+1	-1	+1	-1	+1	-1	**+1**		
10	**+1**	**-1**	+1	**-1**	+1	-1	+1	**+1**	-1	+1	-1	+1	-1	+1	**-1**		
11	**+1**	**-1**	+1	**+1**	-1	+1	-1	**-1**	+1	-1	+1	+1	-1	+1	**-1**		
12	**+1**	**-1**	+1	**+1**	-1	+1	-1	**+1**	-1	+1	-1	-1	+1	-1	**+1**		
13	**+1**	**+1**	-1	**-1**	+1	+1	-1	**-1**	+1	+1	-1	-1	+1	+1	**-1**		
14	**+1**	**+1**	-1	**-1**	+1	+1	-1	**+1**	-1	-1	+1	+1	-1	-1	**+1**		
15	**+1**	**+1**	-1	**+1**	-1	-1	+1	**-1**	+1	+1	-1	+1	-1	-1	**+1**		
16	**+1**	**+1**	-1	**+1**	-1	-1	+1	**+1**	-1	-1	+1	-1	+1	+1	**-1**		

The assignment of the five inputs selected for the matrix and the ranges specified are outlined in Table II. The levels chosen for the factors, corresponding to maxima and minima for the inputs, also required consideration of equipment limitations and process requirements. It should be noted that factors are usually assigned so as to allow the input which is the most difficult to adjust to be changed the least number of times. For example, in this particular matrix, A is only changed once, whereas E is changed ten times. However, all inputs can be manipulated easily with the Touch Weld® controller. Therefore, the inputs were assigned to the factors after ranking in terms of perceived significance.

Table II. Summary of Inputs and Ranges Selected

Factor	Input	Units	Level 1	Level 2
A	High Pressure (P_1)*	psi	16	20
B	Weld Current	% power line wave form	32	42
C	Weld Cycles	# power line cycles	6	10
D	Forge Initiation	# current decay cycles	1.0	5.0
E	Low Pressure (P_2)*	psi	10	15

* P_1 = Forge Force, $P_1 - P_2$ = Weld Force

2.2 Experimental Procedures

Since there is a wide variety of equipment available, the features of the equipment relevant to the experimental design are discussed first. The resistance spot welder used in this investigation was a Sciaky PMCO 4STMP, rated at 200 kV·A, fitted with a Touch-Weld® Plus controller. This is a 3-phase, direct energy welder equipped with a low-inertia, diaphragm-actuated weld head. In this equipment the frequency of the output is fixed to that of the power line cycles, with the power output set as a percentage of the amplitude of the power line waveform for a specific weld schedule. Therefore, it is convenient to define weld heat and the duration of forces in terms of the size and number of power line cycles, respectively. Weld impulses consist of a specified weld current for a given number of weld cycles, followed by a current decay which involves the gradual bleed-off of the electrical field in the transformer. Weld current is measured as a percentage of the amplitude of a power line waveform. Weld cycles are controlled on the basis of the number of power line cycles. The forge initiation occurs at a specified number of cycles into the current decay portion of the weld impulse. It is at this juncture in a schedule that the low pressure is removed from the diaphragm to allow application of the forge force.

The settings for several of the variables listed in Figure 2 were determined during preliminary investigation of RSW of these material combinations. Both electrodes were RWMA Class 1; the upper; 5/8" diameter, 10" radius and the lower; 1" diameter, flat. Weld coupons were cleaned in a standard commercial caustic etch at room temperature, followed by desmutting in nitric acid at room temperature. The coupons were rinsed in deionized water followed by isopropyl alcohol and dried with a warm air gun. All material preparation was conducted on the same day as the experiment with a maximum lead time of 8 hours to the final weld. Combining Table I with Table II yields the actual schedules for the experiment, as shown in Table III. The high and low settings chosen for each factor are arranged in the orthogonal array. As mentioned earlier, the factor settings were chosen based on extreme levels that still produced welds for the majority of the schedules in the matrix. The runs were randomized to reduce any time-dependent experimental noise and eight repetitions of each run were performed. The manageable sample size represented a compromise between the need for statistically significant data, and the need to conserve time and material. The 128 overlap samples, consisting of pairs of 1" wide by 2" long coupons, were welded on the same day and within a standard shift. Of the outputs considered, only nugget expansion data is generated on-line. This is recorded digitally in terms of electrode separation as a function of time by the welder.

All weldments were inspected to determine nugget diameter and defect population (i.e. the degree of expulsion, porosity and hot tearing) prior to tensile testing. The measurements were performed on radiographs produced on Faxitron equipment, operating at 50 kV and 3 mA, with a resolution of 1% of material thickness. It should be noted that nugget diameter can be measured both by radiography and metallographic examination. Determination of nugget diameter by metallography requires that the weld be sectioned and accuracy relies on selecting the exact centerline. Measurement from a radiograph requires some interpretation, however systematic error was considered comparable to the metallographic technique. The big advantage with radiography is that non-destructive evaluation allows subsequent tensile testing of the same samples. Consequently, six of the weldments produced by each schedule were subjected to single overlap shear tests to determine strength, with the remaining two being sectioned in two planes to provide complementary metallographic data.

2.3 Data Analysis

The data acquired were entered into a computerized spreadsheet for statistical analysis using the TurboTag™ software package [9]. The noise level for the experiment was established through analysis of variance (ANOVA) and F ratio determinations [10]. The F ratio is defined as MS_B/MS_E, where MS_B is a measure of the variability between the means and MS_E is a measure of the variability between the variances. The result of this calculation can be compared to values of F which are tabulated for various degrees of freedom and confidence levels (α) [11]. If the measured F is greater than the tabulated F, it can be said that a factor or interaction is significant with $(1-\alpha).100$ % confidence. A confidence level of 99% was employed in order that selection of the noise level reflected the accuracy of the experimental data. This insured that a realistic number of factors were considered as significant when assessing the effects of inputs and interactions on the various outputs. Use of the F ratio permitted the significance of factors and interactions with respect to experimental noise to be determined. The results were presented

Table III. Outline of Schedules and Outputs

Runs	Inputs					Outputs					
Schedule Number	High Pressure	Weld Current	Weld Cycles	Forge Initiation	Low Pressure	Weld Strength	Nugget Expans'n	Nugget Diameter	Expuls'n	Porosity	Hot Tearing
1	16	32	6	1	10						
2	16	32	6	5	15						
3	16	32	10	1	15						
4	16	32	10	5	10						
5	16	42	6	1	15						
6	16	42	6	5	10						
7	16	42	10	1	10						
8	16	42	10	5	15						
9	20	32	6	1	15						
10	20	32	6	5	10						
11	20	32	10	1	10						
12	20	32	10	5	15						
13	20	42	6	1	10						
14	20	42	6	5	15						
15	20	42	10	1	15						
16	20	42	10	5	10						

as Pareto diagrams which represent a convenient method often used by statisticians to display such information. These diagrams also allowed the significance of the various inputs with respect to each other to be readily identified.

The prediction equations were formulated from the statistical analysis outlined using the menu-driven software [12]. For this two level experiment the equations were of the form listed below. For each of the six experimental outputs, the grand average was determined from the 128 responses obtained for all 16 weld schedules. The weighting coefficients for each of the input factors were determined by taking the average of the 64 responses when the factor was set high, subtracting the average of the 64 responses when the factor was set low and dividing by two. In order to use the prediction equations, coded values for the factors and interactions were substituted for the factor settings (i.e., -1 and +1, for low and high respectively). The predicted values generated by the six equations, one for each output, were then compared to the measured values for the three quantitative and three qualitative outputs.

$$\hat{\mathbf{Y}} = \bar{\mathbf{Y}} + (\Delta \mathbf{A}/2)\bullet\mathbf{A} + (\Delta \mathbf{B}/2)\bullet\mathbf{B} + \;\ldots\ldots\; + (\Delta \mathbf{ABC}/2)\bullet\mathbf{ABC}$$

where:

$\hat{\mathbf{Y}}$ = the predicted response
$\bar{\mathbf{Y}}$ = experimental grand average
A thru **E** = coded input factors
AB thru **ACD** = all 2- and 3-way interactions
(Δ*/2) = weighting coefficients

Using the findings from the prediction equation established for each output, optimum schedules for maximizing the quantitative responses and minimizing the qualitative responses were also identified. Transforming the coded values for the factors back into equipment settings allowed the best schedule for each desired response to be established. Since the schedules for the confirmation runs were not established until after the L_{16} matrix was completed and analyzed, exact details of that aspect of the experimental procedure will be presented later. Generally, the confirmation runs were designed to assess the validity of the prediction equations. They allowed a comparison between the predicted and measured values while targeting a specific response. Two schedules were also included in the family of runs to assess the reproducibility of data. In addition, a number of schedules were designed such that some of the settings fell outside the limits of the L_{16} matrix. This was done in order to assess deviation from linearity and establish whether extrapolation outside the original experimental limits was feasible.

3. RESULTS

3.1 L_{16} Experiment

A summary of the experimental results obtained from the matrix outlined in Table III is presented in Table IV. The outputs for the 16 weld schedules are tabulated against the six responses averaged over the duplicated runs. The general trend in the data is as expected with welds involving little or no nugget formation exhibiting the lowest strength. The single overlap shear tests produced a range of strength from 1060 to 1727 lbs. per spot weld. The corresponding data for nugget expansion covers a range of 4.9 to 13.1 mils and for nugget diameter values varied from zero, i.e., no nugget formed, to a maximum of 290 mils. It is apparent that higher values for the quantitative results can be associated with an increased propensity for the development of defects. As anticipated, the averaged values for the qualitative results were either 0 or 1. There is an isolated case for expulsion in schedule 5 where a value of 0.875 was obtained. This is indicative that 1 of the 8 welds in the group did not produce expulsion.

Table IV. Results for Half-factorial Experiment

Schedule Number	Weld Strength	Nugget Expansion	Nugget Diameter	Expulsion	Porosity	Hot Tearing
1	1148	5.3	0	0	0	0
2	1239	11.8	237	0	0	0
3	1675	13.1	267	0	0	1
4	1153	9.5	145	0	0	0
5	1705	12.2	265	0.875	1	1
6	1382	10.7	249	0	0	0
7	1600	11.7	283	0	0	1
8	1678	12.2	290	1	1	1
9	1216	7.2	20	0	0	0
10	1060	4.9	0	0	0	0
11	1183	5.9	0	0	0	0
12	1209	10.3	163	0	0	0
13	1310	5.4	0	0	0	0
14	1438	11.1	250	0	0	0
15	1727	12.4	283	0	0	1
16	1402	9.7	220	0	0	0

Details of the statistical analysis are not presented because it was furnished automatically by the Turbotag™ software [9]. The outcome of the analysis conducted is summarized in Figures 4-7 and Tables V and VI. The Pareto diagrams for the 6 outputs resulting from the analysis are shown in Figure 4. The five factors are indicated by shaded bars, while the interactions are indicated by hollow bars; the noise level is marked by a dashed line. All of the factors and the interactions between factors addressed in the experiment are included for comparison. First, the diagrams illustrate the relative importance of the inputs with respect to each other, and second, the significance with respect to the experimental noise level provided by the statistical analysis. Thus, Pareto diagrams identify the significant factors and interactions pertaining to each output and allow a hierarchy of input settings to be established. In the case of the quantitative results, all five inputs may be considered significant relative to the noise levels established for the strength, nugget expansion and diameter data. However, with respect to the qualitative results this is true for the hot tearing data, but not for the expulsion and porosity data.

The information provided by the Pareto diagrams enabled derivation of the prediction equations shown in Table V. These were employed primarily to predict the response for a particular weld schedule for each output. This allowed the average value and range of values obtained for each weld schedule to be compared with the predicted value in each case. The settings for the inputs predicted by the equations to produce the optimum response for each output independently were also defined. These results, which aided in designing the confirmation run experiment, are presented in conjunction with each equation. As a consequence of the quantity of data generated, the results can be addressed most effectively by considering each output independently. An assessment of the quantitative responses is presented in Figures 5, 6 and 7 and of the qualitative responses in Table VI.

3.1.1 Weld Strength

The Pareto diagram for weld strength, Figure 4(a), ranks the five factors studied as more important than any of the interactions. After applying the F ratio, it was determined that the five main factors and four interactions were statistically significant. Considering the hierarchy of input factors established, Table V(a)(i), it is apparent that weld current (B) has the greatest effect on strength. Low pressure (E) has the next greatest effect, with increasing low pressure giving an increase in strength. Weld cycles (C), high pressure (A) and forge initiation (D) have nearly equal effects. Four interactions between these factors (ABC, CD, BCD and AD) are also significant with respect to the established noise level, but there is much less effect than for the five main factors.

The prediction equation for weld strength, formulated using the hierarchy established for the relative contribution of each input, is shown in Table V(a). The equation uses the coded values (i.e., -1 for a low setting and 1 for a high setting) of the various factors and interactions. For each weld schedule, inserting the coded values of the input settings into the equation yields the predicted response for weld strength. Figure 5 shows a comparison of predicted values generated with the average values measured in the experiment for all the schedules. Although there is considerable variability in strength in some instances, the predicted value lies within the measured range for all of the weld schedules. The predicted strength varies about the average measured strength, rather than being consistently high or low. However, there is good agreement ($\pm$ 2%) between the measured and predicted values. Thus, the experimental methodology employed is effectively able to simulate the process with respect to weld strength.

Table V. Prediction Equations

(a) **Quantitative Responses** ($\hat{Y}$ = Predicted Response)

(i) Weld Strength

$$\hat{Y} = 1383 + 147\mathbf{B} + 103\mathbf{E} + 71\mathbf{C} - 65\mathbf{A} - 63\mathbf{D} + 32\mathbf{ABC} - 30\mathbf{CD} + 24\mathbf{BCD} + 22\mathbf{AD}$$

To maximize the response:

Hierarchy	B	E	C	A	D
Coded Value	+1	+1	+1	-1	-1
Real Input	42	15	10	16	1

(ii) Nugget Expansion

$$\hat{Y} = 9.6 + 1.7\mathbf{E} - 1.2\mathbf{A} + 1.1\mathbf{B} + 1.0\mathbf{C} - 0.6\mathbf{CD} + 0.5\mathbf{D} + 0.4\mathbf{ABC} + 0.4\mathbf{ACD} + 0.3\mathbf{ABD} + 0.2(\mathbf{AB} + \mathbf{AC} + \mathbf{AD}) - 0.2(\mathbf{BC} + \mathbf{BD} + \mathbf{BCD})$$

To maximize the response:

Hierarchy	E	A	B	C	D
Coded Value	+1	-1	+1	+1	-1
Real Input	15	16	42	10	1

(iii) Nugget Diameter

$$\hat{Y} = 167 + 63\mathbf{B} + 55\mathbf{E} - 50\mathbf{A} + 39\mathbf{C} - 29\mathbf{CD} + 27\mathbf{D} + 14\mathbf{AD} + 14\mathbf{ABC}$$

To maximize the response:

Hierarchy	B	E	A	C	D
Coded Value	+1	+1	-1	+1	-1
Real Input	42	15	16	10	1

(b) Qualitative Responses ($\hat{Y}$ = Predicted Response)

(i) Expulsion

$$\hat{Y} = 0.117 - 0.117\mathbf{A} + 0.117\mathbf{B} + 0.117\mathbf{E} - 0.117\mathbf{AB} + 0.117\mathbf{CD} - 0.117\mathbf{ACD} + 0.117\mathbf{BCD}$$

(ii) Porosity

$$\hat{Y} = 0.125 - 0.125\mathbf{A} + 0.125\mathbf{B} + 0.125\mathbf{E} - 0.125\mathbf{AB} + 0.125\mathbf{CD} - 0.125\mathbf{ACD} + 0.125\mathbf{BCD}$$

To minimize both responses:

Hierarchy	C	D	A	B	E
Coded Value	+1	-1	+1	+1	-1
Real Input	10	1	20	42	10
Coded Value	-1	+1	+1	+1	-1
Real Input	6	5	20	42	10
Coded Value	+1	-1	-1	-1	-1
Real Input	10	1	16	32	10
Coded Value	-1	+1	-1	-1	-1
Real Input	6	5	16	32	10
Coded Value	-1	-1	+1	-1	-1
Real Input	6	1	20	32	10
Coded Value	+1	+1	+1	-1	-1
Real Input	10	5	20	32	10

(iii) Hot Tearing

$$\hat{Y} = 0.313 - 0.188\mathbf{A} + 0.188\mathbf{B} + 0.188\mathbf{C} + 0.188\mathbf{D} + 0.188\mathbf{E}$$

To minimize the response:

Hierarchy	A	B	C	D	E
Coded Value	+1	-1	-1	-1	-1
Real Input	42	32	6	1	10

The observation of an increase in weld strength with either higher weld current or increased number of weld cycles is consistent with weld strength being strongly dependent on heat input. However, due to the resistance heating nature of the process, anything which increases the resistance of the system will also cause an increase in the heat input. A decrease in high pressure or, as mentioned earlier, an increase in low pressure yields a decrease in weld force. The lower the force, the higher the contact resistance and the greater the heat input leading to the influence of these factors on weld strength observed. However, as shown in Table V, there is only a positive effect associated with increasing the heat input providing that the propensity for defects has not increased. It has been documented that a lower strength will be realized for a weld containing defects than for a defect-free weld with a comparable nugget diameter.

3.1.2 Nugget Expansion

The Pareto diagram for nugget expansion, Figure 4(b), ranks four of the factors as more influential than the interactions, however a two-way interaction (-CD) is more important than the fifth factor (D). The F ratio determination of noise level revealed that all factors and interactions were significant. The ranking of the five main factors here is different than for weld strength. Low pressure (E) has the greatest effect, increasing low pressure increases nugget expansion. High pressure (A), weld current and weld cycles have the next largest effect. An increase in high pressure decreases nugget expansion, while an increase in weld current (B) and weld cycles (C) increases nugget expansion. An interaction (CD) between weld cycles and forge initiation comes next; increasing this interaction decreases nugget expansion. Forge initiation (D) has the least effect of any of the main factors, an increase in forge initiation produces an increase in nugget expansion. The remaining interactions have about the same level of effect.

The comparison between the predicted and measured values for nugget expansion are shown in Figure 6. There is considerable variability in nugget expansion for some schedules, although not necessarily those which produced a large variation in strength as seen in Figure 5. As with weld strength, there is good agreement ($\pm$ 2%) between the measured and predicted responses. Similarly, all of the predicted values are inside the range of measured values, and again the predicted nugget expansion varies about the measured expansion rather than being consistently high or low. All of the main factors having an effect can be rationalized on the basis of the amount of nugget expansion being a balance between the thermal expansion of the material during heating and the amount of force applied by the electrodes. High pressure and forge initiation affect the amount of force applied to the nugget, whereas low pressure affects the weld force as well as the heat input. Weld current and weld cycles affect the heat input alone and therefore the thermal expansion of the weld only. The inherent variability associated with all inputs, and all interactions between inputs, being considered significant may explain the scatter in nugget expansion data observed.

3.1.3 Nugget Diameter

The Pareto diagram for nugget diameter, Figure 4(c), ranks four of the factors as having more effect than the interactions, however a two-way interaction is more important than the fifth factor as in the case of nugget expansion. From the F ratio it was determined that all main factors and three interactions were significant. The ranking of the five main factors is different from that of both nugget expansion and weld strength. The most important factor is weld current (B) followed by low pressure (E). This represents the same hierarchy determined for weld strength. High pressure (A) and weld cycles (C) have the next greatest effect on nugget diameter. Again, this is similar to that noted for strength, although there is a reversal in the order. Forge initiation (D) turns out to have the least effect of the five main factors on nugget diameter.

As can be seen in Figure 7, which compares measured and predicted values for nugget diameter, there is considerable variation in the measured nugget diameter for some schedules. The schedules which have the greatest variability do not correspond with those which resulted in the greatest variability in weld strength or nugget expansion. With the exception of schedule 8, predicted and measured nugget diameters are in fairly good agreement. It is surprising that in the case of the eight schedules which produced few or no nuggets, the model is still able to predict the response with reasonable accuracy. It should be noted that the worst lack of fit occurred for schedule 8 where every sample experienced expulsion, Table IV.

Nugget diameter is normally considered to be dependent on the balance between the heat input to the material and the thermal conductivity of the material (i.e. the transport of heat away from the weldment). Consequently, anything which increases the heat input will increase the nugget diameter, for a specific material in a particular heat treatment condition. However, setting the forge initiation high, which translated into delaying the onset of application of the forge force, did have the effect of increasing nugget diameter. Again the resistance heating nature of the process is involved. The longer time the lower (weld) force is applied and subsequent delay in the onset of the higher (forge) force, the greater the resistance. As a result, the size of the nugget increases commensurate with the associated increase in the heat input.

3.1.4 Qualitative Outputs

The Pareto diagrams for the qualitative responses have a different appearance than those for the quantitative responses. The Pareto diagrams for the qualitative responses, Figure 4(d), (e) and (f), consist of only two values, one above the noise level, as determined by the F ratio, and one below. The Pareto diagrams for expulsion and porosity have the same significant factors and interactions. These two responses are the only ones in which two of the main factors, C and D, have no significant effect on the output when considered independently. However, when considered in terms of interactions, the combination of the factors becomes significant. Only the main factors are significant for hot tearing, all the interactions being below the noise level.

The expulsion and porosity data can be addressed together since the same factors and interactions are significant. Expulsion is due to excessive weld current for a given electrode force, whereas porosity can be due to several factors, such as dirty material, low electrode force or even expulsion itself. The latter fact indicates that it is not surprising that schedule settings should be similar, if not the same, to eliminate these defects. It can be seen that weld current, low pressure and high pressure are all significant at the same levels. In order to decrease the amount of expulsion and porosity, weld current and low pressure should be decreased and high pressure should be increased. Weld cycles and forge initiation considered independently are not significant factors. However, they are present in combination for three of the significant interactions. Thus, these main factors must be considered when endeavoring to minimize these responses. The fact that the prediction equations for expulsion and porosity contain the same factors and interactions indicates that the porosity which occurred was probably due to expulsion.

It is clear for the data concerning hot tearing that all of the main factors are significant at the same level, but no interactions are significant. In order to minimize hot tearing, high pressure and forge initiation should be set high, while weld current, weld cycles and low pressure should be set low. These settings are diametrically opposed to those required for a high strength weld. Hot tearing is usually due to the application of the forge force before the weld nugget has solidified enough to support the force. It is noteworthy that during preliminary testing it was determined that early forge initiation was the major factor contributing to hot tearing. This does not appear to be reflected by these experimental results which may be a consequence of assigning categorical values (i.e. 0 or 1).

In the case of the qualitative responses, the Pareto diagrams show that the well-defined hierarchy of effects observed with the quantitative responses does not exist. However, the bimodal distribution of effects observed does lead to a ranking of the significance of factors and interactions. Thus, the information provided by the analysis can still be used to formulate the prediction equations. Table VI compares the average measured responses for the qualitative results with the predicted responses obtained through the equations. It can be seen that, with one exception, the averages for the measured data are either zero or one for the eight welds produced by each schedule. This indicates that the 16 schedules produced spot welds either all with, or all without, defects. The predicted results do show a broader spectrum of values between zero and one as a result of the statistical nature of the analysis. In this case the predicted values other than zero or one have been interpreted as the relative likelihood of occurrence. A comparison of the results for the three types of defects shows that there is reasonably good agreement between the measured and predicted values. For example, considering schedule 8, all samples exhibited expulsion, while 95% were predicted to exhibit evidence of expulsion. However, it is unclear from this limited data whether the predicted values for the qualitative responses actually do represent probabilities or if they may be better considered as threshold values. If indeed the former is the case, the accuracy of the prediction equations would be greatly improved by increased sample size. In any event it is necessary to run many more samples to determine the meaning of the values obtained from the prediction equations for the qualitative results.

3.2 <u>Confirmation Runs</u>

3.2.1 Results from Prediction Equations

The information contained in Table V reveals the weld schedules required to maximize or minimize the predicted response for the quantitative and qualitative outputs, respectively. The factor settings required to optimize the quantitative responses in combination were determined by evaluating the three prediction equations for all combinations of factor levels and picking the schedule which produced the optimum output balanced between the three responses. The factor settings required to maximize all quantitative responses proved to be the same, i.e. A=-1(low), B=+1(high), C=+1(high), D=-1(low) and E=+1(high).

Table VI. Qualitative Results - Average vs Predicted

Schedule Number	Expulsion		Porosity		Hot Tearing	
	Ave.	Pred.	Ave.	Pred.	Ave.	Pred.
1	0	0	0	0	0	0.125
2	0	0	0	0	0	0.125
3	0	0	0	0	1	0.875
4	0	0.016	0	0	0	0.125
5	0.875	0.922	1	1	1	0.875
6	0	0	0	0	0	0.125
7	0	0	0	0	1	0.875
8	1	0.953	1	1	1	0.875
9	0	0	0	0	0	0.125
10	0	0	0	0	0	0
11	0	0	0	0	0	0.125
12	0	0.016	0	0	0	0.125
13	0	0	0	0	0	0.125
14	0	0	0	0	0	0.125
15	0	0	0	0	1	0.875
16	0	0.016	0	0	0	0.125

The factor settings required to minimize the qualitative responses were arrived at in a similar manner. It was found that for expulsion and porosity there are six schedules which produce a minimum predicted value. This complication is introduced by the fact that all factors and interactions are equally weighted in the prediction equation, permitting the interactions to increase the degree of freedom. The optimized schedules can be categorized into two scenarios for factor settings. In the first group of four schedules, the interaction CD=-1, i.e. C and D are set opposite to each other (one high / one low) and factors A and B are set the same (both high / both low). In the second group of two schedules, CD=+1, i.e. C and D are set the same (both high / both low), while A is set high and B is set low. Factor E is set low for all schedules to minimize the predicted response, which translates into a higher weld force.

There is only one schedule which minimizes hot tearing and it is the same as the fifth in the series of schedules identified for minimizing expulsion and porosity in Table VII, i.e. A=+1(high), B=-1(low), C=-1(low), D=-1(low) and E=-1(low). Therefore, it is possible to minimize all qualitative responses with one schedule, but these settings tend to be diametrically opposed to those required for high strength. Thus, it is anticipated that this schedule will not produce a good weld. This is best illustrated by considering the closest schedules run in the original experiment (#'s 9, 10 & 11), all of which failed to produce a weld nugget. As a result, care must be exercised in selecting settings for schedules to be incorporated into confirmatory experiments which are aimed at achieving a balance between maximum strength and minimum defect population.

For the purpose of designing confirmation runs, the schedules required to optimize specific responses were compared with the L_{16} matrix to determine if they had been included. If these weld schedules had not been performed, the schedules that were closest were identified. The net result of this exercise is summarized in Table VII. In each case, the closest schedule is the one in which the factor deviating from the optimum was least important. The schedules listed under 'closest' are ranked accordingly, with the setting variant identified in parentheses. It is apparent that no one schedule can optimize all six responses simultaneously. However, one schedule maximizes strength, nugget expansion and nugget diameter. The schedule predicted to minimize expulsion, porosity and hot tearing is almost diametrically opposed to these settings. The other settings for minimizing expulsion and porosity are a mixture of these two schedules.

Table VII. Optimized Schedules for Specific Responses

Response:	A	B	C	D	E	Closest Sch. (Setting Var'n)
Strength	-1	+1	+1	-1	+1	**8(D)**, 15(A), 5(C)
Nugget Expansion	-1	+1	+1	-1	+1	**8(D)**, 5(C), 3(B)
Nugget Diameter	-1	+1	+1	-1	+1	**8(D)**, 5(C), 15(A)
Expulsion	+1	+1	+1	-1	-1	**15(E)**, 11(B), 7(A)
Porosity	+1	+1	-1	+1	-1	**14(E)**, 10(B), 6(A)
	-1	-1	+1	-1	-1	**3(E)**, 7(B), 11(A)
	-1	-1	-1	+1	-1	**2(E)**, 6(B), 10(A)
	+1	-1	-1	-1	-1	**9(E)**, 13(B), 1(A)
	+1	-1	+1	+1	-1	**12(E)**, 16(B), 4(A)
Hot Tearing	+1	-1	-1	-1	-1	**9(E)**, 10(D), 11(C)

3.2.2 Rationale for Confirmatory Design

The information contained in Table VII was used to design the schedules for the subsequent confirmation runs, outlined in Table VIII. The combinations of factor levels tabulated represent the optimum schedules, based on the input ranges selected for the experiment only. It is possible to interpolate between, or extrapolate beyond, these levels. Consequently, nine scenarios were established in order to test the prediction equations. The first confirmation run made, C1, was the weld schedule predicted to produce maximum strength, even though high defect levels were predicted. While one of our goals was to minimize defects, it was decided not to run any of the schedules identified in Table VII as minimizing qualitative responses since all schedules close to these in the L_{16} did not produce welds. The next two confirmation runs, C2 and C3, were repeats of schedule 2 and schedule 15 of the original experiment to assess the reproducibility of the process.

Table VIII. Confirmation Run Schedules

Schedule Number	High Pressure	Weld Current	Weld Cycles	Forge Initiation	Low Pressure
C1	16	42	10	1	15
C2	16	32	6	5	15
C3	20	42	10	1	15
C4	18	37	8	3	12
C5	18	42	8	3	15
C6	16	42	8	3	15
C7	16	39.2	10	1	15
C8	18	46	8	3	15
C9	22	47	7	4	19

In order to assess the degree of linearity of the effects of the factors on outputs, two sets of specimens were produced for confirmation run C4 with all factors set as closely as possible to the mid-point of the selected ranges. In designing runs C5 through C9 settings for B and E, which have the most effect on strength per the prediction equation, were kept high. Factors A, C, and D have a lesser, and nearly equal, effect and were varied to achieve a balance between quantitative and qualitative responses. Confirmation runs C5 and C6 were made with factors D and E set at the mid-point of their range, as was done in the weld schedule established prior to the experiment, C and E set high while factor A was varied. The idea behind confirmation run C7 was to hold A, C, D and E at the settings predicted to produce maximum strength, while varying B to give a target value of 1750 lbs. As mentioned earlier, confirmation runs C8 and C9 represent an extrapolation of settings outside the range of the original experiment.

3.2.3 Confirmatory Results

A summary of the results obtained from the confirmation runs outlined in Table VIII is presented in Table IX. The outputs for the nine weld schedules are tabulated against the six responses averaged over the duplicated runs. The single overlap shear tests produced a range of strength from 1127 to 1725 lbs. per spot. The corresponding data for nugget expansion covers a range of 8.9 to 13.6 mils and for nugget diameter values varied from 201 to 297 mils. It is apparent from Table IX that there is an increased likelihood of defects associated with higher values for the quantitative responses. For example, three of the four welds with the highest strength also showed evidence of expulsion.

Table IX. Results for Confirmation Runs

Schedule	Weld Strength	Nugget Expansion	Nugget Diameter	Expulsion	Porosity	Hot Tearing
C1	1713	12.6	290	0.750	1	1
C2	1127	11.1	230	0	0	0.125
C3	1501	11.0	273	0	0	0
C4	1191	8.9	201	0	0	0
C5	1505	11.8	280	0.875	0	0.125
C6	1651	13.6	291	0.250	0.875	0.250
C7	1725	13.2	286	0.125	1	0.375
C8	1601	12.4	297	0	0	0
C9	1553	12.1	292	0	0	0

The average measured weld strength for all schedules, shown in Figure 8, was consistently below the predicted weld strength, however the predicted strength did follow the general trend of the measured weld strength. Those schedules with defects exhibited the most extreme variation in range (250-300 lbs.) between the weakest and strongest specimen for each weld schedule. The average strength for confirmation runs C2 and C3 is far below that of these schedules as run in the original experiment. Using the F ratio on these results reveals, with a 99% confidence level, that the two samples are from different statistical populations. That is, the differences between the confirmation runs and the original experiment are not due to experimental scatter.

The discrepancy between the confirmation runs and the L_{16} is also apparent in Figures 9 and 10 for nugget expansion and nugget diameter, respectively. In both cases, predicted values were rarely close to measured values, and no trend in predicted vs measured was apparent. The data for nugget expansion show a deviation from 0.2 to 2.5 mils and for nugget diameter, from 3 to 86 mils. There is no apparent correlation between the schedule settings and the amount of deviation. Likewise the data for expulsion, porosity and hot tearing, as shown in Table X, show very poor agreement. These results are indicative that some change in the equipment has occurred during the interlude between experiments which has affected the data. Some possible reasons for the discrepancies observed will be addressed in more detail later.

Table X. Qualitative Results - Average vs Predicted for Confirmation Runs

Schedule Number	Expulsion		Porosity		Hot Tearing	
	Ave.	Pred.	Ave.	Pred.	Ave.	Pred.
1	0.750	0.234	1	0.250	1	1
2	0	0	0.125	0	0	0.125
3	0	0	0	0	0	0.875
4	0	0.094	0	0.100	0	0.275
5	0	0.352	0.125	0.375	0	0.688
6	0.250	0.586	0.250	0.625	0.875	0.875
7	0.125	0.169	0.375	0.018	1	1
8	0	0.445	0	0.475	0	0.837
9	0	0	0	0	0	0.612

4. DISCUSSION

4.1 Simulation of the RSW Process

The main objective of this investigation was to assess whether factorial designs can effectively be applied to RSW. It is clear that the relative success of a factorial experiment is strongly dependent on the results of the initial "brainstorming" session. This mainly concerns definition of the scope of the matrix through assumption of fixed effects and selection of appropriate process variables. A convenient way to gauge the merit of the design of the experiment is to compare the predicted values with the measured values for the outputs. Although this is only possible for the quantitative responses, it provides insight into the ability of the experiment designed to simulate the RSW process. Plots of measured response versus predicted response for weld strength, nugget expansion and nugget diameter are presented in Figures 11, 12, and 13, respectively.

Figure 11 demonstrates that there is excellent agreement between the predicted and measured strength for all schedules run in the L_{16} experiment. The solid line plotted represents a 1-to-1 correlation and over the range of strengths from 1000 to 1800 lbs the largest variation from predicted is only 32 lbs (schedule 8). A straight line fitted to the data from the L_{16} coincides exactly with this line. However, the data pertaining to the confirmation runs shows very poor agreement between measured and predicted values. As the design of the experiment was linear, any lines fitted to the data must be a first order regression. When a linear fit is attempted it can be seen that the resulting dashed line is nearly parallel to the solid line but shifted to the right. This indicates that, although the general prediction model is still valid, a change in performance of the RSW equipment has occurred, yielding a lower strength weld for a given schedule. This is illustrated by the 13-15% drop in strength documented for the schedules common to the L_{16} and confirmation run data (i.e. 2 vs C2 and 15 vs C3).

The correlation between measured and predicted values for nugget expansion in the L_{16} and the confirmation runs are plotted in Figure 12. Again the line plotted represents a 1-to-1 correlation and it is clear that the data from the original experiment shows exceptionally good agreement. The close correlation is somewhat surprising for the lower values where the schedules did not result in nugget formation. The nugget expansion data for the five schedules which formed only diffusion bonds reflect the behavior of solid material, while the data from the other 11 schedules, which produced significant volumes of molten material, contained contributions to expansion from both liquid and solid material. The experimental design is obviously incapable of differentiating between the two contributions but there is still an excellent straight line fit.

However, with regards to the confirmation run data, considerable scatter exists about the best straight line fit. It is apparent that there is very poor agreement in this case with the majority of the measured data being lower than predicted values. Again addressing the two schedules common to both sets of data, which were included to assess reproducibility, the decreases are significant. Compared with a maximum deviations of $\pm$ 0.1 mils for all of the L_{16} data, the difference between the measured and predicted values for confirmatory schedules C2 and C3, corresponding to original schedules 2 and 15, deviate by 0.7 and 1.4 mils, respectively. Again the magnitude of the shift in data is indicative of a change in the performance of the equipment between experiments.

The corresponding data for nugget diameter is presented in Figure 13. Regardless of whether a weld nugget was formed or not, the agreement between measured and predicted values was not good over the whole range of nugget diameters observed. The lack of correlation is independent of which set of data is assessed. There is considerable scatter in all the results about the 1:1 line including consideration of diffusion bonded or small nugget weldments. The absence of an identifiable trend can perhaps be accounted for by the fact that the diameter of nuggets can be affected by the presence of defects. Consequently, it is difficult to rationalize the deviation between measured and predicted values in the absence of a simultaneous quantitative assessment of expulsion, porosity and hot tearing.

4.2 Reproducibility of Results

The lack of agreement between the schedules run for the original matrix and the confirmation runs could be due to several sources. In an attempt to determine the effect of equipment-related changes on weld schedules following disassembly, a confirmation run and a run from the L_{16} with the same settings were selected. A comparison of the output from the RSW for the two runs is presented in Figure 14 for schedule 15 from the L_{16} and schedule C3 from the confirmation runs. The most outstanding difference is the portion of the output data which is related to weld force. Using the same schedule settings there has been an increase in weld force of 57 lbs. If the change in weld force were the only change to the welder, a 10% increase would lead to a drop in the heat input. This drop is difficult to quantify as the controller does not permit such small changes to be made. There would be two effects on nugget expansion expected due to the increase in weld force; less electrode separation as a result of higher clamping force and a reduced volume of molten material. This manifests itself in a 12.7% decrease in nugget expansion from 12.4 to 11.0 mils, accompanied by a 3.5% decrease in nugget diameter from 283 to 273 mils. The net result is a 15% reduction in weld strength from 1727 to 1501 lbs. The change in weld strength with respect to the change in nugget expansion is consistent with the correlations made from the experimental matrix. Therefore, the reduction in weld force may be a contributing factor, but there are probably other factors providing the major contribution to the equipment-related changes.

The change in weld force is significantly greater than the normal weld-to-weld variation in weld force of ± 10 lbs. A comparison of the readouts for high and low pressure, which generate the electrode forces, shows that there is no significant change in the amount of pressure applied between schedule 15 and schedule C3. This suggests that the increase in weld force observed may well be due to the way in which the pressure is applied. Consequently, another factor which can be considered is that the electrodes were changed between experiments with the replacements being nominally the same geometry. A change in electrode tip geometry, such as a decrease in tip radius would produce a smaller contact area and a correspondingly higher pressure for the same applied force. The resultant change in pressure would affect the contact resistance of the interface between the workpieces and the two workpiece/electrode interfaces. The decrease in resistance between the workpieces would cause a decrease in weld current leading to a lower heat input. The weld current data reveals that there has been a reduction in maximum current of 1840 amps between the two schedules, which is consistent with this hypothesis.

Further work is obviously required to define the sensitivity of the welding process to subtle changes in electrode geometry. Both weld force and current strongly influence the heat input for a given weld schedule and can be affected by assembly or calibration procedures. Although uncertain at present, it may well be that reproducibility between experiments is a strong function of electrode tip radius. It may be surmised that, in the near term, the same electrodes must be employed for consecutive experiments or, in the far term, the optimum weld schedule must be designed to be robust to such fluctuations. Another solution may be to introduce tighter tolerances during electrode manufacture but this would not be a particularly practical approach.

4.3 Linearity of Responses

In the original experiment, it is not possible to assess whether the effect on a response due to a specific factor can be approximated by a straight line, or can best be described by a curve. This is due to the absence of mid-point settings in a two-level design such as the L_{16} employed. The scatter in data may be indicative that the original assumption of process linearity was an oversimplification. Thus, it has proved necessary to establish if non-linearity exists and, if so, the degree of curvature. This highlights the rationale behind running two schedules which represented opposite ends of the strength spectrum (C2 and C3) and a schedule which represented mid-point (or mid-range) settings (C4) in the confirmation runs.

It has been established that the L_{16} and the confirmation run data are statistically separate populations. However, the internal agreement which exists in the confirmatory experiment (Figure 11) allows a valid assessment of the deviation from linearity. Figure 15 illustrates the effect of weld current (B) on weld strength for the C2 (low strength), C3 (high strength) and C4 (mid-range) schedules. If the RSW process is linear, the strength of the welds from schedule C4 should fall on the dashed line between schedule C2 and C3. However, it can be seen that there is considerable deviation from linearity of -130 lbs. for the mid-point schedule. This demonstrates one of the limitations of a two-level experiment and why it is most useful as a screening test. As a consequence of this study, it will be possible to design an effective three-level experiment, which will permit such higher order effects to be evaluated.

4.4 Evaluation of Interactions

The philosophy of factorial designs is that, unlike OFAT experimentation, information concerning interactions between all inputs can be obtained simultaneously [7]. For the RSW process, important interactions between various equipment settings were identified and useful information was obtained in the absence of extensive testing. For example, consider the interaction between weld cycles and forge initiation (CD). Looking at nugget expansion and examining the individual terms, weld cycles and forge initiation should both be set high to maximize expansion. When producing an 'optimized' schedule through OFAT experimentation, the settings for C and D would probably also be high. The selections would not reflect the interaction. However the effect of the CD interaction (Table V) is greater than the effect of D alone. Therefore, the setting for CD must be determined prior to the setting for D. Through the use of the prediction equation CD is set low by setting D low, and a better predicted response for nugget expansion is achieved.

Even further removed from evaluation by OFAT experiments, considerations can be extended to three-way interactions. For example in two of the qualitative outputs, Figure 4, the CD interaction is significant and is present three times, once by itself and twice as part of three-way interactions with A (high pressure) and B (weld current). However, the factors C (weld cycles) and D (forge initiation) are not significant when considered individually. The only way to evaluate the effects of this interaction is through the use of designed experiments. Knowledge of the effect of the interaction, CD, and the other two- and three-way interactions was gained from just 16 runs. The effect would be difficult or impossible to quantify using traditional OFAT techniques while still maintaining a manageable matrix size.

Figure 4 reveals that the effect of interactions between inputs is much more significant for the qualitative outputs than for the quantitative outputs. While the effects of the five main factors on both types of responses would be discernable through extensive OFAT experimentation, the effect of interactions would remain unclear. This is of particular significance with respect to the relationship between equipment settings and the formation of defects. Although the presence of defects is cause for rejection of a weld, such categorical responses are frequently neglected in OFAT experiments. This is a consequence of the difficulties often faced in quantifying defects such as the degree of expulsion. For example in Fig 4(d), the CD interaction referred to earlier has a threefold influence on the occurrence of expulsion. If consideration of defect generation had been included in OFAT experiments, only the fact that C and D were insignificant would have been revealed. Identification of the importance of these interactions in this study reinforces the philosophy behind the use of designed experiments.

4.5 Optimization of Weld Schedules

An important aspect of the application of factorial designed experiments to RSW is the optimization of a weld schedule from a restricted number of tests. The optimum schedule is that which consistently produces the highest strength welds in the absence of any weld defects. Presented in Table XI are the weld schedules ranked in order of decreasing strength for the L_{16} and the confirmation runs, until a defect-free schedule is reached in each case. In the L_{16} experiment, Table XI(a), schedule 14 produced defect-free welds with the highest strength. The responses predicted by the analysis are in excellent agreement with the measured responses. It is apparent from Table XI(b) that the confirmation run schedule C8 produced the most desirable results, i.e. even higher strength in combination with zero defects. Although the maximum strength has increased with respect to the original experiment, the measured responses do not agree well with the predicted responses. Again this may be indicative that disassembly of the welder between the experiments caused changes in the performance of the equipment.

Baseline for the OFAT experiments was a generic schedule developed for other aluminum alloys of approximately the same (dissimilar) thicknesses. By adjusting the inputs over a series of 100 weldments with 20-30 equipment settings, the schedule was gradually refined to produce what was considered to be optimum settings (A=16, B=37, C=8, D=3, E=15). An average weld strength of 1410 lbs., with a range of ±70 lbs., was achieved using these welder inputs. This schedule represents the nominal center point about which the ranges for factor settings were established. As a result of the factorially designed experiment, the best defect-free weld had an average strength of 1601 ±100 lbs, and was produced using schedule C8 (A=18, B=46, C=8, D=3, E=15). Thus, a modest gain in strength has been realized, but at the expense of an increase in variability.

The above comparison between the L_{16} matrix and the confirmation runs may not be appropriate as a result of the change in equipment performance experienced between the experiments. As an example, it is worthwhile noting that prior to extensive recalibration of the welder, the baseline OFAT schedule produced welds with strengths in excess of 1700 lbs. On a more encouraging note, when the equipment settings from this schedule are inserted into the prediction equation for strength arrived at through the L_{16} matrix, a value of 1421 lbs. is predicted. This is only an 11 lb. difference with respect to the average of the measured values (1410 lb.). This variation is indicative of excellent agreement, since the deviation within the measured data was ±30 lbs. Therefore, the design employed is able to provide valid predictions, even though the assumption of a linear behavior of responses to inputs has been shown to be an oversimplification. However, the variation in equipment performance has necessarily restricted the number of comparisons that can be made between measured and predicted responses by using theoretical schedules. At present, it is not possible to evaluate the influence of equipment-related changes on variability in the quantitative responses or the effect on the qualitative responses.

4.6 Effect of Equipment Changes

The change in equipment performance inferred by the above observations prompted an examination of the archived data for welder outputs collected over the 9 month period surrounding the experiment. Table XII outlines the maintenance history for the equipment in conjunction with the weld strengths obtained from comparable schedules arrived at by both

OFAT and statistical methods. In January 1990 using OFAT the best defect-free weld strength achieved was 1700 lbs. In May 1990 the weld controller was modified with new hardware and software and then recalibrated. The L_{16} matrix was run during July with a maximum strength of 1727 lbs produced by schedule 15. It is important to note that the highest strength, defect-free weld was 1438 lbs (schedule 14). In August 1990 the equipment was again recalibrated following disassembly and replacement of the electrodes. The confirmation runs were made in September 1990 and schedule C8 produced a defect-free weld with a strength of 1601 lbs. While this may appear as a drop of 100 lbs from the best OFAT result, running the OFAT schedule again in September yielded a strength of only 1410 lbs.

Table XI. Maximum Strength Defect-Free Welds

(a) L_{16} Experiment

Schedule	Strength	Nugget Expansion	Nugget Diameter	Expulsion	Porosity	Hot Tearing
15	1727	12.4	283	0	0	1
5	1705	12.2	265	0.9	1	1
8	1678	12.2	290	1	1	1
3	1675	13.1	267	0	0	1
7	1600	11.7	283	0	0	1
14	1438	11.1	250	0	0	0
14, predicted	1431	11.2	252	0	0	0.1

(b) Confirmation Runs

Schedule Number	Weld Strength	Nugget Expansion	Nugget Diameter	Expulsion	Porosity	Hot Tearing
C7	1725	13.2	286	0.1	1	0.4
C1	1713	12.6	290	0.8	1	1
C6	1651	13.6	291	0.3	0.9	0.3
C8	1601	12.4	297	0	0	0
C8, predicted	1751	13.2	335	0.4	0.8	0.5

Even though equipment-related changes resulted in a decrease in weld strength of 290 lbs for the OFAT schedule between January and September, an increase in strength of 190 lbs over the September OFAT schedule was still realized through the experiment. This increase in strength is a reflection of the adjustments to the weld schedule made possible through the use of the designed experiment. Care must be exercised in comparing these particular results because schedule C8 contained some settings which were extrapolated outside the ranges for variables defined in the original experiment. However, it is interesting to note that the Mil-W-6858D requirement applicable to these materials, [2], calls for an average weld strength of only 585 lbs. which represents 30-50% of the strengths achieved throughout this study.

Table XII. Effect of Equipment Changes on Weld Strength

Date	Experiment	Maximum Strength	Max. Strength w/o Defects
Jan '90	OFAT		1700 lbs
May '90	Equipment disassembly / recalibration		
Jul '90	DOE (L_{16})	1727 lbs	1438 lbs
Aug '90	Equipment disassembly / recalibration		
Sep '90	DOE (CR)	1725 lbs	1601 lbs
Sep '90	OFAT		1410 lbs

4.7 Implications for On-Line QC

Controlled generation of data on various aspects of the RSW process has the potential to permit the evaluation of welder feedback as on-line QC signals. An example of this is the possible correlation of measured weld strength with nugget expansion output data. In order to evaluate this relationship, Figure 16 was constructed from the data obtained from the present study. The weld schedule which produced each point is indicated on the plot and a first order linear regression through the data points highlights the general trends. Three scenarios were considered; first, all points from the L_{16} were fit with a solid line, second, the five points which did not produce a nugget, as shown in Table IV, were neglected, and the remaining 11 points were fit with a dashed line. Thirdly, a dotted line was fit to the points from the confirmation runs. It is clear that there is a gradual increase in strength with nugget expansion in the range of 4 to 14 mils. There is considerable scatter about the line fit to all points from the L_{16} experiment. However when considering only those points where a nugget was produced the fit becomes much better. There is good correlation for the confirmation runs, and reasonable agreement between the confirmation runs and the L_{16} experiment.

Information can be extracted from the plot which can provide insight into improving weld quality by addressing the schedule settings which yield the individual data points. The deviations from the line fit to the data points can be linked to two sources; the sequence of events within a given schedule and the generation of defects. As mentioned previously, those schedules which did not produce a nugget have different expansion characteristics from those with nugget formation. Schedules 2, 4, and 12 produced spot welds with lower than expected strength for a given nugget expansion, however these schedules included late forge initiation. This increased delay in application of the forge force would impose less restriction on expansion. Schedule 16 had high weld pressure which would provide increased resistance to electrode separation and thus limit nugget expansion. The deviations for schedules 3, 5, 7, 8, and 15 can be linked to the defects that were observed in welds produced by these schedules. The amount of nugget expansion was lower than expected as a consequence of the occurrence of expulsion. The deviation for schedules 1, 9, 10, 11 and 13 is related to the lack of nugget formation and the presence of diffusion bonds only. For reasons unclear at this time, there is a much better fit with deviations resulting from the effects mentioned above being markedly less. The only large variation from the trend line is schedule C2, which was a duplicate of schedule 2 from the L_{16} experiment, which probably deviates for the same reasons. Based on this synthesis of the nugget expansion data, RSW equipment outputs have the potential to enhance quantitative assessments of weld quality [4]. It appears that the generation of such plots from a broader database will enable weld strength to be correlated with nugget expansion, while simultaneously detecting the presence of defects.

5. CONCLUDING REMARKS

1. The successful application of a Taguchi L_{16} half-factorial design to the RSW process relied heavily on the initial brainstorming session. The exercise identified the significant process variables and the number of factors to be fixed for a manageable matrix size. The effects of five inputs on three quantitative and three qualitative outputs were considered in the experiment.

2. Taguchi methodology permitted the relative contribution of factors and interactions pertaining to each response to be established through the use of predictive equations. Dedicated software (TurboTag™) provided statistical analysis of the 6 data sets compiled for the 16 schedules. The results were rationalized in terms of the balance of responses obtained for each weld schedule.

3. It was determined that weld current, weld cycles and low pressure had a large impact on most responses, whereas high pressure and forge initiation affected mainly qualitative responses. The most significant interaction identified was between weld cycles and forge initiation, which affected all of the responses except hot tearing.

4. The confirmation runs designed to assess the validity of the experiment and monitor reproducibility of results produced inconsistent data. Statistical analysis revealed that weld schedules common to both experiments were not part of the same sample population. The difference was accounted for through equipment-related changes associated with disassembly.

5. The statistical approach allowed the baseline schedule to be refined efficiently by improving both the quantitative and qualitative outputs simultaneously. The ability to assess the impact of interactions between the inputs on the susceptibility of a weld schedule to generate defects was particularly beneficial and would not have been recognized through OFAT experimentation.

6. An assessment of the merits of Taguchi methodology for optimizing a weld schedule proved to be impractical, but in this application it proved to be an effective screening test for defining follow-on studies. It is noteworthy that the level of weld strength achieved throughout this study was more than double the average weld strength (585 lbs.) required by Mil-W-6858D.

6. The reasonable correlation between nugget expansion output and weld strength in both sets of data had positive implications for on-line quality control. However, an assessment of the merits of the experimental approach for optimizing weld schedules was impractical. The technique did prove to be an effective screening test for defining future investigations.

7. Weld schedules which included mid-range settings for input variables revealed that the initial assumption of a linear relationship between process inputs and outputs was an oversimplification. It is clear that impending studies must include three level designs, in order to assess the impact of higher order interactions and the deviation from linearity.

6. ACKNOWLEDGEMENT

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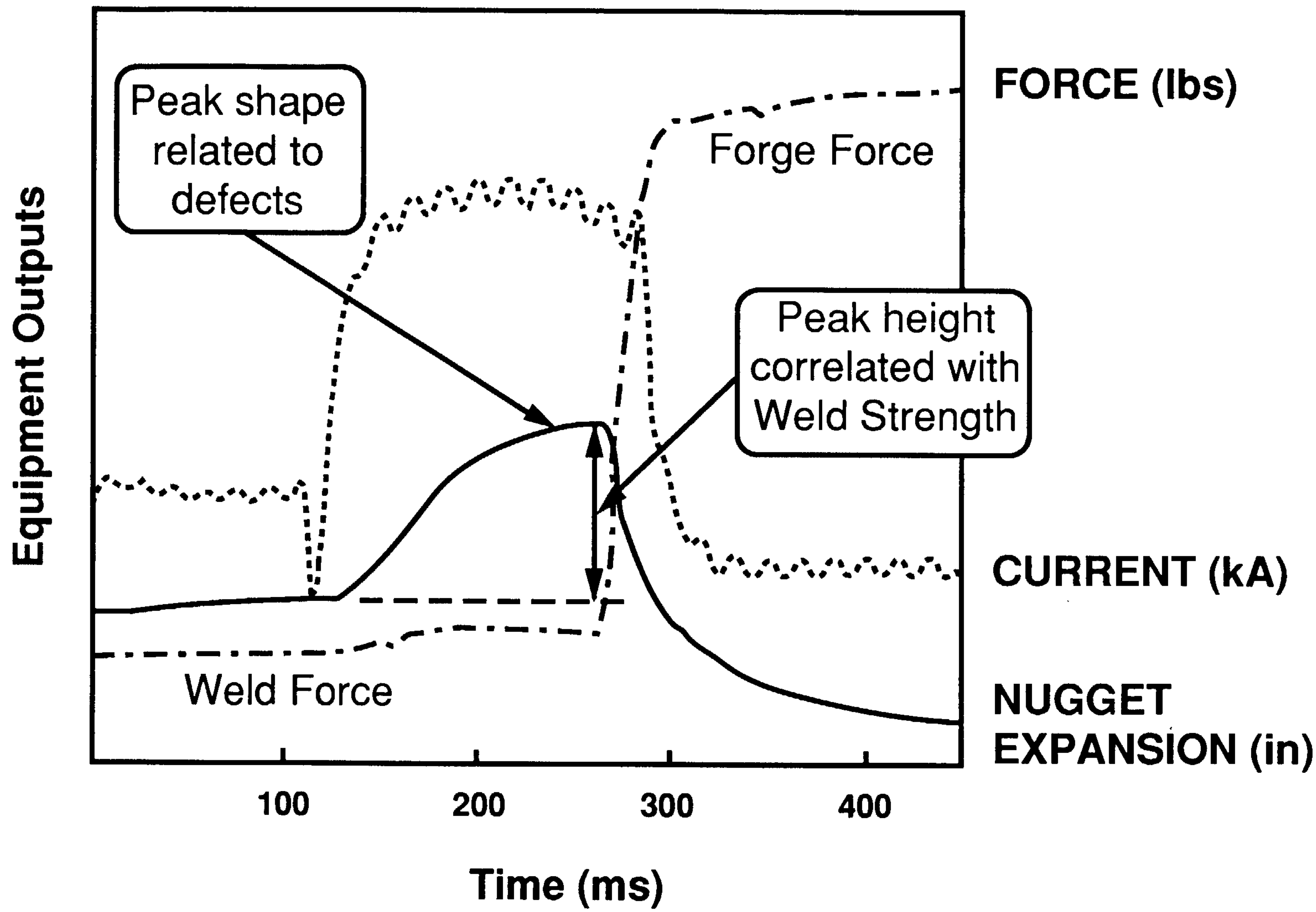


Figure 1. An example of one method of presentation of outputs from modern RSW equipment

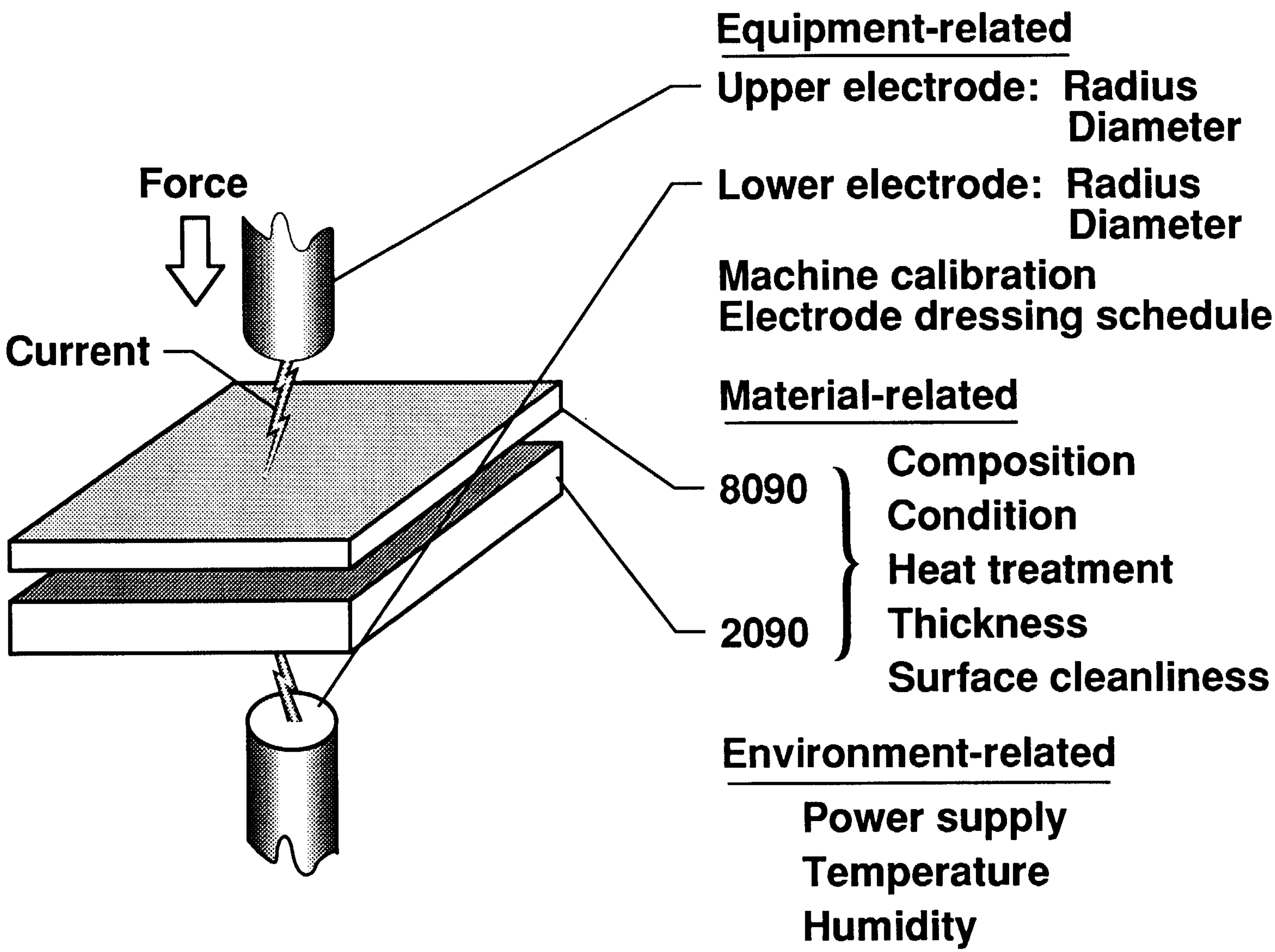


Figure 2. Summary of physical variables identified for the process which were assumed fixed in the experimental design

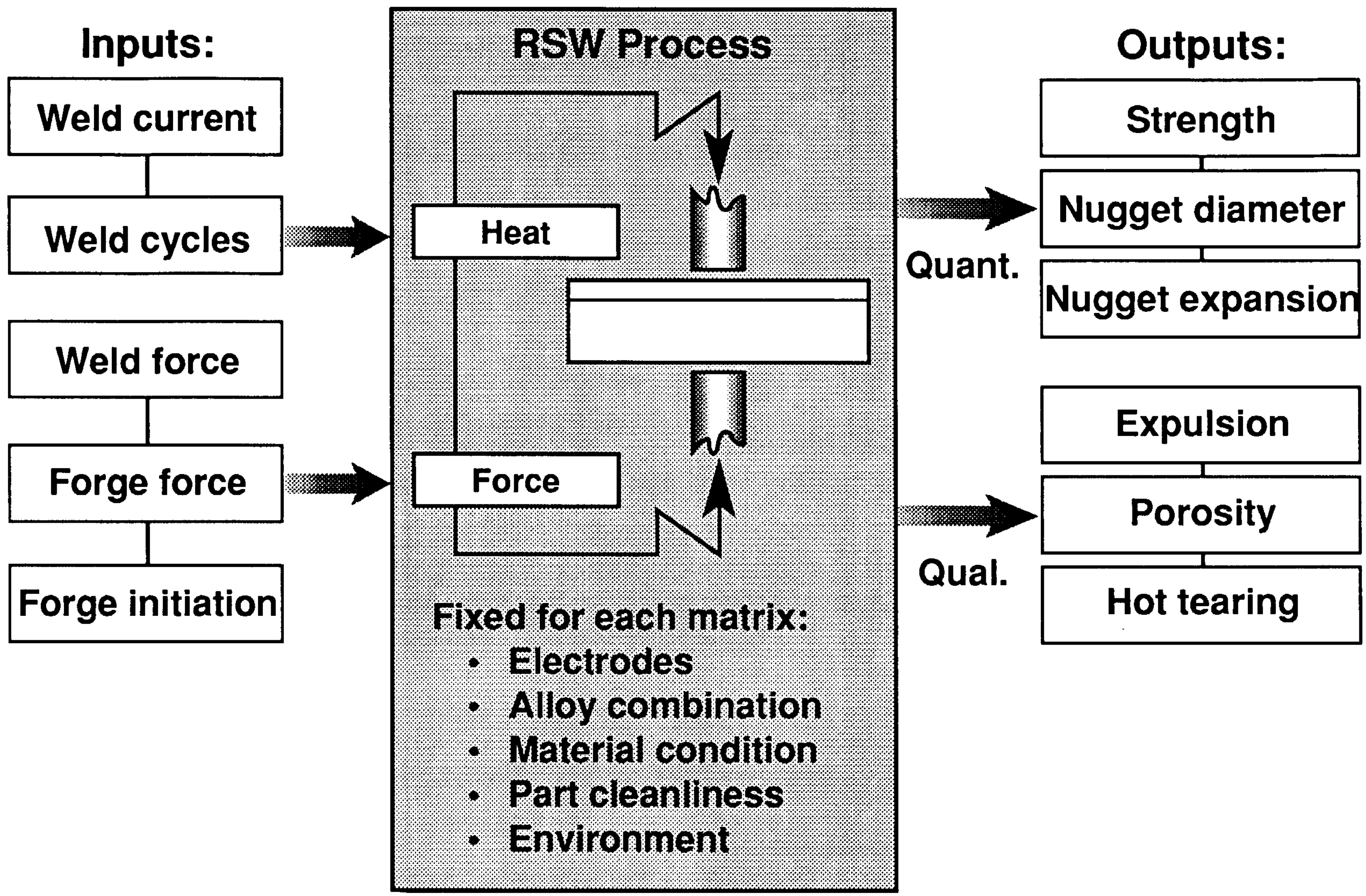


Figure 3. Process inputs and outputs included in experimental design as a result of brainstorming exercise

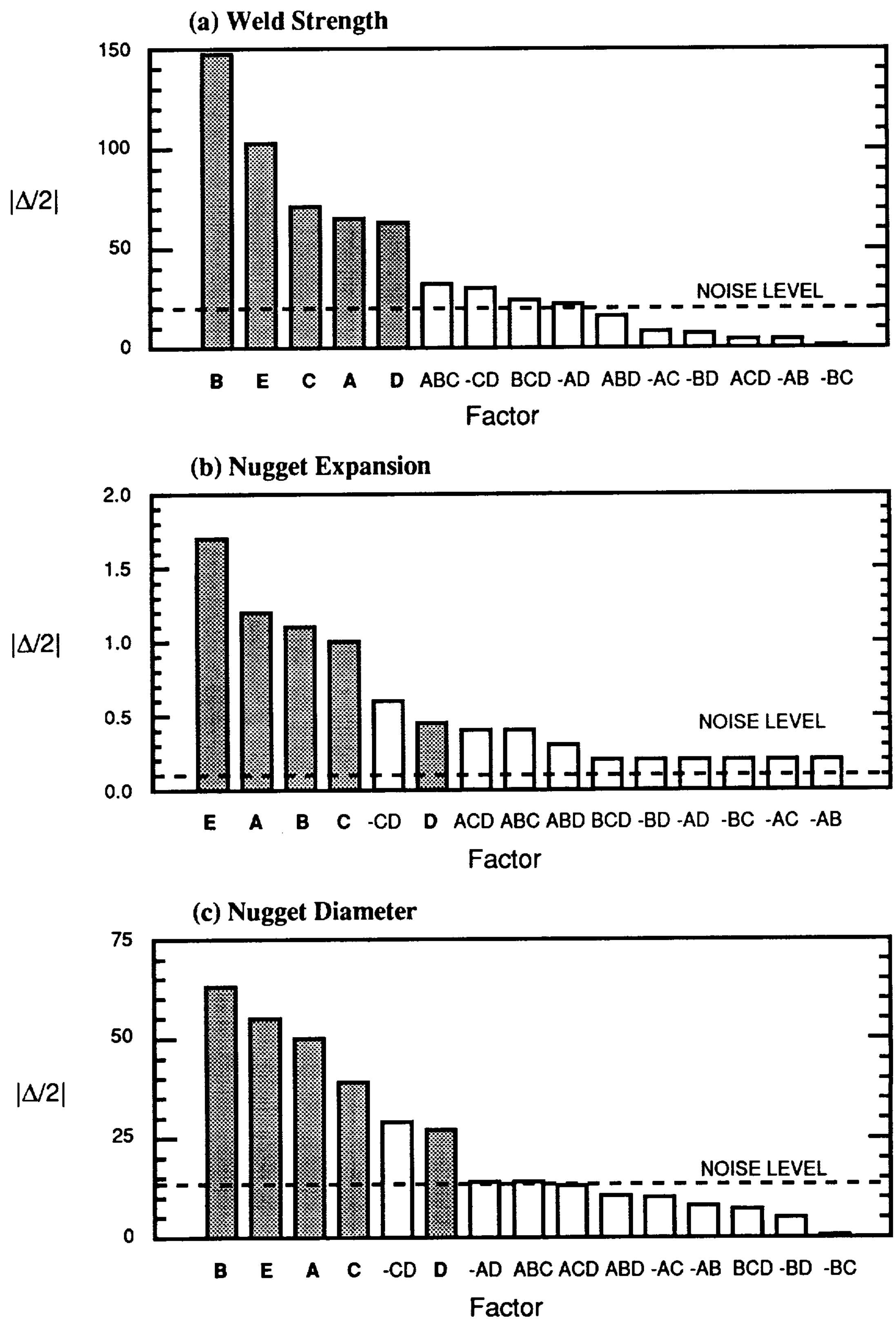
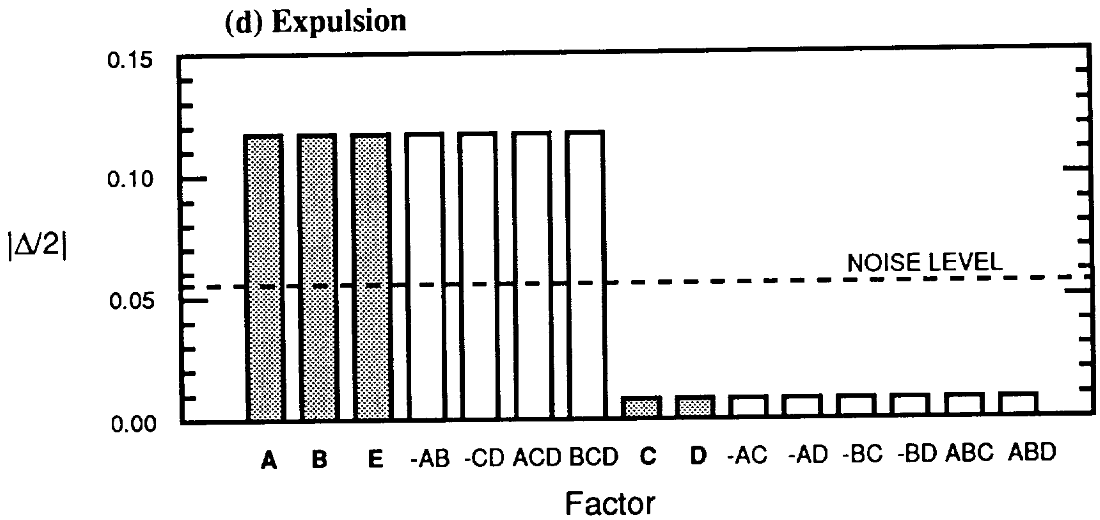
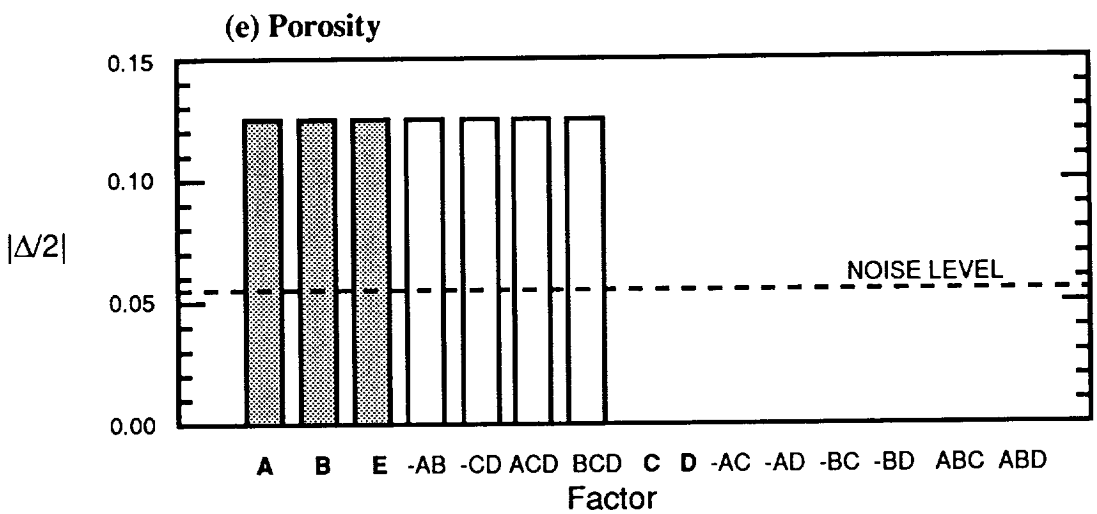


Figure 4 . Pareto diagrams for all responses from L_{16} Experiment





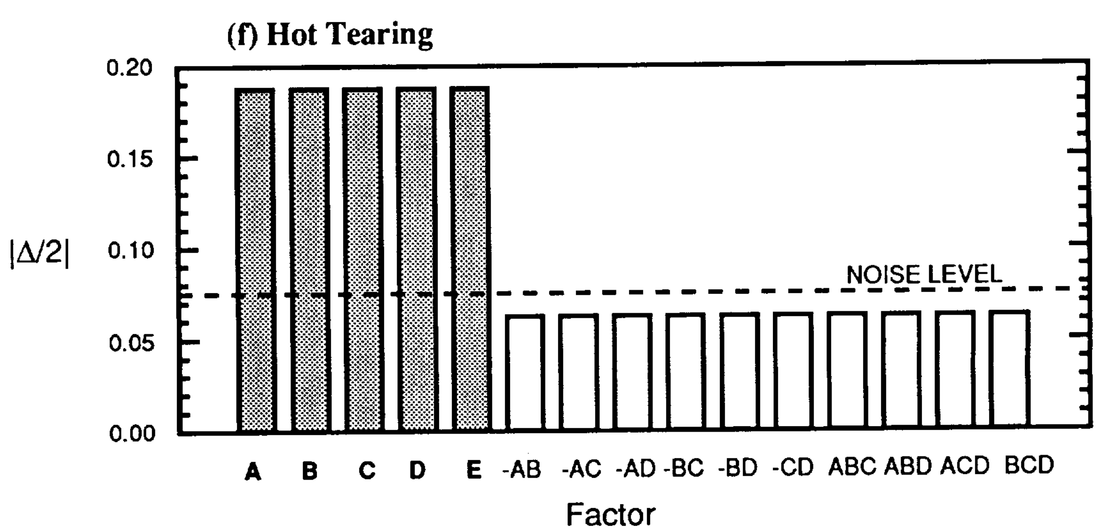


Figure 4 (cont.). Pareto diagrams for all responses from L_{16} Experiment

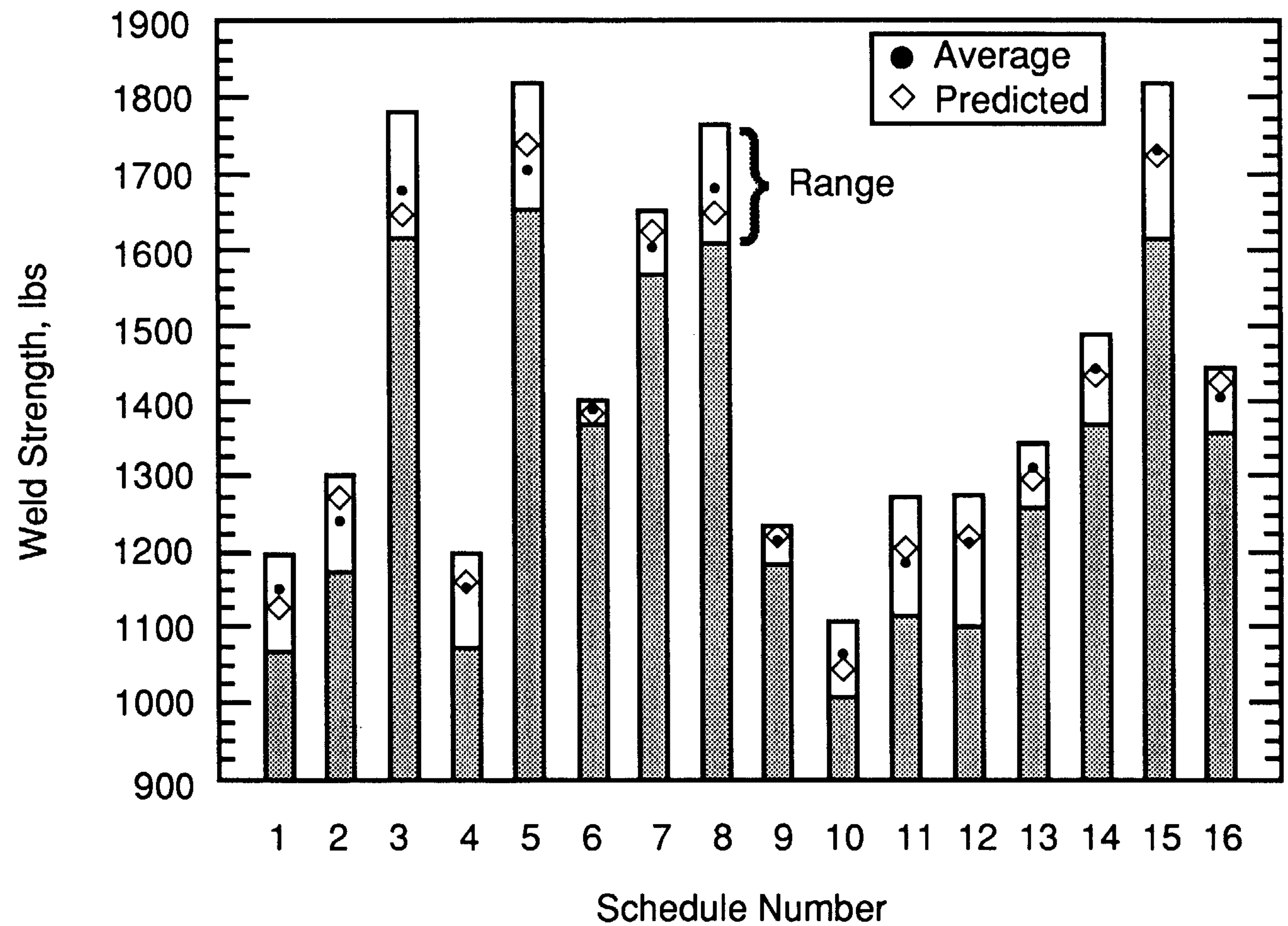


Figure 5. Weld strength data from L_{16} Experiment - high, low, average and predicted values

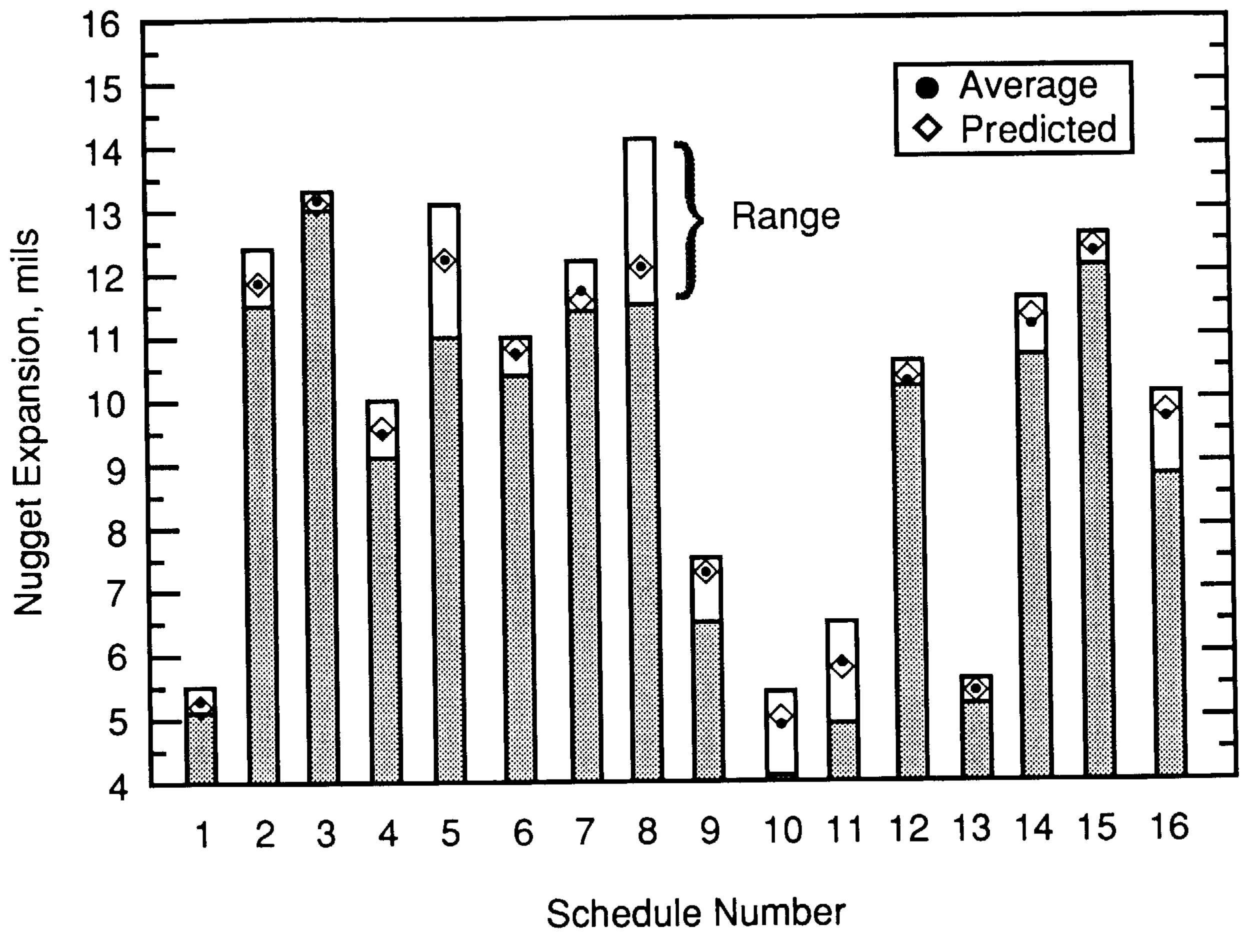


Figure 6. Nugget expansion data from L_{16} Experiment - high, low, average and predicted values

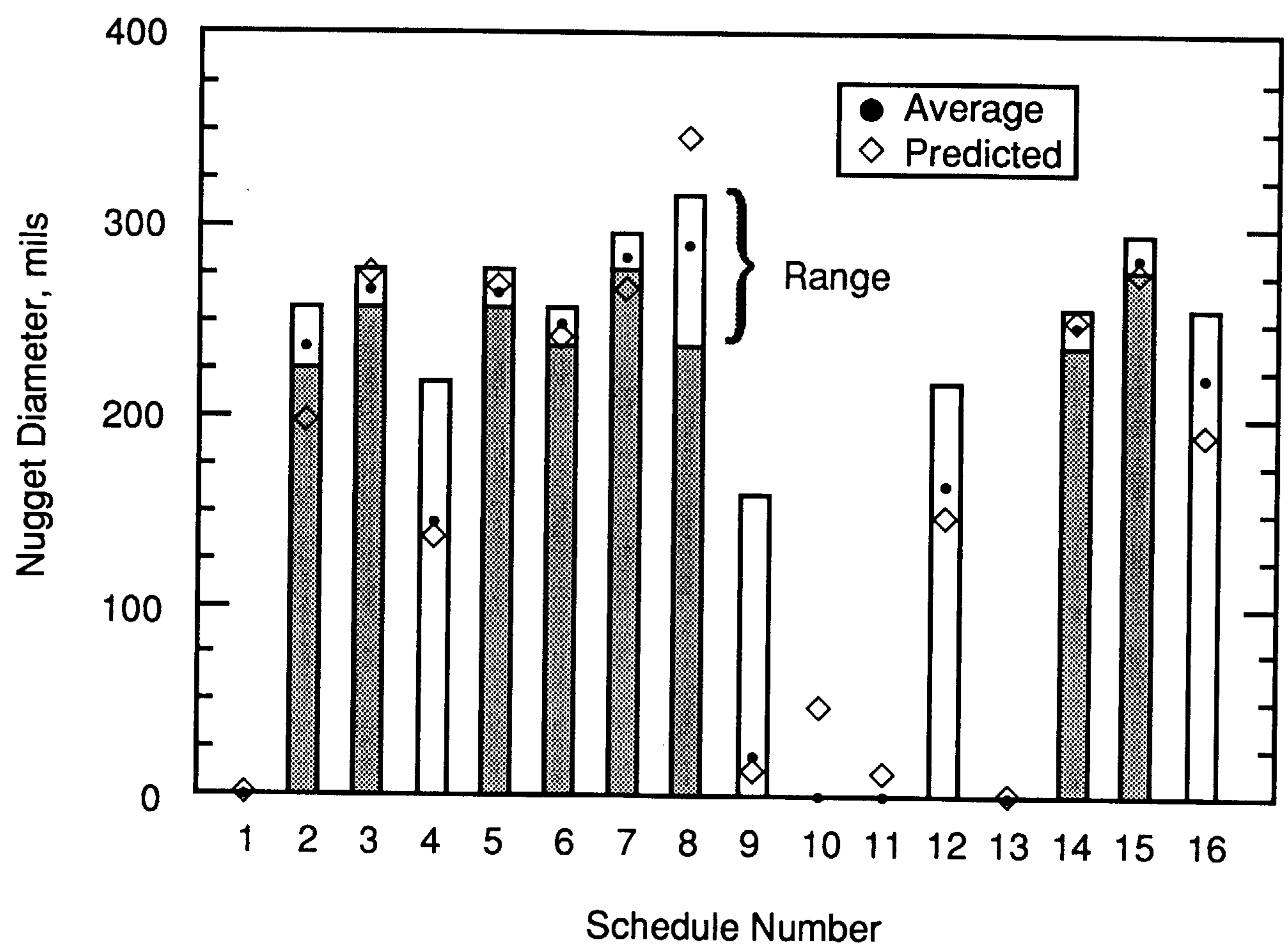


Figure 7. Nugget diameter data from L_{16} Experiment - high, low, average and predicted values

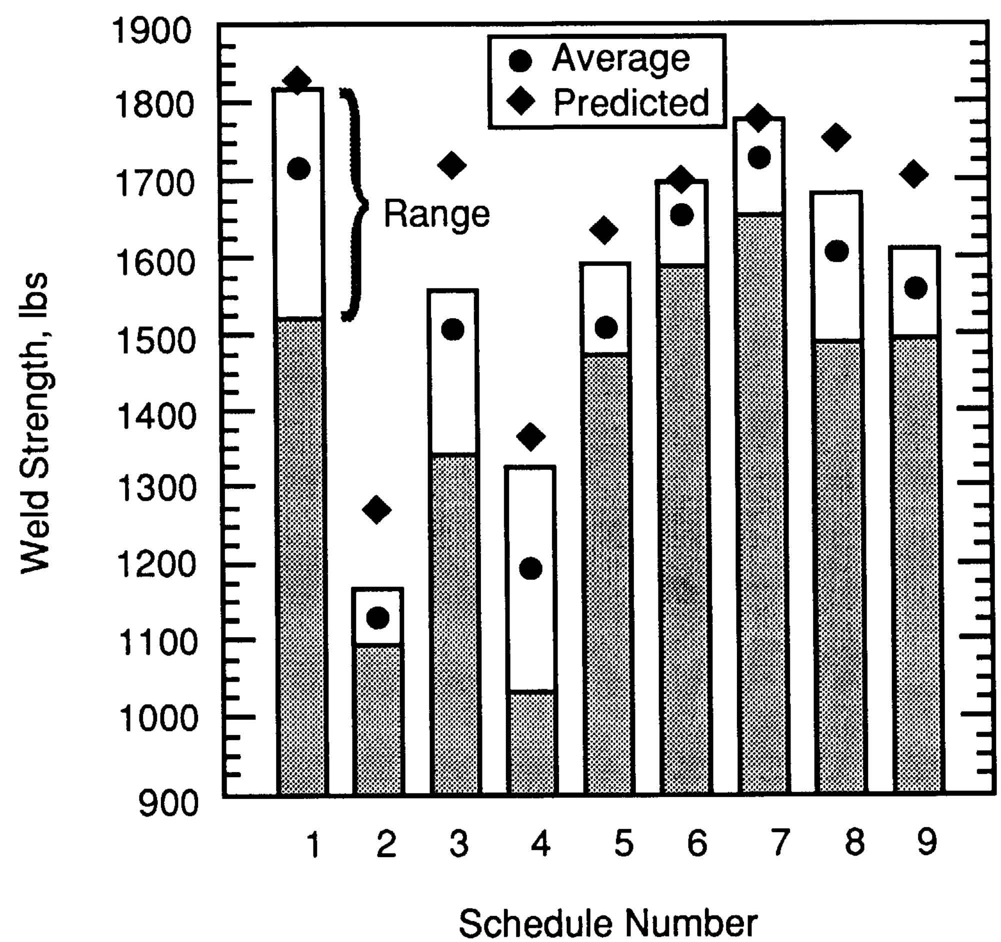


Figure 8. Weld strength data from confirmation runs - high, low, average and predicted values

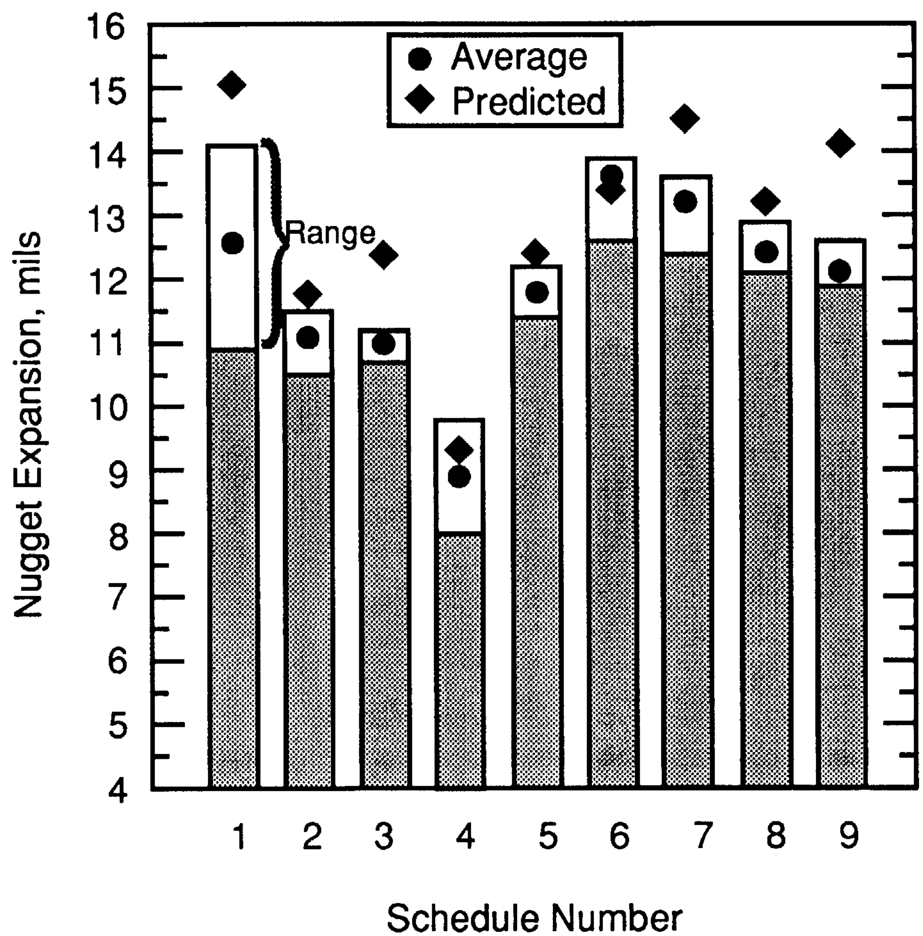


Figure 9. Nugget expansion data from confirmation runs - high, low, average and predicted values

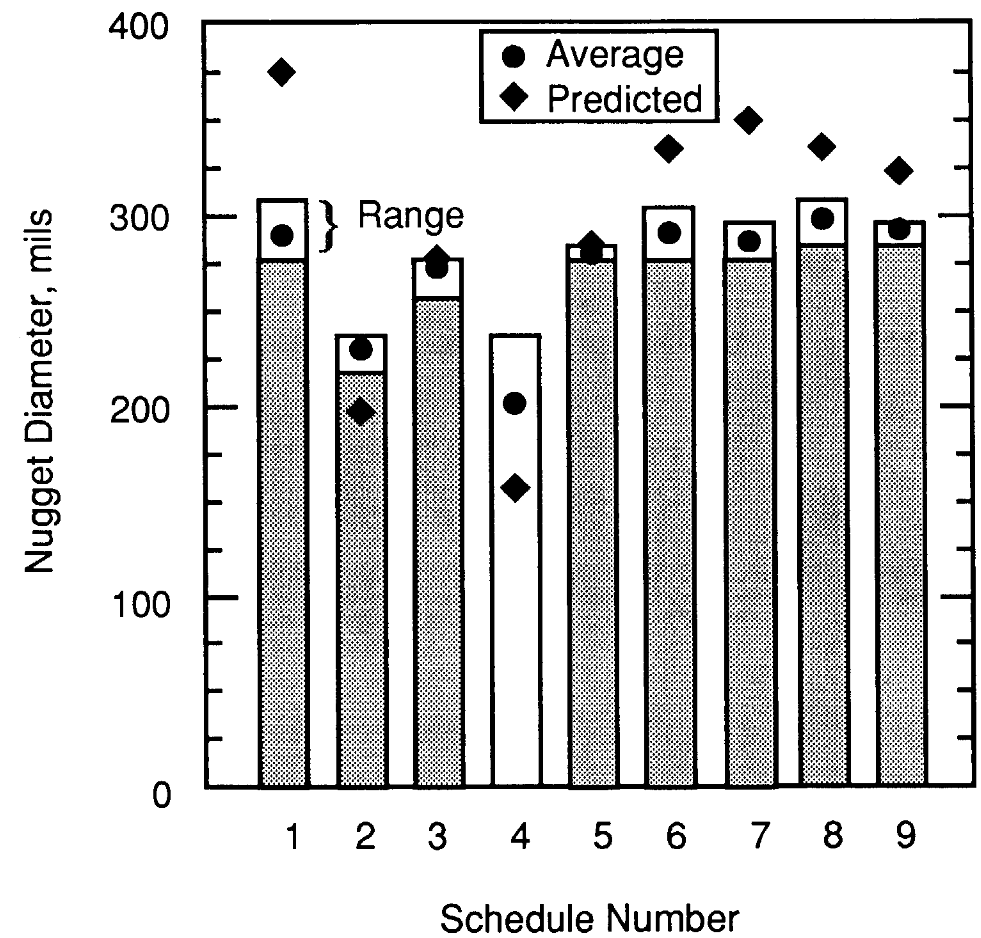


Figure 10. Nugget diameter data from confirmation runs - high, low, average and predicted values

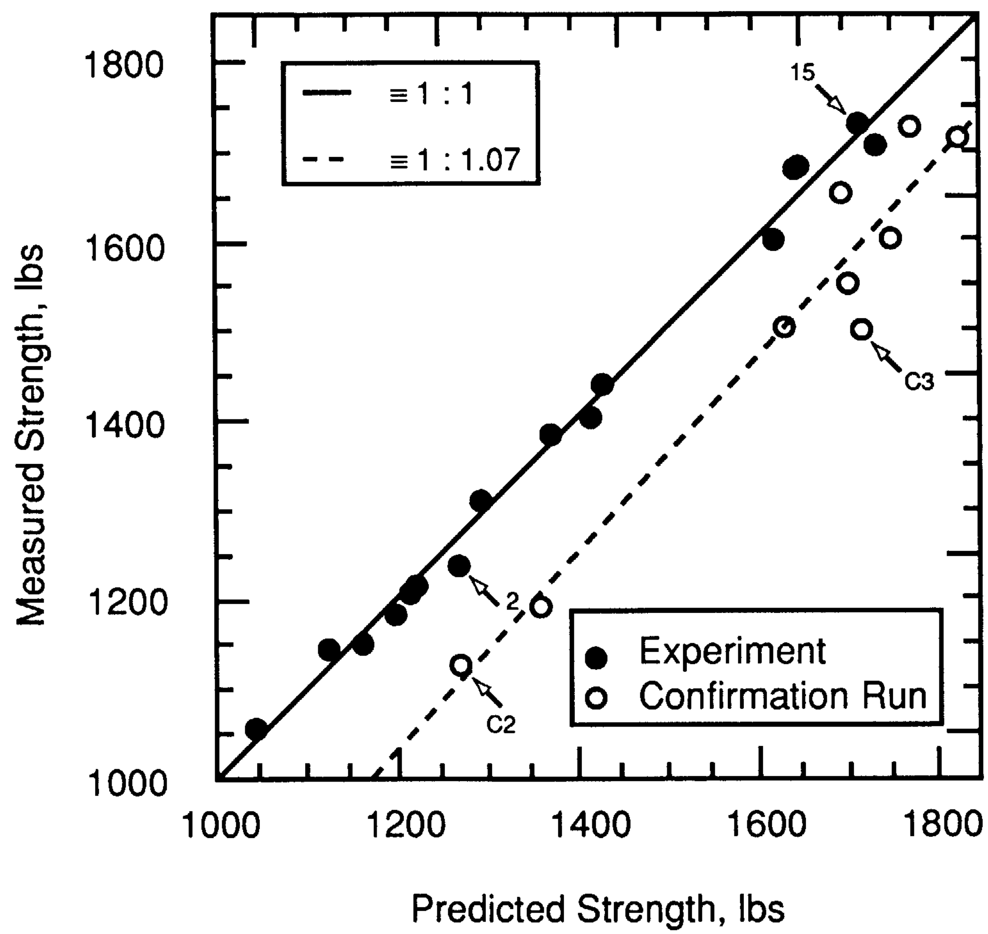


Figure 11. Correlation of measured with predicted weld strength

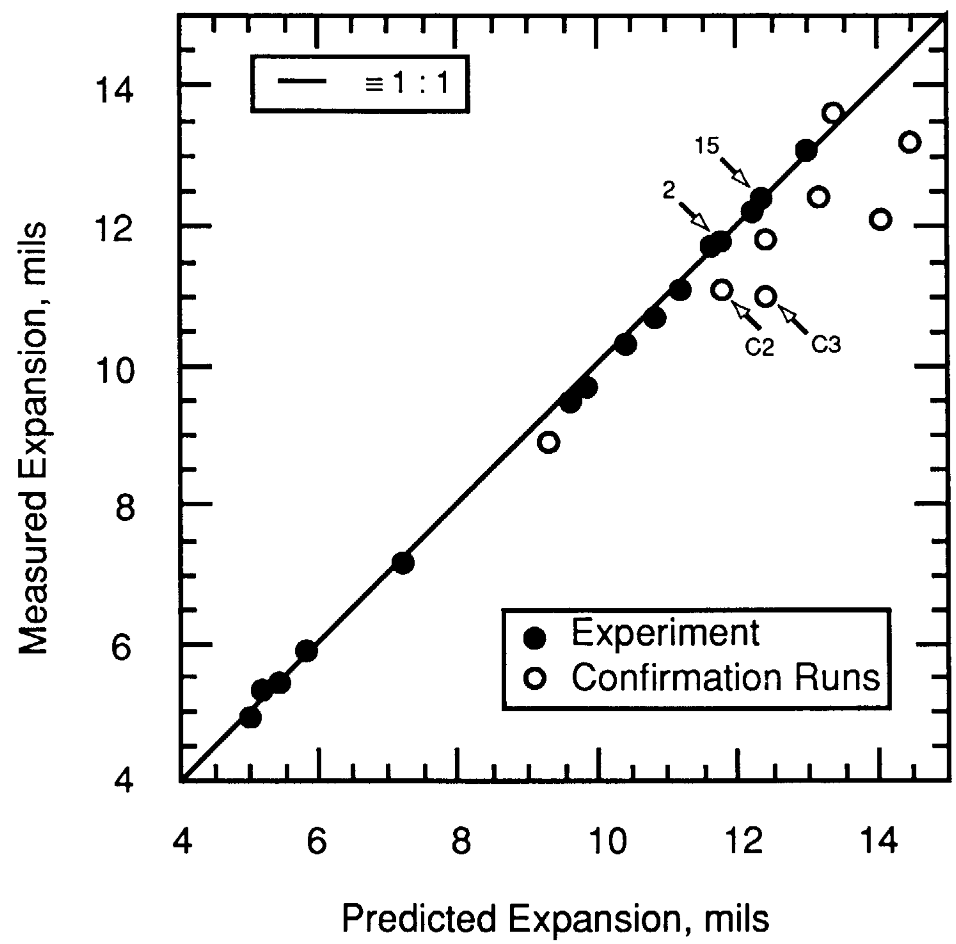


Figure 12. Correlation of measured with predicted nugget expansion

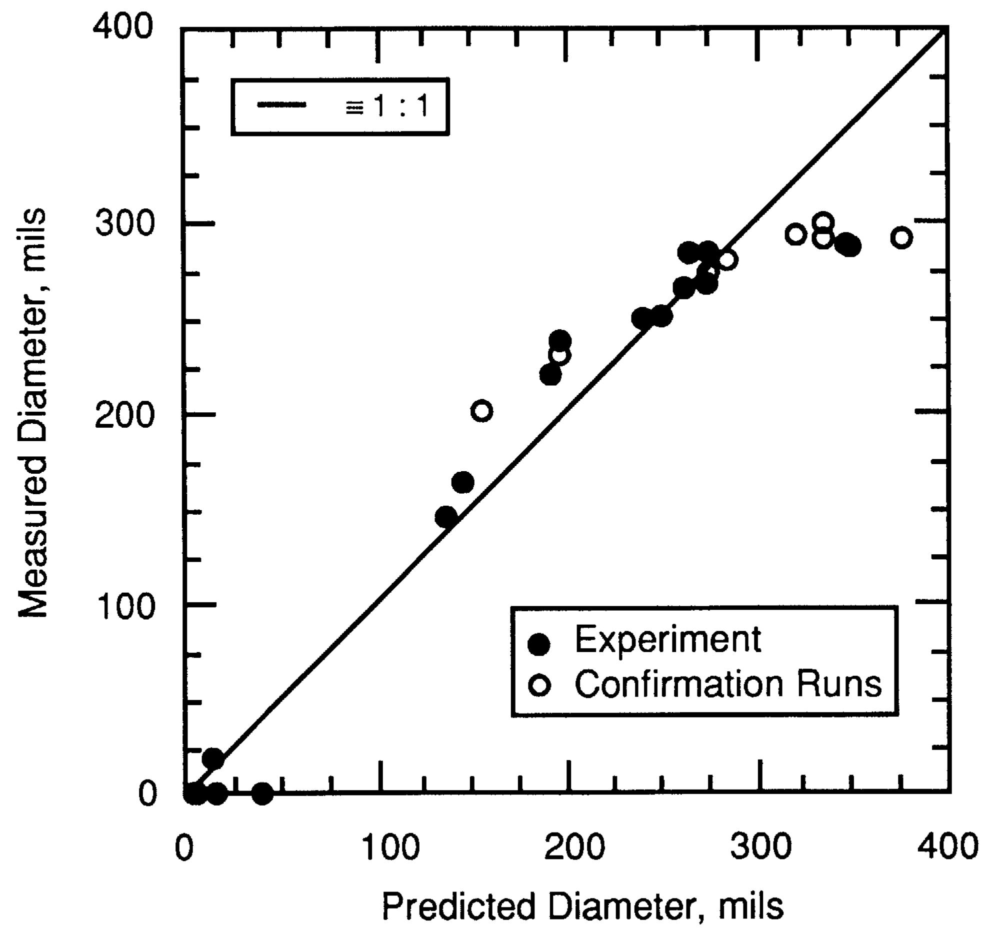


Figure 13. Correlation of measured with predicted nugget diameter

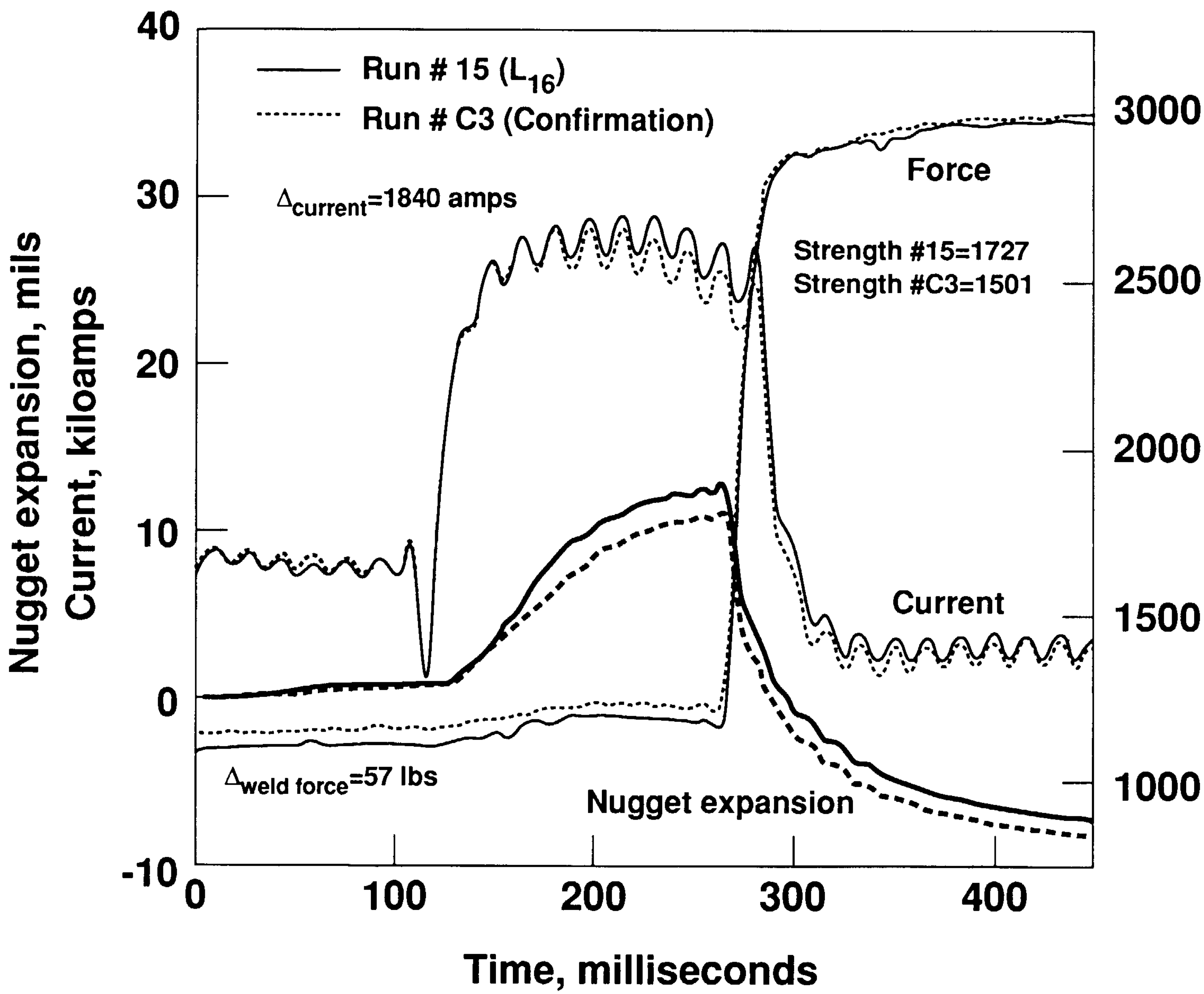


Figure 14. Comparison of schedule 15 (L_{16}) with schedule C3 (CR).

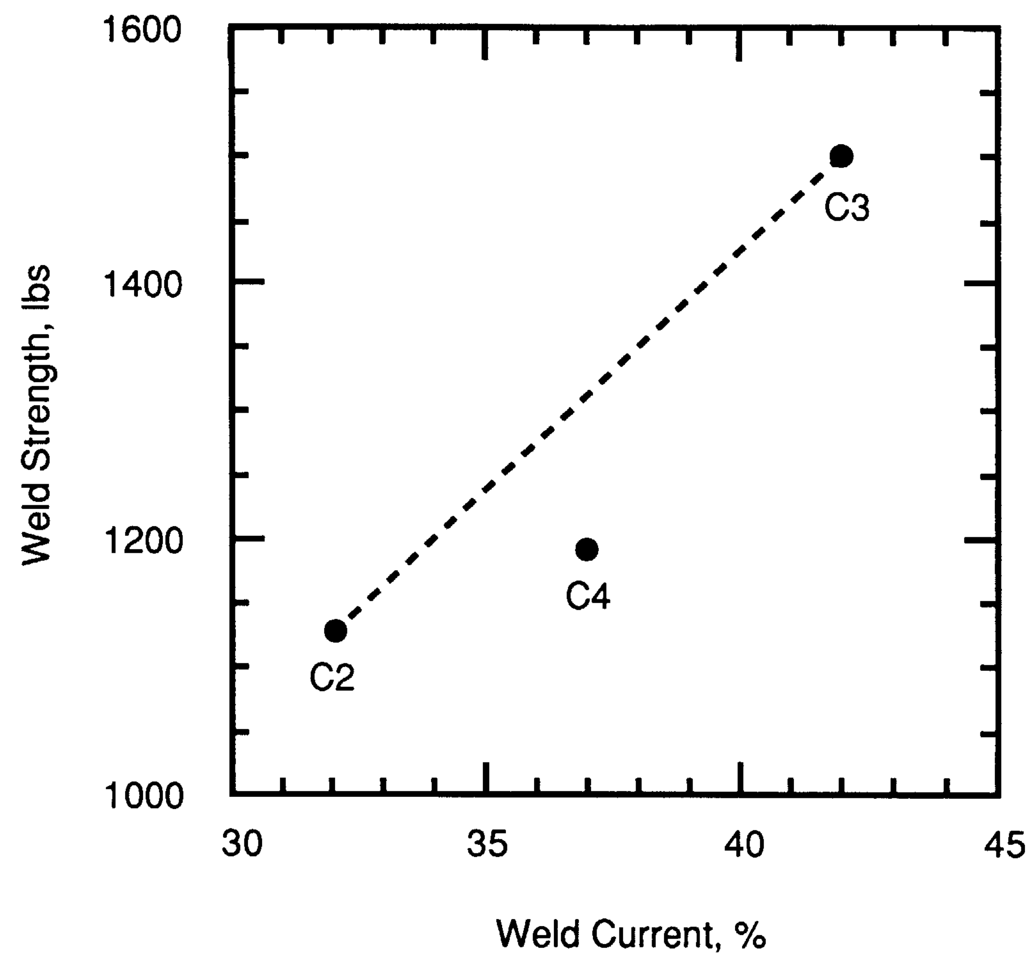


Figure 15. Non-linear response of weld strength with respect to weld current

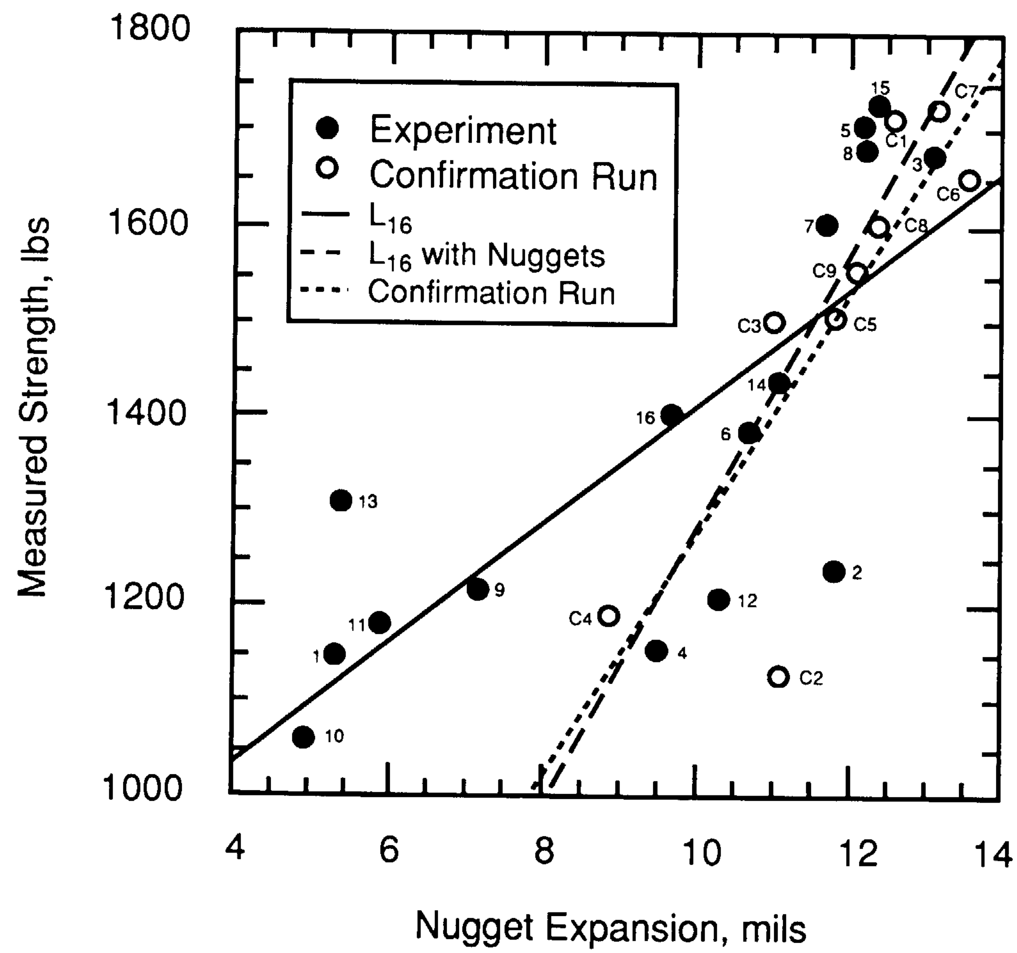


Figure 16. Correlation of weld strength with nugget expansion

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State-of-the-art Resistance Spot Welding (RSW) equipment has the potential to permit real-time monitoring of operations through advances in computerized process control. In order to realize adaptive feedback capabilities, it is necessary to establish correlations between process variables, welder outputs and weldment properties. The initial step toward achieving this goal must involve assessment of the effect of specific process inputs and the interactions between these variables on spot weld characteristics. This investigation evaluated these effects through the application of a statistically designed experiment to the RSW process. A half-factorial, Taguchi L_{16} design was used to understand and refine a RSW schedule developed for welding dissimilar aluminum-lithium alloys of different thickness. The baseline schedule had been established previously by traditional trial-and-error methods based on engineering judgement and one-factor-at-a-time studies. A hierarchy of inputs with respect to each other was established, and the significance of these inputs with respect to experimental noise was determined. Useful insight was gained into the effect of interactions between process variables, particularly with respect to weldment defects. The effects of equipment-related changes associated with disassembly and recalibration were also identified. In spite of an apparent decrease in equipment performance, a significant improvement in the maximum strength for defect-free welds compared to the baseline schedule was achieved.

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