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DISSERTATION

THE APPLICATION OF RESPONSE SURFACE METHODOLOGIES TO MICROJOINING OF MAGNET WIRE WITHOUT PRIOR REMOVAL OF INSULATION

Submitted by

Donald Patrick Lynch

Department of Mechanical Engineering

In partial fulfillment of the requirements

for the Degree of Doctor of Philosophy in Mechanical Engineering

Colorado State University

Fort Collins, Colorado

Fall 2001

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COLORADO STATE UNIVERSITY

July 2, 2001

WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED UNDER OUR SUPERVISION BY DONALD PATRICK LYNCH, THE APPLICATION OF RESPONSE SURFACE METHODOLOGIES TO MICROJOINING OF MAGNET WIRE WITHOUT PRIOR REMOVAL OF INSULATION, BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY IN MECHANICAL ENGINEERING.

Committee on Graduate Work

R. A. Rademacher

Advisor

AT Kirkpatrick

Department Head

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ABSTRACT OF DISSERTATION

THE APPLICATION OF RESPONSE SURFACE METHODOLOGIES TO MICROJOINING OF MAGNET WIRE WITHOUT PRIOR REMOVAL OF INSULATION

Concerns with stripping and soldering copper magnet wire in ignition coils and other related products have led to the investigation of an alternative product and process design, microjoining. The use of microjoining with a folded over welding tab terminal design along with a parallel gap welding process provides a suitable method for joining a tin plated brass terminal to the 0.65mm magnet wire without prior removal of the polyesterimide over-coated polyamideimide insulation. Design of experiments, response surface methodologies, mathematical modeling and non-linear optimization have provided an optimized welding process using nonlinear design of experiments that has been used to provide a breakthrough welding process that is an alternative to soldering. The statistical methods used to develop the process build current documented research efforts. Goal programming, weighting methods and other non-linear optimization techniques are applied to welding process models. The dissertation research results significantly extend the level of knowledge of designed experiment applications in the welding field.

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1.0 INTRODUCTION

Historically design of experiment techniques have not been widely applied in the development of welding processes. This is also the case for microjoining, a specific type of welding addressed in this dissertation research. However, due to the complicated nature of welding processes, the physical relationship between the process parameters and the inherent variability of welding processes, there is a need to employ statistical methods in the development of welding processes. The majority of the welding process development to date has depended heavily on experience and trial and error.

Insulated copper wire, also called magnet wire, is a critical component used in the manufacture of ignition coils as well as transducers, transformers, coils, motor windings and many other electromagnetic products. Traditionally, the magnet wire used in these products is joined to terminals, pins or tags using soldering techniques. The magnet wire often has a high enough temperature grade insulation that mechanical stripping of the insulation is required prior to soldering. The terminal designs / configurations used in ignition coils vary depending on the requirements of the product but their material is usually brass, which is often tin plated. The joining processes for an ignition coil - primary coil circuit utilizes 0.65mm enameled round copper magnet wire with 0.0295mm of polyesterimide over-coated polyamideimide insulation. In this application the magnet wire is mechanically stripped using a four blade centrifugal stripping machine prior to soldering. The stripped magnet wire is then soldered to a terminal design that is 0.8mm thick, 2680R yellow brass (65Cu-35Zn) w/ 3-5µ tin plating.

The product/process described in the above paragraph provides the application for which the research in the area of response surface methodologies and design of experiments is applied. This research involves developing a mathematical model of the application product/process through the use of experimental design and response surface methodologies. This model is then optimized to determine the ideal product/process parameters for this specific application.

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2.0 BACKGROUND

2.1 DOE Techniques

Design of experiments is an important tool in product/process development. As outlined by Hinz (1995) design of experiments can be classified into one of three main categories. These categories are Classical, Taguchi and Shainin. The Classical designs range from fractional factorials to evolutionary optimization (EVOP). Typical Classical methods include Plackett-Burman, Box-Behnken and Central Composite. The Taguchi methods use orthogonal arrays (inner and outer) in "tolerance design," employing analysis of variance and signal-to-noise ratio for statistical evaluation. The Shainin methods use multi-variate, components search, paired comparisons, variable search, full factorials, B versus C and scatter plots. Shainin methods are newer and their use is not widespread. The majority of the applications of experimental design to date have either been based on Classical or Taguchi methods.

Taguchi built on existing classical methods whose development dated back to the 1920's. The original classical methods were very cumbersome and computationally inefficient because of the number of runs and thus their use was not wide spread. Classical methods included two factor interaction effects but ignored any higher interaction effects. The interaction effects are those effects on the variable of concern (response variable) which are caused by two or more of the main process parameters reacting in conjunction with each other. Classical methods ignored interaction effects higher than two factor because it was thought that the probability of these effects being statistically significant was very low. Classical methods assumed that any effects from interaction effects higher than two factor interactions were comprised mainly of experimental noise rather than from legitimate cause and effect relationships. Taguchi simplified the prior research by concentrating on critical factors and de-emphasizing interaction effects to greatly reduce the number of runs. Taguchi made this simplification because it was thought that in the majority of applications, interaction effects down to two factors were minimal in significance in comparison to the main effects. Taguchi felt that the focus in early experimentation should only be on main effects.

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The use of Taguchi methods has been widespread, however in certain applications the de-emphasis of interaction effects has led to the exclusion of important terms in the mathematical model. With the exclusion of important terms based on interaction effects in the mathematical model, the models performance in being able to predict the response variable values is severely hampered in some applications. Also, with a poor performing mathematical model, optimization methods applied may fail to identify the ideal process parameters.

2.2 Wire Stripping

The mechanical stripping of the magnet wire poses many challenges. The goal of the process is to utilize the centrifugal stripping machine to strip off the 0.0295mm thickness of insulation without cutting into the copper appreciably. Issues arise when the strippers do not remove all of the insulation or when the strippers cut too deep into the copper causing copper chips. If the strippers do not remove all of the insulation, the soldering process is affected adversely. If the strippers cut too deep into the copper, the copper shavings run the possibility of contaminating the product causing product reliability issues through internal electrical shorts. Historically these issues have been difficult to eliminate because a number of factors, including variation in the copper wire diameter and insulation thickness, variation / capability of the equipment, operator error in setting of the equipment and mechanical wear of the stripper blades. Other concerns centered around stripping of ignition coil magnet wire are the cost of replacing stripper blades (consumable), the introduction of metal cutting into an otherwise clean manufacturing environment and the fact that it is a non-value added operation.

2.3 Soldering

Soldering offers an equal amount of challenges. Issues with soldering include insufficient solder, excess solder, solder balls (solder contamination in the product), cold solder joints and others, all of which can lead to product quality concerns. Historically these issues have been difficult to eliminate primarily because of the numerous process variables associated with soldering. Additional factors leading to problems of control of the above issues are the requirement of the proximity (gap) between the parent metals and oxidation and/or corrosion of the parent metals. Other concerns centered on soldering of

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ignition coil magnet wire to terminal joints include the environmental and safety issues associated with the use of lead based solder, fluxes and ventilation concerns as well as the cost of solder and solder tips (consumable).

These issues led to the investigation of alternatives to the current soldering approach that would be reliable, robust and would be able to effectively terminate the magnet wire without prior removal of the insulation. Possibilities investigated included insulation displacement terminals, high temperature soldering, laser welding, laser soldering, sonic welding, explosion welding, soft beam soldering, micro flame soldering and microjoining (small scale resistance welding). Further information regarding wire stripping and soldering may be found in the description of the development of the microjoining product/process located in the Appendix. The Appendix includes details on the microjoining product and process goals, materials, equipment, welding procedure, joint quality assessment methods as well and the product and process design and feasibility trial results.

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3.0 RESEARCH

3.1 Research Problem

For the application addressed in this dissertation, microjoining was selected as the technology to pursue. With microjoining chosen, the research focused on the product design and processes required to successful join the materials in a high volume production environment. This is accomplished through addressing the deficiencies that exist in the state-of-art practice of design of experiment / optimization methods in welding as well as many in other applications. These deficiencies are excluding interaction effects higher than two factor and square terms.

3.2 Dissertation Research

In this dissertation, microjoining is developed for use in a high volume production environment. The product design, process design and capability of the product/process are investigated. Response surface methodologies based non-linear mathematical models of the process are developed. Optimization techniques are used to find the optimal product design and process parameter values.

The work outlined in this dissertation offers a substantial contribution to the state-of-the art in three distinct areas;

1. The use of response surface methodology based non-linear design of experiment techniques in the development of a welding process.
2. The integration of non-linear mathematical programming optimization techniques to prescribe the optimum welding process.
3. The development of the microjoining product/process in terminating magnet wire without prior removal of the insulation.

While all three developments offer substantial contributions to the state of the art, the first two are the focus of this dissertation. For that reason, descriptions of many of the technical issues in the development of the microjoining product/process have been located in the Appendix.

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Response Surface Methodology

Even though design of experiment techniques have been available for sometime, their use in the welding industry is not widespread (see the literature search below). This dissertation provides the first available documented study outlining the use of response surface methodology based on non-linear design of experiment techniques in welding that includes higher order (higher than two factor) interaction effects. The other design of experiment works documented in the welding industry dealt with simplified design of experiment approaches in which higher order interaction effects were not significantly analyzed.

The microjoining production process development detailed in the Appendix serves as the application to investigate advances in design of experiments theory applied to welding. It was found in this research that welding assessment measures have much more complex relationships with welding control variables that had been previously thought. Thus, the results offered in this research are substantial in that they provide the groundwork for more effectively defining these relationships. Also, weld success assessment measures developed in this work build on existing measures to provide advancements in that area. This is especially the case with percent or the circumference and percent reduction in diameter measures. The non-linear relationships, modeling interaction effects and response variables outlined and defined in this research are transferable to a wide variety of product/process applications.

Optimization

Another substantial contribution to the welding process design industry is in the integration of non-linear mathematical programming optimization techniques to prescribe the optimum welding process. Non-linear programming techniques are taught in academia and are widespread in other industries. However, their application in the welding industry is not widespread. This dissertation provides the first available documented study utilizing non-linear programming optimization techniques. This contribution advances the state-of-the-art in that it establishes an optimum welding process using a non-linear relationship.

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Microjoining

The development of the state-of-the art microjoining product/process documented in this dissertation and in the Appendix provides a new process design approach to the various industries utilizing magnet wire in a product. This dissertation describes the first documented study detailing the elimination of the need to mechanically strip the insulation from primary magnet wire (0.65mm) prior to attachment. As outlined by Riches (1994) in the Appendix insulation type may significantly affect the results. One of the hurdles that had to be overcome in the course of application, as outlined in the Appendix was the identification and selection of a reliable joint quality assessment method.

The potential impact on industries seeking to eliminate the need for prior removal of magnet wire insulation and on those seeking a replacement to conventional soldering methods is widespread.

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4.0 LITERATURE SEARCH

The literature search was accomplished by searching through key professional journals, by browsing the Internet and the related web sties (Informs, etc) and by searching four separate databases. These four databases were;

ProQuest Direct

A database that includes abstracts and citations for over 1,450 academic, engineering, management, marketing, quality and business journals. Full text is available for over 800 of these journals and a number of search methods are available including keyword, title and author. ProQuest also includes information from UMI's vast database of thousands of academic dissertation and thesis works.

OCLC FirstSearch

A database that includes full text of one million newspapers and magazine articles, citations to thirty million books and abstracts for more than 15,000 journals and newspapers.

WeldNet

A member's only database of technical journals, papers, dissertations, thesis and other documented works associated with the material joining industry. WeldNet is administered by the Edison Welding Institute (EWI) in cooperation with Ohio State University in the United States and by The Welding Institute (TWI) in the United Kingdom. WeldNet houses thousands of related works published and unpublished in public forum that deal directly with all aspects of welding – including microjoining.

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Based on the results from the literature search a number of conclusions can be drawn:

- There has been no prior documented work in microjoining of primary coil magnet wire (0.5-0.7mm diameter) without prior removal of insulation and minimal documented work in welding all types of magnet wire.
- Documented cases of use of design of experiments in welding have been minimal and there have been no prior documented cases of response surface methods in welding design of experiments.
- Even through designed experiments including interaction effects higher than two factor and squared terms are taught in academia and industry, their application makes up a very small percentage of the total number of design of experiments actually performed.
- Traditional design of experiment practice (Classical and Taguchi methods) documented in many academic texts assumes higher order interaction effects will not be statistically significant.
- There are very few experimental design studies in which higher order (higher than two factor interactions) interaction effects have been examined for statistical significance and included in a mathematical model.

The references identified below provided insight into design of experiments use in welding and other fields and provided background on advanced design of experiments techniques. Other references provided insight into the current level of technology used to weld magnet wire prior to removal of insulation.

Traditional Body of Knowledge

Texts by Neter et al (1996), Ramsier (1999), Vining (1998) and Wortman (2000) are statistical, design of experiments, engineering and quality texts that provided the necessary statistical background to perform the analysis. The Neter text provided addresses regression analysis including residual analysis and testing. Ramsier provided the theory behind the central composite DOE designs. Vinning provided insight into the t-tests and F-tests used to determine statistical significance. Wortman provided insight into variation analysis, which was used to quantify the variation in the process and evaluation methods.

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Additional references that provided the framework for the traditional theoretical body of knowledge in experimental design were Anderson and Mclean (1974), Box and Draper (1987 & 1969), Box et al. (1978), Cachran and Cox (1957), Cox (1958), Dehnard (1989), DeVor et al. (1992), Draper and Smith (1981), Duncan (1986), Dunn and Clark (1974), Hamda and Wu (1995), Hicks (1964), John et al. (1964), Mason et al. (1989), Montgomery (1984), Mood et al. (1974), Ryan (1989), Taguchi (1976 & 1979) and Walpole (1978). This body of knowledge represents what has been taught regarding classical design of experiment and Taguchi methods. The current assumption in these references is that interaction effects higher than two factor interactions are not statistically significant and consist primarily of experimental noise.

Traditional Body of Knowledge - Updated

Recent theoretical body of knowledge regarding experimental design can be pulled from Anderson (2000), Argyropoulos and Pouskouleli (1995), Burnham (1996), Cornell (1990), Levin (1996), Nixon (1992) and Whitman (1993). This group of references provide a supplement to the traditional references above. This body of knowledge begins to stress the importance of the inclusion of interaction effects. However, higher order effects (above two factor interactions) are not specifically mentioned. All of the above articles refer to the inclusion of only two factor interaction effects.

Manufacturing Applications of Experimental Design

In order to establish the state of the art expertise and add to the theoretical basis a number of experimental design applications were reviewed from various processes and industries. The processes referenced include; machining (Alexander et al. (1994), Beauchamp et al. (1996), Koelsch (2000), MacParland (1993), Youssef et al. (1994)), extrusion (Boatman (1992), Fragomeni (1999), Lindviksmoen (1989)), circuit board manufacturing (Baldwin et al. (2001), Hansotia (1992), Hu et al. (1991), McQuarrie et al. (2001), Peters (1999), Ramkumar et al. (2001), Brathwaite et al. (1996)), adhesives (Broughton (1999)), rocket engine fabrication (Chokshi (2000)), sintering (Davala (1992)), casting (Enright (1988), Ertas et al. (1992), Levy (1991)), molten metal processing (Fung and Bradley (1991)), ski manufacturing (Hubbell (1995)), soldering (Hinz (1995), Mesenbrink (1995), Pusarla (2001)), metal forming (Kim (1999)) and coatings

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(Mendelson (1998), Russel (1995)). How these various investigators handled (or failed to handle) interactions are described below.

Manufacturing Applications of Experimental Design

Only Main Effects Considered

Listed below are the manufacturing applications of experimental design that included only main effects in their statistical investigations. In these works all interaction effects either were not statistically significant or not even addressed in the corresponding papers:

Koelsch (2000) is a design of experiments on a grinding operation where no interaction effects were considered.

MacParland (1993) reviews the implementation of experimental design at a company called Anglesey Aluminum, Ltd.. The paper discussed the use of experimental design but did not specifically mention interaction effects.

Boatman (1992) talks about the application of statistical methods including experimental design in an extrusion facility. In this paper the three approaches to experimental design (Classical, Taguchi and Shainin) are compared. However, there are not specific references to interaction effects.

Lindviksmoen (1989) uses design of experiments to study the process parameters in a tube extrusion process where no interaction effects were reviewed.

Baldwin (2001) is a printer circuit board manufacturing design of experiment where only main effects were considered.

Hansotia (1992) is a very straightforward design of experiments applied to computer panels where only main effects are considered.

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Hu et al. (1991) is a full factorial design of experiments to study thermosonic gold wire bonding of semiconductors where the response variables were bond strength and viewing under a microscope. No interaction effects were reviewed.

Ramkumar (2001) approach to design of experiments used Taguchi methods to study surface mount computer circuit board processing. No interaction effects were considered.

Brathwaite et al. (1996) uses a design of experiments on automated tape bonding of multichips. While a screening design (fractional factorial experiment) and an optimizing design (full factorial experiment) was performed, no reference was made to the inclusion of more than main effects.

Enright (1988) used a design of experiments to solve casting problems where the optimum process targets are identified and then statistical process control is used to control those variables. However, interaction effects are not considered.

Ertas et al. (1992) utilized an experimental investigation in the galling resistance in connectors where there is no discussion of interaction effects.

Levy (1991) reviews the use of design of experiments in casting of aluminum but does not consider interaction effects.

Hubbell (1995) performed a design of experiments in recreational ski manufacturing where no interactions are investigated – only main effects.

Fung and Bradely (1991) uses an experimental design in molten metal processing where collinearity exists among predictor variables in developing a predictive model through regression analysis. However, the model developed does not take into consideration interaction terms.

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Manufacturing Applications of Experimental Design

Only the Main Effects and Two-way Interactions Considered

Listed below are the manufacturing applications of experimental design that investigated the statistical significance of main effects and two factor interaction effects. In these works interaction effects higher than two factor were not statistically significant or not even addressed in the corresponding papers:

Alexander et al. (1994) uses a design of experiments on laser machining of ceramics using three levels and provides profile plots of interactions.

Beauchamp et al. (1996) uses a design of experiments performed on a lathe where only two factor interactions were statistically significant.

Youssef et al. (1994) is another design of experiment on a lathe where two factor interaction effects were not statistically significant.

Fragomeni (1999) outlines an experimental design to determine the effect of extrusion variables on the mechanical properties of an Al-Li alloy where two factor interaction effects are analyzed in conjunction with the main effects.

McQuarrie et al. (2001) reviews a design of experiments on a printed circuit board manufacturing process that investigated interaction effects but only included linear terms.

Peters (1999) reports a semiconductor design of experiments that uses software to determine the significance of two-factor interaction effects.

Broughton (1999) details a design of experiments performed on adhesively bonded joints under cyclic loading where two factor interactions are considered and analyzed.

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Chokshi (2000) reports of a design of experiments utilized in rocket engine fabrication where only two factor interaction effects are reviewed.

Davala (1992) reports a work that reviews the use of design of experiments in a powder metal process to solve technical sintering problems. In this experiment a fractional factorial experiment was performed on several variables and two factor interactions were considered but not determined to be statistically significant.

Hinz (1995) provides a very good overview of design of experiments and is an application of experimental design to a hand soldering process. In this analysis main effects and only two factor interaction effects are considered. In his study one of the two-factor interaction effect was significant.

Mesenbrink (1995) applies an experimental design to a wave soldering process were main effects and two factor interactions are considered with major aliasing. The analysis includes the multivariate case including non-linearity.

Pusarla (2001) reports a design of experimentation on a hybrid optical receiver for free space optical where the key manufacturing parameters are determined. In this analysis the interaction effects of some key parameters were studied.

Kim (1999) compares the application of neural networks and experimental design in the process design in a metal forming operation.

Mendelson (1998) implements an experimental design to improve coating life where a fractional factorial experiment is applied to maximizing the fatigue life of thermal barrier coatings. The

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experiment considers the non-linearity of two factor interaction effects but does not look at three factor interaction effects.

Russel (1995) performs a design of experiments study the effect of coatings on cemented carbide substrates. The experiment involves a full factorial matrix where only main effects and two factor interactions are considered.

Applications of Experimental Design Outside Manufacturing

Applications of experimental design outside of manufacturing were referenced in the following other industries; pollution control (Bettonvil (1997)), economic theory (Brandouy (2001), Brandts and Schram (2001)), advertising (Farris et al. (2000)), pharmaceutical (Hwang and Peck (2001)), marketing (Kohli (1988), Simmel and Berger (2000)), engineering design (Panda et al. (1979), Spuzic et al. (1997)), irrigation (Paul and Pretheeba (1998)), health care (Swisher et al. (2001)) and air conditioning, heating and refrigeration (Wagner (2000)). These references expanded the level of this dissertation's author's expertise in the area of experimental design beyond the application scope (welding) of this dissertation. These additional manufacturing processes and other applications lead to the conclusion that higher interaction effects are often not considered while performing design of experiments.

Applications of Experimental Design Outside Manufacturing

Only Main Effects Considered

Brandouy (2001) reports an economic theory experimental design where laboratory incentive structure and control is studied. However, interaction effects are not discussed.

Simmel and Berger (2000) reports of a design of experiments in marketing (telefundraising) that only considers main effects.

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Panda et al. (1979) reviews a statistical design of experiments as a tool for research and development of alloys. In the paper a factorial designed experiment is used to develop equations for stress corrosion failures however only main effect terms are discussed.

Swisher et al. (2001) reviews a health care design of experiment that modeled and analyzed a physician clinic environment but did not consider any interaction effects.

Applications of Experimental Design Outside Manufacturing

Only the Main Effects and Two-way Interactions Considered

Bettonvil (1997) reviews a design of experiment in pollution control and attempts to simulate the green house effect by approximating the simulation with a first-order polynomial (main effects) model, possibly augmented with interactions between the factors.

Brandts and Schram (2001) reports an economical theory experimental design with the voluntary contribution mechanism for public goods that attempts to predict human behavior. The paper proposes a potential two-factor interaction effect for explaining the situation of concern over time.

Farris et al. (2000) reviews a design of experiments that deals with over control in advertising expenditures and reviews the importance of inclusion of two factor interaction effects.

Hwang and Peck (2001) reports an experimental design in pharmaceutical that calculated two factor and three factor interaction effects but only concentrated on two factor interaction effects.

Kohli (1988) provides a marketing research design of experiments that considered main and two factor interaction effects.

Spuzic et al. (1997) reports a two level fractional factorial design of experiments applied to a wear simulation. Fractional factorial experimental design with main effects and interactions

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characterizing abrasive wear were diagnosed. Non-linear effects including two factor interaction effects are considered but no three factor interaction effects were analyzed.

Paul and Pretheeba (1998) reviewed a irrigation process optimization using Taguchi orthogonal arrays. This design was used to maximize yield by determining the main effect and two factor interaction effect optimal values.

Wagner (2000) reports an air conditioning, heating and refrigeration experimental design used to develop a medical cooler that included main effects as well as two factor interaction effects in the analysis.

An interesting conclusion was made after review the above experimental designs. It was found in the majority of the cases the analysis in the design of experiments were more sophisticated in the studies outside manufacturing than those performed on manufacturing processes. The experimental designs applications outside of manufacturing had a much higher proportion of applications that included both main effects and two factor interaction effects.

Experimental Designs that Included Interaction Effects Higher than Two Factor Interactions

The industries and processes instances where there were applications of experimental design with inclusion of higher order interaction effects considered were few.

Cornell and Montgomery (1996) developed mathematical models that included interaction effects as alternatives to low-order polynomials. This reference stresses the importance of inclusion of the interaction effects to accurately model non-linearity.

Durrant (1988) reviews the Japanese (Taguchi) approach to design of experiments versus the statistical methods developed in the 1930's and calls out short comings in Taguchi methods by not including interaction effects. Taguchi de-emphasized interaction effects in his original designs in order to reduce the number of runs and simplify the designs. While his methods are very useful in

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selected applications, they could lead to the exclusion of important variables in those applications that have bonafide interaction effects. Taguchi's effort have been very successful in promoting experimental design to achieve its current widespread use however utilizing the methods without understanding their limitations could lead to poorer performing models.

Fine (1996) provides a reference that is solely dedicated to promote the inclusion of interaction effects while performing design of experiments.

Graham and Cable (2001) reviews an application of experimental design on policy that studies the effects of firm attributes on job seeker's reputation evaluations. In this particular application all interactions effects were analyzed resulting in a statistically significant four factor interaction effect.

Gopalakrishnan and Srihari (1999) addresses a solder paste operation design of experiment on circuit board – surface mount assembly where a three factor interaction effect is statistically significant.

Lewandowski and Lindeke (1989) reports a reference that reviews a computer program developed to look at pairwise interaction effects in orthogonal arrays for use in Taguchi designed experiments.

Salter and Doherty (1981) provides the only other welding work that has been done to investigate higher order interaction effects. The work focuses on arc welding and performs an ANOVA of parameters and multiple regression analysis that outlines a three-factor interaction effect as significant.

Thomas et al. (1996) reviews a machining design of experiment on a lathe the considered higher order interaction effects and determined that a three-factor interaction was significant. These

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references further the traditional experimental design practice and further support the work in this dissertation that includes higher order interaction effects in selected processes.

Design of Experiments in Welding

Gould and Lehman (1994, 1994, 1996 & 1997) provided the starting point for the research efforts in the area of design of experiments in welding. The reports were a two part series that utilized statistical design of experiment techniques to characterize the effects of a number of factors related to the resistance spot welding process. The report details the use of a two level fractional factorial design. The results from the research were evaluated using the general linear model analysis of variation (ANOVA) and analysis-of-means techniques. Welds were evaluated using mechanical testing and average button diameter measurements. The report relies on traditional practice in that three factor interaction effects are assumed to not be statistically significant are therefore are ignored. The initial report documents single factor (main) effects confounded with three factor interaction effects (resolution IV design) and provides a quantitative review of the single factor effects.

The second report draws conclusions based on groups of two factor interaction effects (again a resolution IV design). The groups represent three separate two factor interaction effects confounded with one another but arranged in such a way that interactions thought to be statistically significant before experimentation are confounded with other effects thought to not be statistically significant. This arrangement allows conclusions to be drawn despite the confounding.

These two investigations follow the traditional practice for design of experiments use in welding. They also provided the starting point for the initial analysis performed in this dissertation.

The reports were initially published in the EWI Journal as closed documents and were later republished to make the results public.

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Salter and Doherty (1981) reported another welding paper on experimental design applied to welding. The paper documented a multiple regression analysis for arc welding where some non-linear aspects were reviewed on a cursory level.. This work failed to evaluate the performance of the mathematical model in detail but merely evaluated the significance of terms and proposed a model. This paper also reviewed the process development work for arc welding over the prior ten years and described the need for the use of analytical techniques in the development of welding processes.

Operations Research

The non-linear multiobjective optimization method used in this research is based on Labadie et al. (1992). That paper provided the theoretical background for the use of the weighting and goal programming methods. The paper outlined the use of these methods applied to reservoir systems operation. The references by Cohon and Marks (1975), Goicoechea et al. (1982) and Loganathan and Bhattacharya (1990) were the primary references for Labadie et al. (1992).

Microjoining

Riches (1994) provided the background for joining magnet wire without prior removal of insulation. This paper focused on evaluating alternatives to soldering by investigating four welding techniques (ultrasonic, resistance, laser and arc spot). This paper focused on fine (<100μm diameter) insulated copper wires where difficulties are being encountered with traditional techniques in the automation and consistency of joining to microelectronic components. The work provided insight into the product and process design, including suggesting the parallel gap and the dual pulse welding process and the fold over terminal design. This work also referenced the work by Dawes (1980), that provided a starting point for acceptable welds specifically for the pull strength joint quality assessment method.

Ely (1997) provided much of the basic fundamental understanding of the microjoining process. This reference is an overview of microjoining and serves as training materials in this specific area. The work provided the original insight into the fold over terminal design for use in magnet wire and also provided insight into the parallel gap process. The work also added insight into the development of the process

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including electrode materials, process parameter starting points and selection of the type of welder, weld head and weld controller. The work provided general knowledge of the microjoining process including lobe curve theory, metallurgical properties of copper, tin and brass, and introduction into the fundamental empirical equations pertinent to microjoining.

Lynch and Duff (2001) dealt with microjoining the same terminal design used in this research. This paper focused on microjoining two parts of the terminal together utilizing a high frequency inverter and capacitive discharge welder. A design of experiments was performed resulting in a linear model of the process that was optimized to determine the optimum process parameter values. Residual analysis showed that a transformation to one of the variables was needed to make its effect linear. This work provided insight into the factors and their associated levels that were used in this research.

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5.0 STATISTICAL ANALYSIS

The feasibility results outlined in the Appendix served to substantiate the product and process concept of utilizing microjoining of the brass terminal to the magnet wire without prior removal of the insulation. The statistical results reported below targeted the assessment of the product and process developed for use in a high volume production application. This evaluation was performed by performing a set of designed experiments and analysis of variation with the goal of determining a mathematical model of the process to use to establish the optimum product and process parameters.

A progressive set of designed experiments were performed that elaborated and improved upon existing documented research. The initial design (Initial DOE – Existing Terminal Design – Section 5.1) that was developed and analyzed was based on the approach used by Gould and Lehman (1994 & 1997). This approach relies on traditional practice in performing designed experiments, especially the manner in which it has been carried out in the welding field. This approach utilized a two-level fractional factorial design for all 5 factors and considered only main and interaction effects through 2-way. A fractional factorial experiment was thought to be acceptable because conventional practice again suggested that interaction effects higher than 2-way were unlikely to be statistically significant. In a fractional factorial experiment, fewer treatments are required because of the confounding between terms. Confounding occurs when the effects of different factors are combined. This is usually done to reduce the number of treatments in a run. The results are often still useful because main and 2 way interaction effects are often confounded with high order interaction effects that are assumed not to be statistically significant. In addition, non-linear terms (other than the 2-way interaction effects) were not included. Due to these issues with unresolved confounding as well as production / process design control issues in this experiment, no model was developed from the analysis.

The next experimental design (#1 - Initial DOE – Modified Terminal Design – Section 5.4) addressed the product/process concerns and investigated the impact of including interaction effects higher than 2-way. This design also eliminated any confounding issues by using a two-level full factorial design for all 5

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factors. The design included main effects and interaction effects through 5-way. The elimination of confounding allowed for the proper determination of significance of the higher interaction effects. This design also included additional replications for each of the two response variables to address potential questions concerning accuracy and repeatability of the results. There was a pair of mathematical models (model #1) developed from the analysis of this design for both response variables: pull strength and percent insulation removed.

The next experimental design (#2 - Central Composite Design I – Section 5.5) investigated the impact of including effects from squared terms and to review the overall non-linearity of the process. The design did follow traditional practice however, by only including interaction effects through 2-way. This design addressed the perceived non-linear nature of the process by using a central composite design with center and axial points for all factors except upslope. The elimination of confounding allowed for the proper identification of statistical significance of all terms included. This design did not include additional replications of the experiment. A pair of mathematical models (model #2) was developed from the analysis of this design for both the pull strength and the percent insulation removed response variables.

The final design (#3 - Central Composite Design II – Section 5.5) was a substantial departure from the earlier work by Gould and Lehman (1994 & 1997) in that this design investigated the impact of including effects from squared terms and all higher interaction effects with no confounding of effects and with replications. This design used a central composite design with center and axial points for all factors and incorporated 2 replications for both response variables. The elimination of confounding allowed for the proper determination of significance of all terms: main, interaction through 5-way and squared. There was a pair of mathematical models (model #3) developed from the analysis of this design for both pull strength and percent insulation removed.

A summary of all of the experimental designs developed is presented in Table 5.1. This table also provides a description of the design, the background, the effects included and reference to the applicable section in

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this dissertation. This table lays out a consistent set of terminology for designs, effects and models that is used throughout this dissertation.

Table 5.1 – Summary of DOE's Performed

Section	*Section Name*	*Design*	*Effects Included*	*Model*	*Background*
5.1	***Initial DOE – Existing Terminal Design***	Two-level ½ fractional factorial design – 5 factors – 2 replications	Main and interaction effects through 2-way	No Model	Based on Gould's design - product changed because of variation issues
5.4 Design #1	***Initial DOE – Modified Terminal Design***	Two-level full factorial design – 5 factors - 10 replications for pull strength and 2 for percent insulation	Main and interaction effects through 5-way	Model #1	Builds on Gould's design to include full factorial (no confounding), all interaction terms and replication
5.5 Design #2	***Central Composite Design I***	Central composite design – 4 factors – no replications	Main, squared and interaction effects through 2-way	Model #2	Builds on Gould's design to include squared terms and reduced 1 predictor variable
5.6 Design #3	***Central Composite Design II***	Central composite design – 5 factors – 1 and 2 replications run for both response variables	Main, squared and interaction effects through 5-way	Model #3	Builds on all previous designs to include squared terms, higher interaction effects, no confounding and replications

5.1 Initial DOE – Existing Terminal Design

The initial design of experiment (DOE) was run on the existing terminal design and focused on the welding pulse (second pulse) defined in the feasibility results in the Appendix. The purpose of this initial DOE was to serve as a screening design to identify potential statistically significant variables for use in subsequent models. It was determined that the seating pulse (first pulse) was optimized by the minimization of contact resistance. Any additional optimization of this pulse is beyond the scope of this research. From the feasibility results listed in the Appendix, it was determined that the primary joint quality assessment methods (response variables) used in the design of experiments in this research should be pull strength of the weld and percentage of insulation removed from the surface of the wire. The variables were chosen based on their repeatability and ease of use. The pull strength test was performed as described in the Appendix. The percentage of insulation removed was determined by visual evaluation as also described in the Appendix. The predictors selected for the welding pulse based on the feasibility results above were weld voltage, weld time, upslope, cooling time and weld force. A two-level design was chosen for the

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initial DOE based on the design used by Gould and Lehman (1994 & 1997) and on traditional practice discussed above. Based on the lobe curves developed in the Appendix it was determined that the initial experimental design, used to determine which predictors (factors) were significant, was run at the levels outlined in Table 5.2. Each factor was given a letter designation for easy reference in future figures.

Table 5.2 - Initial DOE Factors

	Factor	*Lower Level (-1)*	*Higher Level (+1)*
A	Weld Voltage	1.6 volts	2.0 volts
B	Weld Time	6 msec	16 msec
C	Upslope	0% of Weld Time	50% of Weld Time
D	Cooling Time	0 msec	20 msec
E	Weld Force	17.5 lbs (7.94kg)	35lbs (15.88kg)

The initial analysis that was performed was a fractional factorial design. As stated above, the purpose of the initial design was to determine which factors were statistically significant in effecting pull strength and percentage insulation removed of the weld. With the five factors, a design was chosen such that confounding of main effects and two-way interaction effects did not occur. It was decided to perform a 2^{5-1} two-level experiment (1/2 fractional factorial – 16 runs) with only one block and zero center points in order to reduce the number of runs while still minimizing any confounding effects. In order to reduce the influence of experimental noise, two replicates were performed to bring the total number of runs to 32.

The design represented a resolution V design meaning that main effects were confounded with 4-way interaction effects and higher. For the purpose of this analysis all 3-way interaction effects and higher were assumed to have negligible effects on the pull strength and percent insulation removed (effect consisting of only experimental noise). This assumption allowed for any statistically significant effects involving main effects to be assigned to only the main effects. With the resolution V design, 2-way interaction effects are confounded with 3-way interaction effects. The defining relation and alias structure of the initial experimental design in listed in Figure 5.1.

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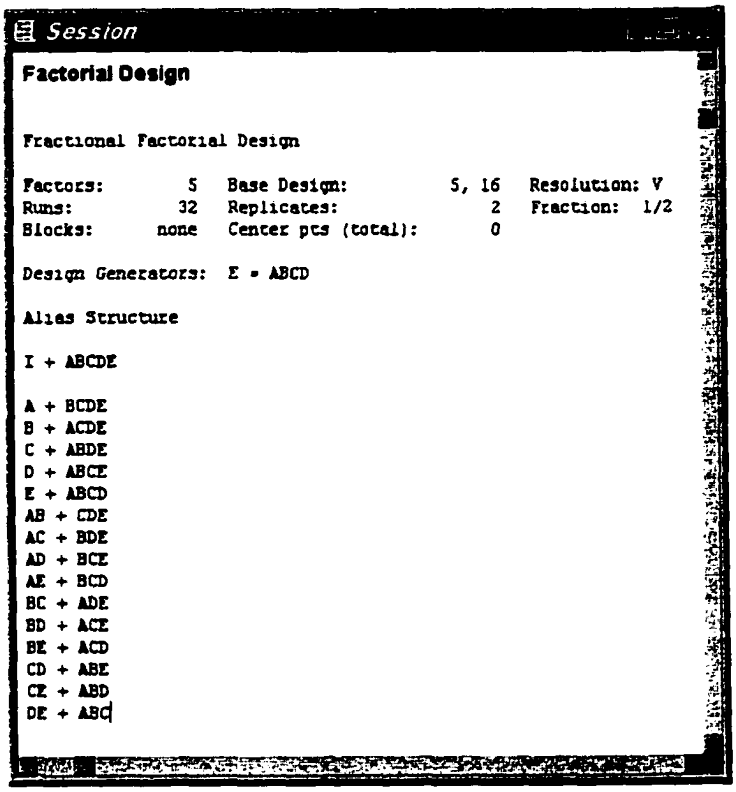
Figure 5.1 – Initial DOE Defining Relation



```
Factorial Design


Fractional Factorial Design

Factors:        5   Base Design:         5, 16   Resolution: V
Runs:          32   Replicates:              2   Fraction:  1/2
Blocks:      none   Center pts (total):      0

Design Generators:  E = ABCD

Alias Structure

I + ABCDE

A + BCDE
B + ACDE
C + ABDE
D + ABCE
E + ABCD
AB + CDE
AC + BDE
AD + BCE
AE + BCD
BC + ADE
BD + ACE
BE + ACD
CD + ABE
CE + ABD
DE + ABC
```

The standard order as well as the order in which the data was run is listed in Table 5.3. The data matrix from the initial 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 evaluated by pull testing the sample and determining the percent of insulation remaining. The data for each joint quality assessment method was recorded and entered into the worksheet as shown in Table 5.3. The factorial design was then analyzed to draw conclusions.

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Table 5.3 – Initial Design Data Matrix

Std Order	Weld Voltage (volts)	Weld Time (msec)	Upslope (% of weld time)	Cooling Time (msec)	Force (lbs)	Local Max Force (lbs)	Global Max Force (lbs)	% Ins Removed (%)
1	1.6	6	0	0	35	20.4	20.4	15
2	2	6	0	0	17.5	11.7	12.2	10
3	1.6	16	0	0	17.5	8.5	9	20
4	2	16	0	0	35	17.3	17.3	100
5	1.6	6	50	0	17.5	13.3	14.5	70
6	2	6	50	0	35	18.2	18.2	10
7	1.6	16	50	0	35	17.1	17.1	80
8	2	16	50	0	17.5	10.1	12.9	55
9	1.6	6	0	20	17.5	10.3	10.3	0
10	2	6	0	20	35	18.8	18.8	60
11	1.6	16	0	20	35	12.7	16.3	90
12	2	16	0	20	17.5	10.8	12.5	95
13	1.6	6	50	20	35	14.3	14.7	5
14	2	6	50	20	17.5	7.7	7.7	85
15	1.6	16	50	20	17.5	8.5	8.5	15
16	2	16	50	20	35	10.4	15.6	0
17	1.6	6	0	0	35	15.9	16.7	30
18	2	6	0	0	17.5	10.8	11.8	15
19	1.6	16	0	0	17.5	8.5	8.5	2
20	2	16	0	0	35	20.2	20.2	90
21	1.6	6	50	0	17.5	7	7	100
22	2	6	50	0	35	17.4	17.4	80
23	1.6	16	50	0	35	15.9	15.9	100
24	2	16	50	0	17.5	9.7	11	95
25	1.6	6	0	20	17.5	8.7	8.7	95
26	2	6	0	20	35	11.7	12.2	10
27	1.6	16	0	20	35	19.6	19.6	100
28	2	16	0	20	17.5	9.6	12.2	80
29	1.6	6	50	20	35	17.8	17.8	15
30	2	6	50	20	17.5	6.4	6.4	90
31	1.6	16	50	20	17.5	8.9	8.9	2
32	2	16	50	20	35	17.1	18.1	100

A significance level of 5% (alpha=0.05) was used throughout the analysis to determine statistical significance. Statistical significance was interpreted throughout the analysis as being important in being able to predict the weld strength or percent of insulation remaining (depending on the response variable utilized). The importance of the regressions and individual predictors were defined by performing F-tests and t-tests. F-tests were used on all regression and DOE analysis to evaluate the significance of the entire

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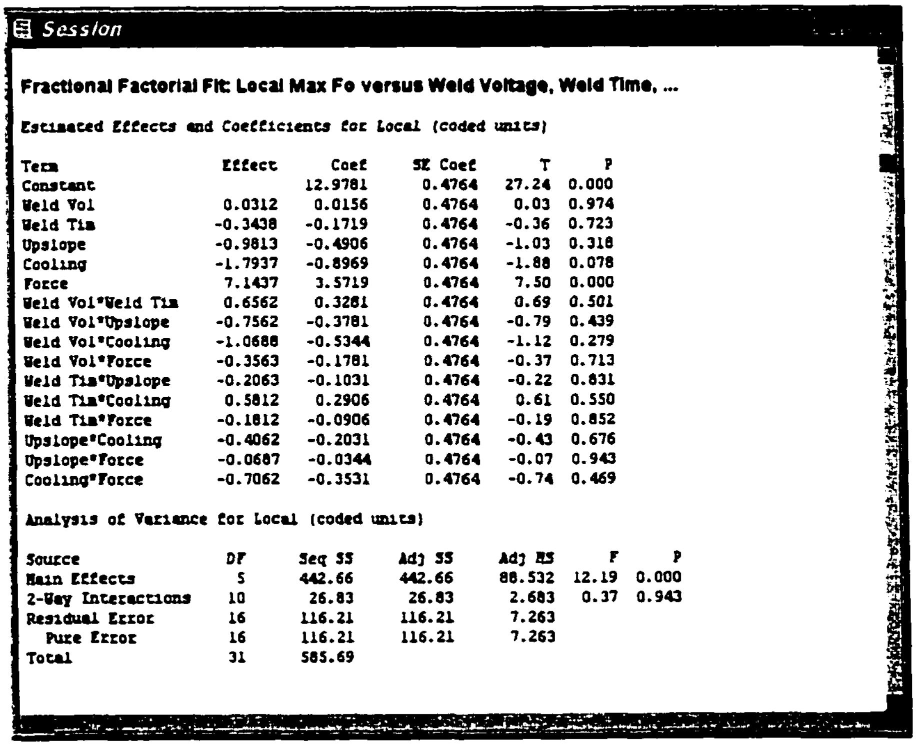
model with regard to the main effects or the two-way interaction effects by comparing the model minimum significance value (p-value) to the required minimum significance 5% level (alpha). The same method was used when evaluating the significance of individual predictor variables in which the t-test predictor minimum significance value (p-value) is compared to the required minimum significance 5% level (alpha). The design was first analyzed with respect to pull strength of the weld (local maximum force). In figure 5.2 the analysis of variation (ANOVA) F-tests showed that the main effects were statistically significant (p=0.000 which is < 0.05) and 2-way interaction effects were not statistically significant (p=0.943 which is > 0.05). However, the only main effect that was determined to be statistically significant by the t-test was weld force (p=0.000 which is < 0.05).

Figure 5.2 – Initial Design Analysis Results – Pull Strength



Fractional Factorial Fit: Local Max Fo versus Weld Voltage, Weld Time, ...

```
Estimated Effects and Coefficients for Local (coded units)

Term                  Effect      Coef    SE Coef       T      P
Constant                       12.9781     0.4764   27.24  0.000
Weld Vol              0.0312    0.0156     0.4764    0.03  0.974
Weld Tim             -0.3438   -0.1719     0.4764   -0.36  0.723
Upslope              -0.9813   -0.4906     0.4764   -1.03  0.318
Cooling              -1.7937   -0.8969     0.4764   -1.88  0.078
Force                 7.1437    3.5719     0.4764    7.50  0.000
Weld Vol*Weld Tim     0.6562    0.3281     0.4764    0.69  0.501
Weld Vol*Upslope     -0.7562   -0.3781     0.4764   -0.79  0.439
Weld Vol*Cooling     -1.0688   -0.5344     0.4764   -1.12  0.279
Weld Vol*Force       -0.3563   -0.1781     0.4764   -0.37  0.713
Weld Tim*Upslope     -0.2063   -0.1031     0.4764   -0.22  0.831
Weld Tim*Cooling      0.5812    0.2906     0.4764    0.61  0.550
Weld Tim*Force       -0.1812   -0.0906     0.4764   -0.19  0.852
Upslope*Cooling      -0.4062   -0.2031     0.4764   -0.43  0.676
Upslope*Force        -0.0687   -0.0344     0.4764   -0.07  0.943
Cooling*Force        -0.7062   -0.3531     0.4764   -0.74  0.469

Analysis of Variance for Local (coded units)

Source              DF    Seq SS    Adj SS    Adj MS      F      P
Main Effects         5    442.66    442.66    88.532  12.19  0.000
2-Way Interactions  10     26.83     26.83     2.683   0.37  0.943
Residual Error      16    116.21    116.21     7.263
  Pure Error        16    116.21    116.21     7.263
Total               31    585.69
```

The design was then analyzed with respect to percent of insulation remaining. The analysis of variation (ANOVA) table in Figure 5.3 shows by the F-test that the main effects were not statistically significant (p=0.365 which is > 0.05). However, 2-way interaction shown to be statistically significant by the F-test

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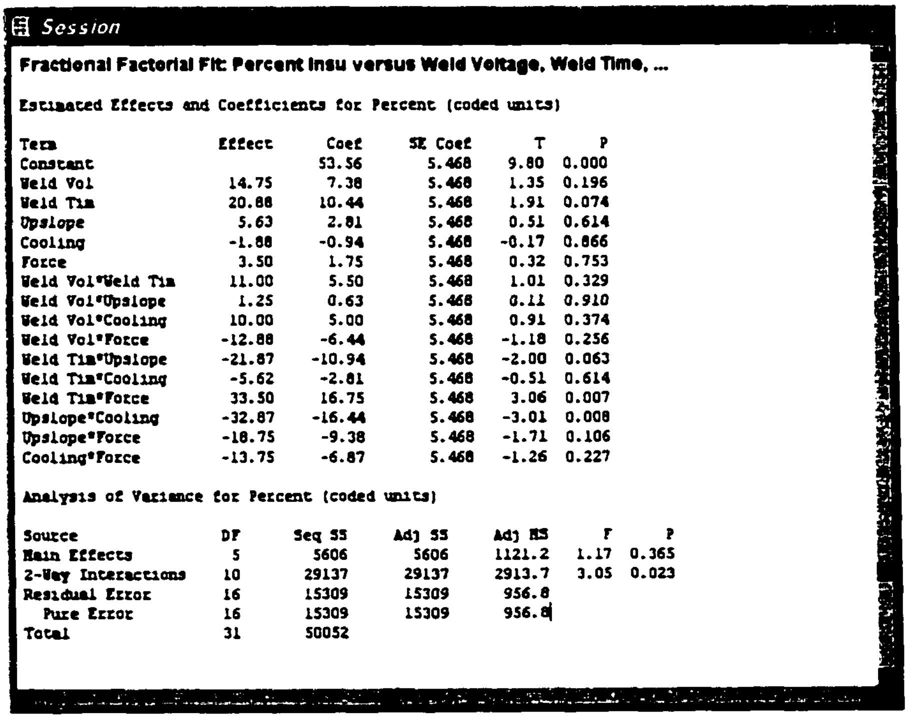
(p=0.023 which is < 0.05). The 2-way interaction effects that were determined to be statistically significant by the t-tests were weld time * weld force (p=0.007) and upslope * cooling time (p=0.008) both of which are < 0.05.

The above results from the initial DOE existing terminal design did not make logical sense. Intuitively it was anticipated that weld voltage and weld time would be statistically significant. It was hypothesized that potentially significant terms were not included. Also, the amount of noise in the experiment may have been hiding some real effects in the experiment. In order to quantify the amount of noise in the results due to the process and the evaluation methods, calculation was made to determine the magnitudes of the variation relative to the mean values.

Figure 5.3 - Initial Design Analysis Results – Percent Insulation Remaining



```
Fractional Factorial Fit: Percent Insu versus Weld Voltage, Weld Time, ...

Estimated Effects and Coefficients for Percent (coded units)

Term                  Effect      Coef    SE Coef       T      P
Constant                         53.56      5.468    9.80  0.000
Weld Vol               14.75      7.38      5.468    1.35  0.196
Weld Tim               20.88     10.44      5.468    1.91  0.074
Upslope                 5.63      2.81      5.468    0.51  0.614
Cooling                -1.88     -0.94      5.468   -0.17  0.866
Force                   3.50      1.75      5.468    0.32  0.753
Weld Vol*Weld Tim      11.00      5.50      5.468    1.01  0.329
Weld Vol*Upslope        1.25      0.63      5.468    0.11  0.910
Weld Vol*Cooling       10.00      5.00      5.468    0.91  0.374
Weld Vol*Force        -12.88     -6.44      5.468   -1.18  0.256
Weld Tim*Upslope      -21.87    -10.94      5.468   -2.00  0.063
Weld Tim*Cooling       -5.62     -2.81      5.468   -0.51  0.614
Weld Tim*Force         33.50     16.75      5.468    3.06  0.007
Upslope*Cooling       -32.87    -16.44      5.468   -3.01  0.008
Upslope*Force         -18.75     -9.38      5.468   -1.71  0.106
Cooling*Force         -13.75     -6.87      5.468   -1.26  0.227

Analysis of Variance for Percent (coded units)

Source                DF     Seq SS     Adj SS     Adj MS      F      P
Main Effects           5       5606       5606     1121.2   1.17  0.365
2-Way Interactions    10      29137      29137     2913.7   3.05  0.023
Residual Error        16      15309      15309      956.8
  Pure Error          16      15309      15309      956.8
Total                 31      50052
```

5.2 Variance Analysis

To quantify the variability in each of the potential evaluation methods, due to the process and evaluation methods in each of the results, the mean and standard deviation was calculated from a sample size of at

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least nine. The mean is a measure of central tendency. The standard deviation is a measure of dispersion. Listed in below in Table 5.4 are the mean values and standard deviation for each of the evaluations performed. These values were determined in the feasibility study in the Appendix with the existing terminal design. Each trial was performed at the same process parameter settings.

Table 5.4 – Assessment Method Variation Analysis

Evaluation	*Mean*	*Standard Deviation*
Pull Strength Measures		
Pull strength from 2.5mm wide terminal – global maximum from optimum point	11.0lbs (4.99kg)	2.2lbs (1.00kg)
Pull strength from 2.5mm wide terminal – local maximum from optimum point	10.3lbs (4.67kg)	2.0lbs (0.91kg)
Pull strength from 3.3mm wide terminal – global maximum from optimum point	18.2lbs (8.26kg)	1.6lbs (0.73kg)
Pull strength from 3.3mm wide terminal – local maximum from optimum point	16.0lbs (7.26kg)	1.5lbs (0.68kg)
Pull strength from soldered joint	15.9lbs (7.21kg)	2.31lbs (1.05kg)
Pull strength of 0.65mm copper magnet wire	20.01kg (9.08kg)	0.46lbs (0.21kg)
Visual Measures		
Percentage of insulation removed from the wire – optimum point	97%	4.8%
Percent bond circumference at a selected position within the lobe curve	8.0%	8.4%
Percent reduction in diameter at a selected position within the lobe curve	-1.3%	3.9%

When reviewing the pull strength measures, the 2.5mm terminal mean was lower than that of the soldered joint. The 3.3mm terminal mean pull strength was not only was higher than then that of the soldered joint but also has a reduced variability over the 2.5mm joint as indicated by the standard deviation. These results from the 3.3mm terminal are very favorable to a production process in that they increase the mean and reduce the variation in the process and to a design of experiment.

It became evident that the percentage of insulation removed from the wire was the best performing assessment method by reviewing the standard deviation in comparison to the mean from the visual measures. The reduced variation as indicated by the standard in comparison with the mean would produce a peaked, narrow histogram. This would be the opposite case with the other visual measures as their

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standard deviation is actually larger than the mean. For the percent bond circumference and the percent reduction in diameter the histogram would be much flatter. This flatter histogram is an indication of a larger distribution spread and heavy tails from the large standard deviation in comparison with the mean. The heavy tails are an indication of likely extreme values.

The standard deviation, compared to the mean range of experimentation, is a relative indication of the amount of noise that would found in the system if a design of experiments were to be performed. The increased values of the standard deviation for the 2.5mm terminal over the wire only and 3.3mm terminal evaluated in the feasibility section of the Appendix suggest that the process caused a significant amount of variation. The cause of this variation can be attributed to the increased amount of material preventing the back of the terminal from blowing out. This allowed for a wider range of process parameter settings. This fact is substantiated by the difference between the pull strength standard deviation for the 0.65mm copper magnet wire and the standard deviations for the rest of the welding tests.

The process was analyzed and the cause for the extreme variation in the process was determined to be caused from inconsistencies in contact area between the part of the terminal that is folded over and the flat part of the terminal. The combination of inconsistencies in the bending process, dimension of the terminal and location of the electrode all exaggerated the effect the contact area. The inconsistencies in the contact area have a direct effect on the variation of the heat flow through the part. The inconsistent heat flow caused significant variation in the welding process. Figure 5.4 demonstrates a weld cross section with minimal contact area between the two parts of the terminal.

In the cross section in Figure 5.4 there is not a weld bond that is formed between the two parts of the terminal. This fact reduces the amount of current flow and heat generated through the part. Figure 5.5 demonstrates another cross section performed on a part with at the same process settings with a significantly more contact area. In this cross section there is a sold state bond between the two parts of the terminal leading to a significant amount of current and heat flow through the part at this junction. The difference in these parts was a direct correlation to the difference in the variation in the process.

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Figure 5.4 – Weld Cross Section

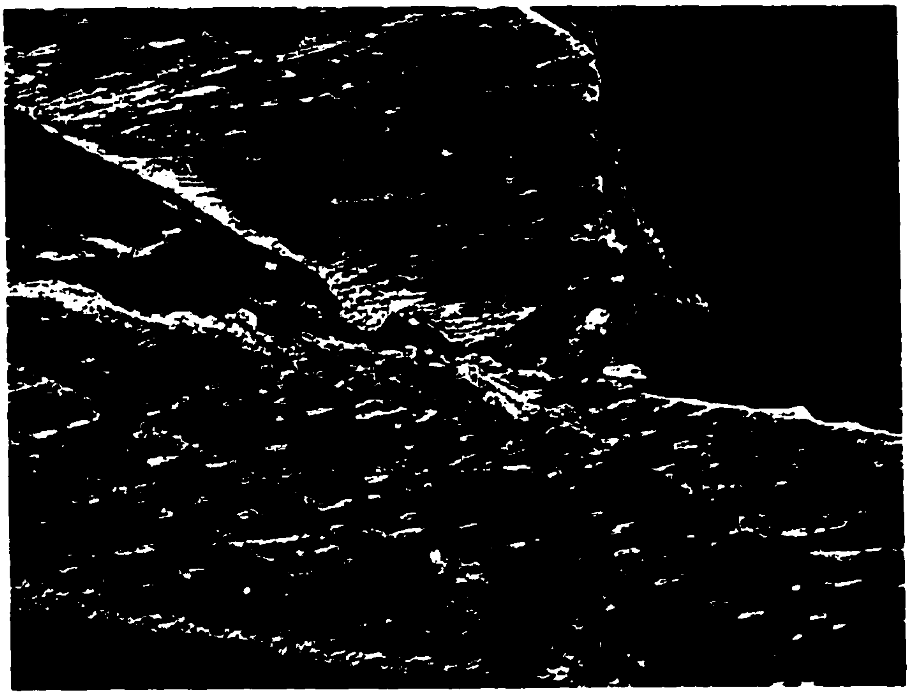

Figure 5.5 - Weld Cross Section

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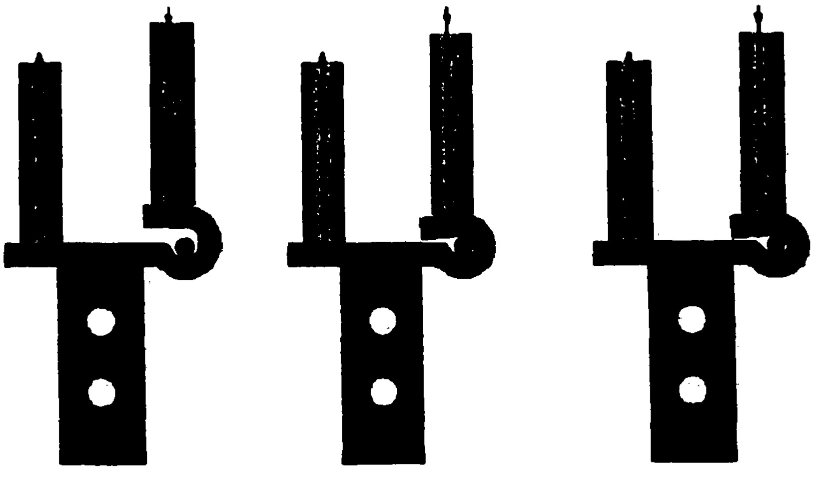
Instead of attempting to control a process with some very complicated dynamic phenomena occurring it was decided to attempt to address the variation with a product development. It was anticipated that it would be very difficult to control the contact area with the given design and process. Efforts were considered to control the tolerances on the part, location of the electrode and even the bending phenomena of the terminal but a much simpler solution was sought involving a terminal design change.

5.3 Modified Product and Process Design

As stated above the terminal was reviewed to determine if design could be developed to produce a constant contact area. It was decided the best way to control the contact area was to eliminate it. A product and process design was developed that was a departure from the design outlined in the Appendix. The new design eliminated the need for the contact area between the two parts of the terminal. This modified product and process design is shown in Figure 5.6.

Figure 5.6 – Modified Product and Process Design



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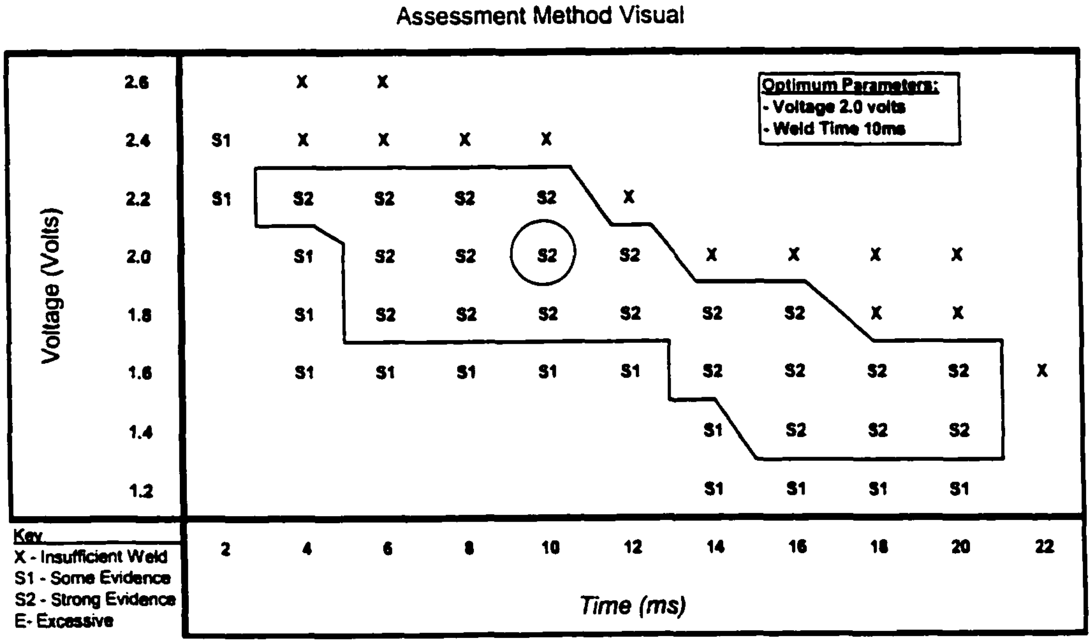
As depicted by Figure 5.6 the two parts of the terminal do not contact each other and the current and heat flow travel only around one side of the wire until the insulation is displaced. One disadvantage to this product and process design is the potential lack of robustness of the joint. This lack of robustness was caused by the elimination of the weld between the two parts of the terminal. The advantages in being able to stabilize the process however outweighed the disadvantage of lack of robustness. Because the current and heat flow around the part changed, the process parameters changed as well. The optimized process parameters developed in the Appendix for the seating pulse (first pulse) were retained due to the fact the in the initial design the two parts of the terminal did not begin to make contact until the second pulse. A lobe curve for the new product/process design welding pulse (second pulse) was developed as shown in Figure 5.7. As indicated by the lobe curve increased area in Figure 5.7 the process robustness was also increased with the modified product/process design over the same lobe curve area developed in the Appendix.

Figure 5.7 – Lobe Curve of Modified Design Assessment Method Visual



To predict the noise in a DOE, the variance analysis performed above was repeated for the pull strength and percent insulation removed. These response variables were target since they were the ones used throughout the research for the designed experiments. A sample size of seven was used to evaluate the variance at the

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point identified above in Figure 5.7. Table 5.5 shows the mean and standard deviation for both of the evaluation methods.

Table 5.5 - Modified Design Assessment Method Variation Analysis

Evaluation	*Mean*	*Standard Deviation*
Pull strength of modified terminal design - global maximum from optimum point	11.0lbs (4.99kg)	1.7lbs (0.77kg)
Pull strength of modified terminal design - local maximum from optimum point	9.4lbs (4.26kg)	1.5lbs (0.68kg)
Percentage of insulation removed form the wire with modified terminal - optimum point	100%	0.0%

The modified product and process design showed an improvement in the variation for pull strength and percent insulation removed, as indicated by the standard deviation, in comparison with the comparable values prior to the modified design.

5.4 Initial DOE - Modified Terminal Design

An initial design of experiment (DOE) was run on the modified terminal design that also focused on the welding pulse (second pulse). The same assessment method (response variables) and predictor variables were selected for the experiment however the factor levels were modified. This design was again developed to serve as a screening design used to determine the significance of the predictors (factors). The levels of the design that were determined from the lobe curve above are outlined in Table 5.6.

Initial DOE Factors - Table 5.6

	Factor	*Lower Level (-1)*	*Higher Level (+1)*
A	Weld Voltage	1.6 volts	2.2 volts
B	Weld Time	4 msec	10 msec
C	Upslope	0% of Weld Time	25% of Weld Time
D	Cooling Time	0 msec	20 msec
E	Weld Force	17.5 lbs (7.94kg)	35lbs (15.88kg)

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The initial analysis that was performed on the modified design was a full factorial design. As stated above, the purpose of the initial design was to determine which factors were statistically significant in effecting pull strength and percentage insulation removed of the weld. With the five factors, a design was developed such that no confounding effects were present. The first initial design was modified because of the issues with the first DOE and ease at which the response variables were analyzed. The modified design consisted of a two-level 2^5 experiment (full factorial – 32 runs) with only one block and no center points. Based on the variation data above, in order to reduce the effects of experimental noise on the pull strength response variable, ten replicates were performed to bring the total number runs with this response variable to 320. Based on the fact that the variation was much lower on the percent of insulation removed only two replicates were performed to bring the total number of runs with this response variable to 64

The design represented a full resolution design meaning that no effects were confounded. This allowed for any statistically significant effects involving any main or interaction effect to be assigned only to that effect. Since the design was full resolution there was no defining relation or alias structure.

Table 5.7 – Initial Design Data Matrix

Std Order	*Weld Time*	*Weld Voltage*	*Upslope*	*Cooling Time*	*Force*	*Local Max Force*	*% Ins. Removed*
1	4	1.6	0	0	17.5	5.6	0
2	10	1.6	0	0	17.5	7.2	90
3	4	2.2	0	0	17.5	7.4	5
4	10	2.2	0	0	17.5	8.7	95
5	4	1.6	25	0	17.5	0	0
6	10	1.6	25	0	17.5	12.5	10
7	4	2.2	25	0	17.5	8.1	0
8	10	2.2	25	0	17.5	16.2	50
9	4	1.6	0	20	17.5	0	0
10	10	1.6	0	20	17.5	12.4	0
11	4	2.2	0	20	17.5	12.3	0
12	10	2.2	0	20	17.5	11.8	25
13	4	1.6	25	20	17.5	0	0
14	10	1.6	25	20	17.5	13.1	5
15	4	2.2	25	20	17.5	15	2
16	10	2.2	25	20	17.5	13.5	15
17	4	1.6	0	0	35	12.4	5
18	10	1.6	0	0	35	18.8	10
19	4	2.2	0	0	35	10.9	15

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20	10	2.2	0	0	35	14.3	40
21	4	1.6	25	0	35	20	10
22	10	1.6	25	0	35	19.4	75
23	4	2.2	25	0	35	21.9	15
24	10	2.2	25	0	35	12.2	100
25	4	1.6	0	20	35	20.4	5
26	10	1.6	0	20	35	16.4	5
27	4	2.2	0	20	35	20.8	20
28	10	2.2	0	20	35	20.3	95
29	4	1.6	25	20	35	16.7	10
30	10	1.6	25	20	35	14.2	5
31	4	2.2	25	20	35	11.3	15
32	10	2.2	25	20	35	13.2	90

The standard order, treatments and experiment results for both joint quality assessment methods (response variable) are shown in Table 5.7 for the first replication. The data matrix from the initial 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 evaluated by pull testing the sample and determining the percent of insulation remaining. The factorial design was then analyzed to draw conclusions.

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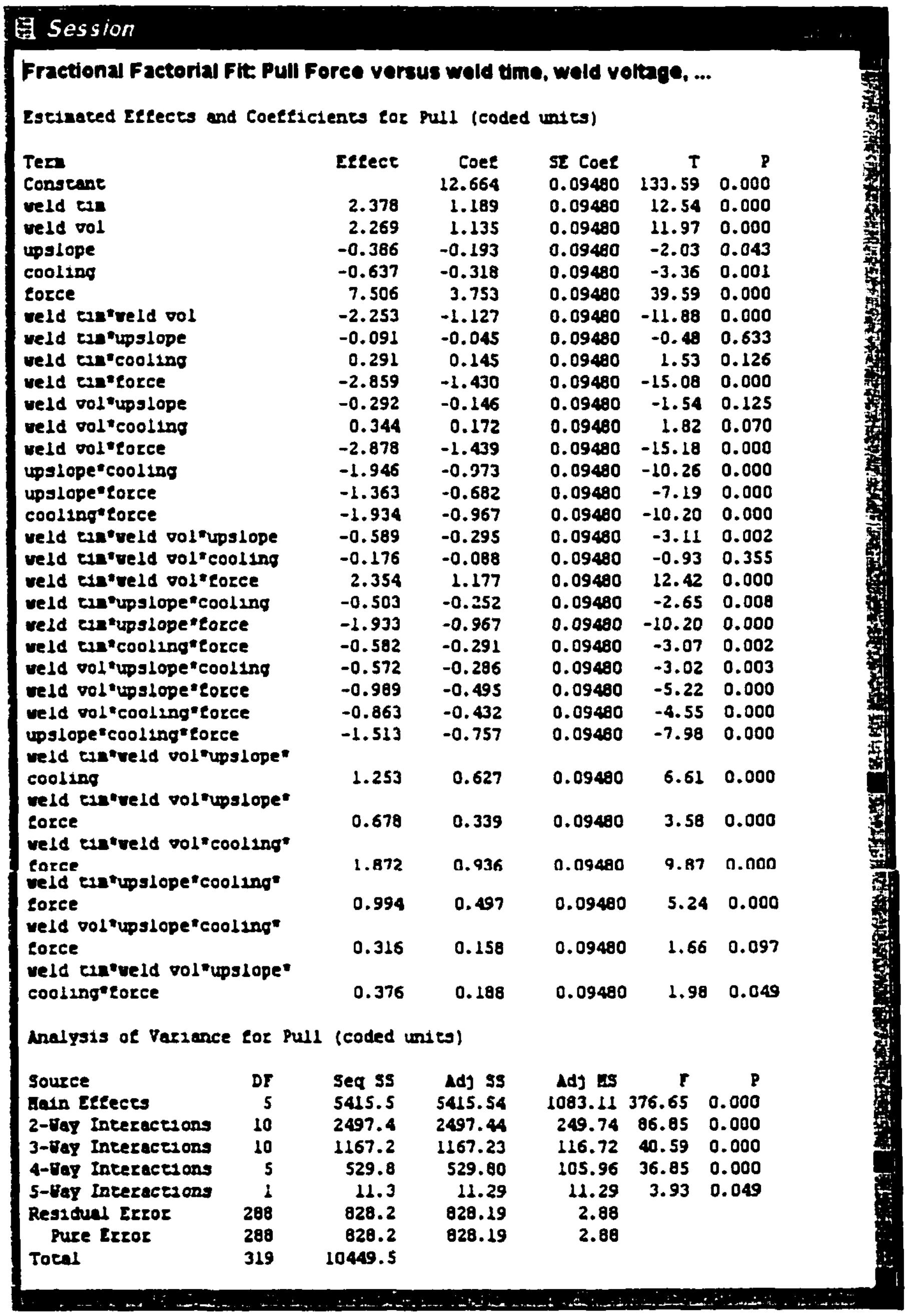
Figure 5.8 – Initial Design Analysis Results – Pull Strength



```
Fractional Factorial Fit: Pull Force versus weld time, weld voltage, ...

Estimated Effects and Coefficients for Pull (coded units)

Term                          Effect      Coef    SE Coef       T      P
Constant                                12.664    0.09480  133.59  0.000
weld tim                       2.378     1.189    0.09480   12.54  0.000
weld vol                       2.269     1.135    0.09480   11.97  0.000
upslope                       -0.386    -0.193    0.09480   -2.03  0.043
cooling                       -0.637    -0.318    0.09480   -3.36  0.001
force                          7.506     3.753    0.09480   39.59  0.000
weld tim*weld vol             -2.253    -1.127    0.09480  -11.88  0.000
weld tim*upslope              -0.091    -0.045    0.09480   -0.48  0.633
weld tim*cooling               0.291     0.145    0.09480    1.53  0.126
weld tim*force                -2.859    -1.430    0.09480  -15.08  0.000
weld vol*upslope              -0.292    -0.146    0.09480   -1.54  0.125
weld vol*cooling               0.344     0.172    0.09480    1.82  0.070
weld vol*force                -2.878    -1.439    0.09480  -15.18  0.000
upslope*cooling               -1.946    -0.973    0.09480  -10.26  0.000
upslope*force                 -1.363    -0.682    0.09480   -7.19  0.000
cooling*force                 -1.934    -0.967    0.09480  -10.20  0.000
weld tim*weld vol*upslope     -0.589    -0.295    0.09480   -3.11  0.002
weld tim*weld vol*cooling     -0.176    -0.088    0.09480   -0.93  0.355
weld tim*weld vol*force        2.354     1.177    0.09480   12.42  0.000
weld tim*upslope*cooling      -0.503    -0.252    0.09480   -2.65  0.008
weld tim*upslope*force        -1.933    -0.967    0.09480  -10.20  0.000
weld tim*cooling*force        -0.582    -0.291    0.09480   -3.07  0.002
weld vol*upslope*cooling      -0.572    -0.286    0.09480   -3.02  0.003
weld vol*upslope*force        -0.989    -0.495    0.09480   -5.22  0.000
weld vol*cooling*force        -0.863    -0.432    0.09480   -4.55  0.000
upslope*cooling*force         -1.513    -0.757    0.09480   -7.98  0.000
weld tim*weld vol*upslope*
cooling                        1.253     0.627    0.09480    6.61  0.000
weld tim*weld vol*upslope*
force                          0.678     0.339    0.09480    3.58  0.000
weld tim*weld vol*cooling*
force                          1.872     0.936    0.09480    9.87  0.000
weld tim*upslope*cooling*
force                          0.994     0.497    0.09480    5.24  0.000
weld vol*upslope*cooling*
force                          0.316     0.158    0.09480    1.66  0.097
weld tim*weld vol*upslope*
cooling*force                  0.376     0.188    0.09480    1.98  0.049

Analysis of Variance for Pull (coded units)

Source                 DF     Seq SS     Adj SS     Adj MS       F      P
Main Effects            5     5415.5    5415.54    1083.11  376.65  0.000
2-Way Interactions     10     2497.4    2497.44     249.74   86.85  0.000
3-Way Interactions     10     1167.2    1167.23     116.72   40.59  0.000
4-Way Interactions      5      529.8     529.80     105.96   36.85  0.000
5-Way Interactions      1       11.3      11.29      11.29    3.93  0.049
Residual Error        288      828.2     828.19       2.88
  Pure Error          288      828.2     828.19       2.88
Total                 319    10449.5
```

A significant level of 5% (alpha=0.05) was used again to determine statistical significance. Statistical significance was interpreted throughout the analysis as being important in being able to predict the pull strength or percent of insulation remaining (depending on the response variable considered). The design was first analyzed with respect to pull strength of the weld (local maximum force). The analysis of

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variation (ANOVA) table in Figure 5.8 outlined that the main effects were statistically significant from the F-test ($p=0.000$ which is < 0.05). The ANOVA table also outlined that the sets of interaction effects through 5-way were statistically significant from the F-tests as well ($p=0.000$ which is > 0.05). The only main effect that was marginal in its statistical significance from the t-test was upslope ($p= 0.043$ which is $<$ 0.05 but close).

The above analysis resulted in a mathematical model of the process with 25 terms. With respect to the individual terms of the model there were five main effects that were statistically significant, six 2-way interaction effects significant, nine 3-way interaction effects significant, two 4-way interaction effects and one 5-way interaction effects significant. The results did made logical sense except it was anticipated that some of the higher order interaction effects were not truly statistically significant. Because of issues associated with the higher effects being statistically significant the validity of the model was in question. In typical designed experiments 3-way interaction effects and above are considered to be not statistically significant. It is rare but there are some process that have legitimate higher interaction effects but normally these effects are assumed to consist of experiment noise. Initially, it was anticipated that the higher order effects were incorrectly outlined as being statistically significant in order to explain some second order non-linearity in the first order model assumption and because of cross correlation of the terms. This analysis was used however to provide directional information in developing an accurate mathematical model. In order to predict the performance of the model results for comparison purposes, a regression analysis was performed with 25 statistically significant terms.

The analysis of variation (ANOVA) table from the regression is shown in Figure 5.9. This analysis mirrored the results from the DOE and showed that the model was statistically significant from the F-test ($p=0.000$ which is < 0.05). The analysis also outlined that potentially eight additional interaction effects could be dropped from the analysis based on the t-tests, with no significant degradation in performance of the model. The model also demonstrated a reasonable fit as indication by the coefficient of determination, $R^2 = 86.2\%$ and R^2 (adjusted) $= 85.0\%$. In addition, the model was not over specified as indicated by the

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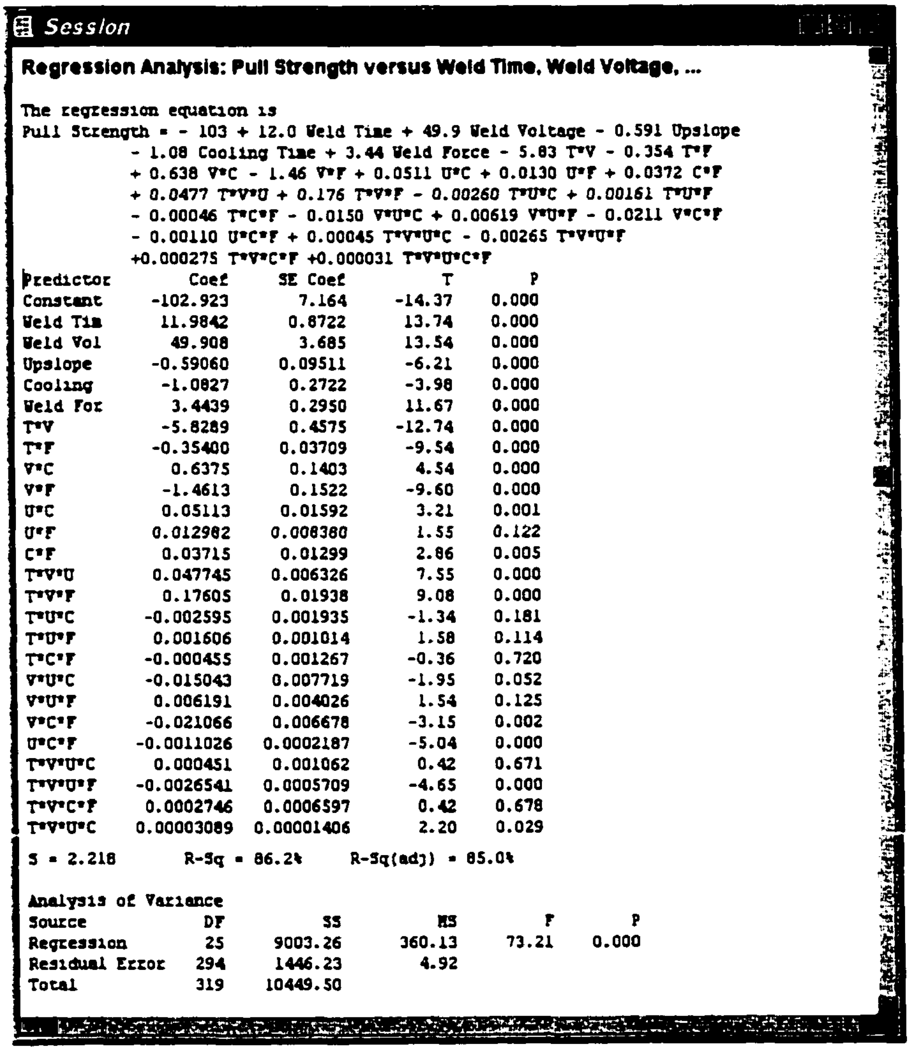
minimal difference between R^2 and R^2 (adjusted) and therefore the eight interaction effects that could be dropped were retained.

Figure 5.9 –Regression Analysis – Pull Strength



Regression Analysis: Pull Strength versus Weld Time, Weld Voltage, ...

```
The regression equation is
Pull Strength = - 103 + 12.0 Weld Time + 49.9 Weld Voltage - 0.591 Upslope
           - 1.08 Cooling Time + 3.44 Weld Force - 5.83 T*V - 0.354 T*F
           + 0.638 V*C - 1.46 V*F + 0.0511 U*C + 0.0130 U*F + 0.0372 C*F
           + 0.0477 T*V*U + 0.176 T*V*F - 0.00260 T*U*C + 0.00161 T*U*F
           - 0.00046 T*C*F - 0.0150 V*U*C + 0.00619 V*U*F - 0.0211 V*C*F
           - 0.00110 U*C*F + 0.00045 T*V*U*C - 0.00265 T*V*U*F
           +0.000275 T*V*C*F +0.000031 T*V*U*C*F
Predictor         Coef       SE Coef          T        P
Constant      -102.923         7.164     -14.37    0.000
Weld Tim       11.9842        0.8722      13.74    0.000
Weld Vol        49.908         3.685      13.54    0.000
Upslope       -0.59060       0.09511      -6.21    0.000
Cooling        -1.0827        0.2722      -3.98    0.000
Weld For        3.4439        0.2950      11.67    0.000
T*V            -5.8289        0.4575     -12.74    0.000
T*F           -0.35400       0.03709      -9.54    0.000
V*C             0.6375        0.1403       4.54    0.000
V*F            -1.4613        0.1522      -9.60    0.000
U*C            0.05113       0.01592       3.21    0.001
U*F           0.012982      0.008380       1.55    0.122
C*F            0.03715       0.01299       2.86    0.005
T*V*U         0.047745      0.006326       7.55    0.000
T*V*F          0.17605       0.01938       9.08    0.000
T*U*C        -0.002595      0.001935      -1.34    0.181
T*U*F         0.001606      0.001014       1.58    0.114
T*C*F        -0.000455      0.001267      -0.36    0.720
V*U*C        -0.015043      0.007719      -1.95    0.052
V*U*F         0.006191      0.004026       1.54    0.125
V*C*F        -0.021066      0.006678      -3.15    0.002
U*C*F       -0.0011026     0.0002187      -5.04    0.000
T*V*U*C       0.000451      0.001062       0.42    0.671
T*V*U*F     -0.0026541     0.0005709      -4.65    0.000
T*V*C*F      0.0002746     0.0006597       0.42    0.678
T*V*U*C     0.00003089    0.00001406       2.20    0.029

S = 2.218       R-Sq = 86.2%     R-Sq(adj) = 85.0%

Analysis of Variance
Source            DF          SS          MS         F        P
Regression        25     9003.26      360.13     73.21    0.000
Residual Error   294     1446.23        4.92
Total            319    10449.50
```

The performance of the above regression model in charted in Figure 5.10. This graph shows the fitted values derived from the model in comparisons with the actual results from the first replication. As shown in the figure the model fairly adequately predicts the pull strength when the values from each standard order treatment are plugged into the mathematical model developed.

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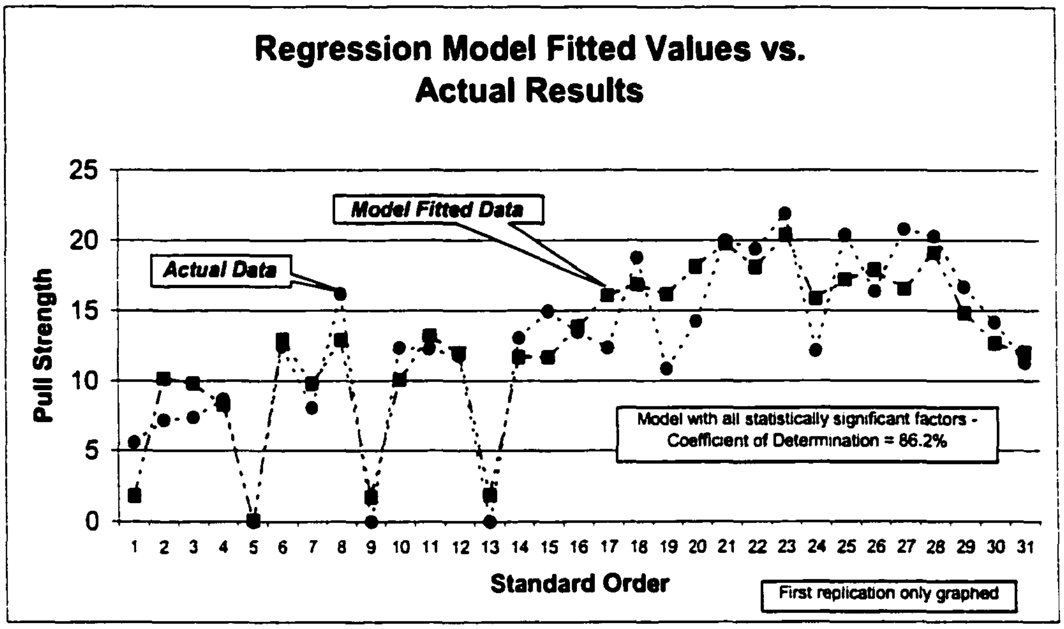
Figure 5.10 – Regression Model vs. Actual Results – Pull Strength



The above analysis resulted in a mathematical model of the process that was used in with 25 terms. The mathematical model (model #1) developed is listed in eqn. (5.1).

eqn. (5.1)

$$\begin{gathered}f_1(\underline{x}) = \text{pull strength(lbs)} = -103+12.0*T+49.9*V-0.591*U-1.08*C+3.44*F-5.83*T*V-\\0.354*T*F+0.638*V*C-1.46*V*F+0.0511*U*C+0.0130*U*F+0.0372*C*F+\\0.0477*T*V*U+0.176*T*V*F-0.00260*T*U*C+0.00161*T*U*F-0.00046*T*C*F-\\0.0150*V*U*C+0.00619*V*U*F-0.0211*V*C*F-0.00110*U*C*F+\\0.00045*T*V*U*C-0.00265*T*V*U*F+0.000275*T*V*C*F+0.000031*T*V*U*C*F\end{gathered}$$

Where:

T is weld time in msec
V is weld voltage in volts
C is cooling time in msec
U is upslope in percentage
F is force in lbs.

A complete residual analysis was performed to check the validity of the model assumptions. The model was checked to ensure the validity of the following assumptions; randomness (well dispersed residuals), constant variance, independence, normality and an overall well behaved distribution. However, the analysis was not reported in this dissertation due to the fact that the results of the model were to be used for

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direction into further models. The number of terms in the model (even at 25 terms) and the significance of higher order interaction effects led to the consideration of a higher order non-linear model to describe pull strength. The number of terms could pose an unnecessary computational hurdle in comparison with a more efficient model. The underlying goal was to developed a simpler model that what be able to perform as well as the existing model #1.

The design was then analyzed with respect to percent of insulation remaining. The analysis of variation (ANOVA) table in Figure 5.11 outlined that the main effects were statistically significant from the F-test ($p=0.000$ which is < 0.05). The analysis also outlined that the sets of interaction effects were statistically significant from the F-test (p=value which is < 0.05). The analysis reported that all main effect factors except for upslope were statistically significant from the t-test.

The analysis resulted in a mathematical model of the process with 23 terms. With respect to the individual terms of the model there were four main effects that were statistically significant, seven 2-way interaction effects significant, eight 3-way interaction effects significant, three 4-way interaction effects and one 5-way interaction effects significant. As in the case of the pull strength, the results did made logical sense except it was anticipated that some of the order interaction effects were not truly statistically significant. Again as in the case of the pull strength, because of issues associated with the higher effects being statistically significant the validity of the model was in question. Initially, it was anticipated that the higher order effects were incorrectly outlined as being statistically significant in order to explain some second order non-linearity in the first order model assumption and from the cross correlation of the terms. This analysis was used however to provide directional information in developing an accurate mathematical model. In order to predict the performance of the model for comparison purposes, a linear regression analysis were performed with 22 statistically significant terms.

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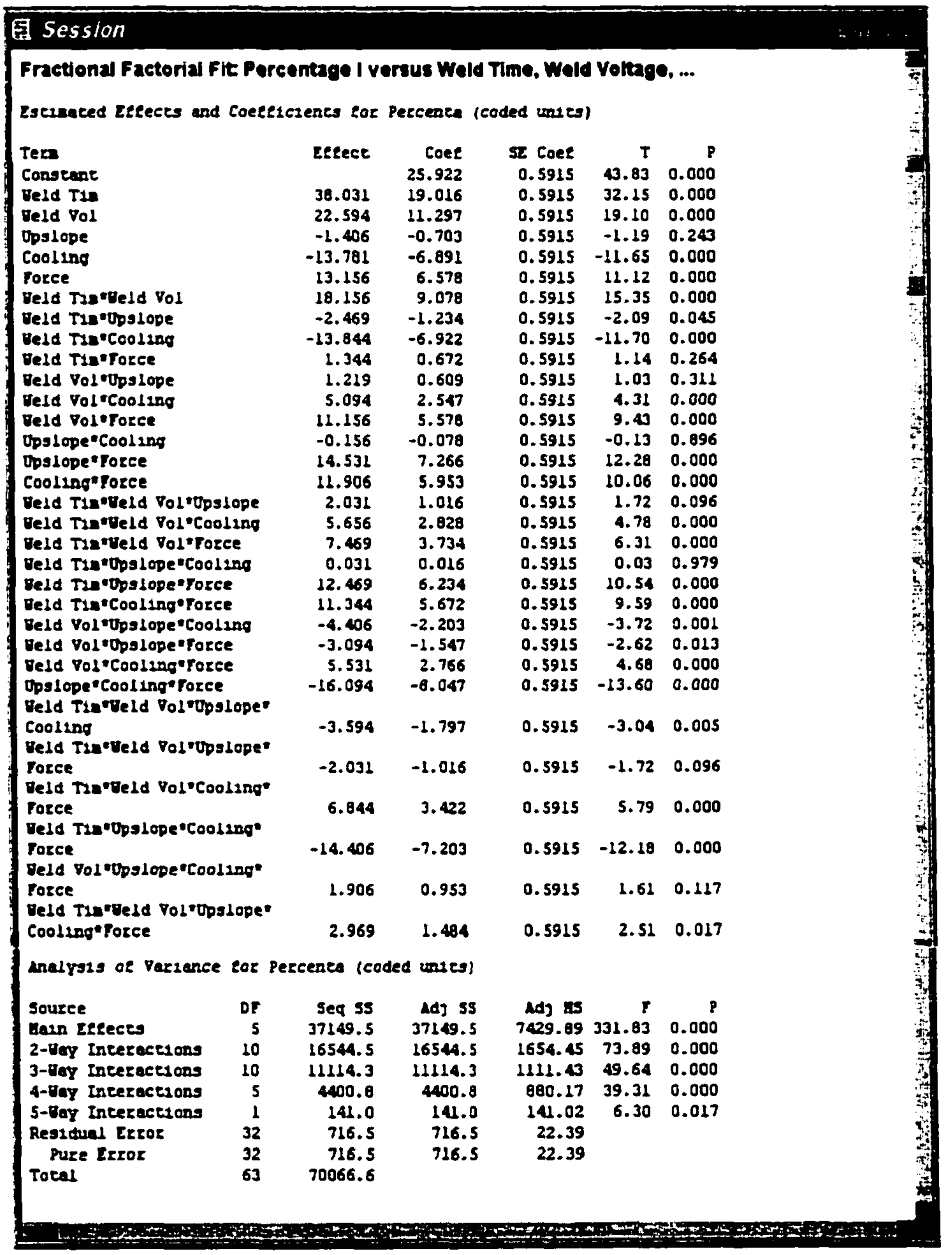
Figure 5.11 - Initial Design Analysis Results – Percent Insulation Remaining



```
Fractional Factorial Fit: Percentage I versus Weld Time, Weld Voltage, ...

Estimated Effects and Coefficients for Percenta (coded units)

Term                          Effect     Coef   SE Coef       T      P
Constant                              25.922    0.5915   43.83  0.000
Weld Tim                      38.031  19.016    0.5915   32.15  0.000
Weld Vol                      22.594  11.297    0.5915   19.10  0.000
Upslope                       -1.406  -0.703    0.5915   -1.19  0.243
Cooling                      -13.781  -6.891    0.5915  -11.65  0.000
Force                         13.156   6.578    0.5915   11.12  0.000
Weld Tim*Weld Vol             18.156   9.078    0.5915   15.35  0.000
Weld Tim*Upslope              -2.469  -1.234    0.5915   -2.09  0.045
Weld Tim*Cooling             -13.844  -6.922    0.5915  -11.70  0.000
Weld Tim*Force                 1.344   0.672    0.5915    1.14  0.264
Weld Vol*Upslope               1.219   0.609    0.5915    1.03  0.311
Weld Vol*Cooling               5.094   2.547    0.5915    4.31  0.000
Weld Vol*Force                11.156   5.578    0.5915    9.43  0.000
Upslope*Cooling               -0.156  -0.078    0.5915   -0.13  0.896
Upslope*Force                 14.531   7.266    0.5915   12.28  0.000
Cooling*Force                 11.906   5.953    0.5915   10.06  0.000
Weld Tim*Weld Vol*Upslope      2.031   1.016    0.5915    1.72  0.096
Weld Tim*Weld Vol*Cooling      5.656   2.828    0.5915    4.78  0.000
Weld Tim*Weld Vol*Force        7.469   3.734    0.5915    6.31  0.000
Weld Tim*Upslope*Cooling       0.031   0.016    0.5915    0.03  0.979
Weld Tim*Upslope*Force        12.469   6.234    0.5915   10.54  0.000
Weld Tim*Cooling*Force        11.344   5.672    0.5915    9.59  0.000
Weld Vol*Upslope*Cooling      -4.406  -2.203    0.5915   -3.72  0.001
Weld Vol*Upslope*Force        -3.094  -1.547    0.5915   -2.62  0.013
Weld Vol*Cooling*Force         5.531   2.766    0.5915    4.68  0.000
Upslope*Cooling*Force        -16.094  -8.047    0.5915  -13.60  0.000
Weld Tim*Weld Vol*Upslope*
Cooling                       -3.594  -1.797    0.5915   -3.04  0.005
Weld Tim*Weld Vol*Upslope*
Force                         -2.031  -1.016    0.5915   -1.72  0.096
Weld Tim*Weld Vol*Cooling*
Force                          6.844   3.422    0.5915    5.79  0.000
Weld Tim*Upslope*Cooling*
Force                        -14.406  -7.203    0.5915  -12.18  0.000
Weld Vol*Upslope*Cooling*
Force                          1.906   0.953    0.5915    1.61  0.117
Weld Tim*Weld Vol*Upslope*
Cooling*Force                  2.969   1.484    0.5915    2.51  0.017

Analysis of Variance for Percenta (coded units)

Source                DF    Seq SS    Adj SS    Adj MS       F      P
Main Effects           5   37149.5   37149.5   7429.89  331.83  0.000
2-Way Interactions    10   16544.5   16544.5   1654.45   73.89  0.000
3-Way Interactions    10   11114.3   11114.3   1111.43   49.64  0.000
4-Way Interactions     5    4400.8    4400.8    880.17   39.31  0.000
5-Way Interactions     1     141.0     141.0    141.02    6.30  0.017
Residual Error        32     716.5     716.5     22.39
  Pure Error          32     716.5     716.5     22.39
Total                 63   70066.6
```

The analysis of variation (ANOVA) table from the regression is shown in Figure 5.12. This analysis mirrored the results from the DOE and that the model was statistically significant from the F-test (p=0.000 which is < 0.05). The analysis also outlined that potentially five additional effects could be dropped from the analysis based on the t-test, with no significant degradation in performance of the model. The model also demonstrated a good fit as indicated by the coefficient of determination, R^2 = 95.2% and R^2 (adjusted)

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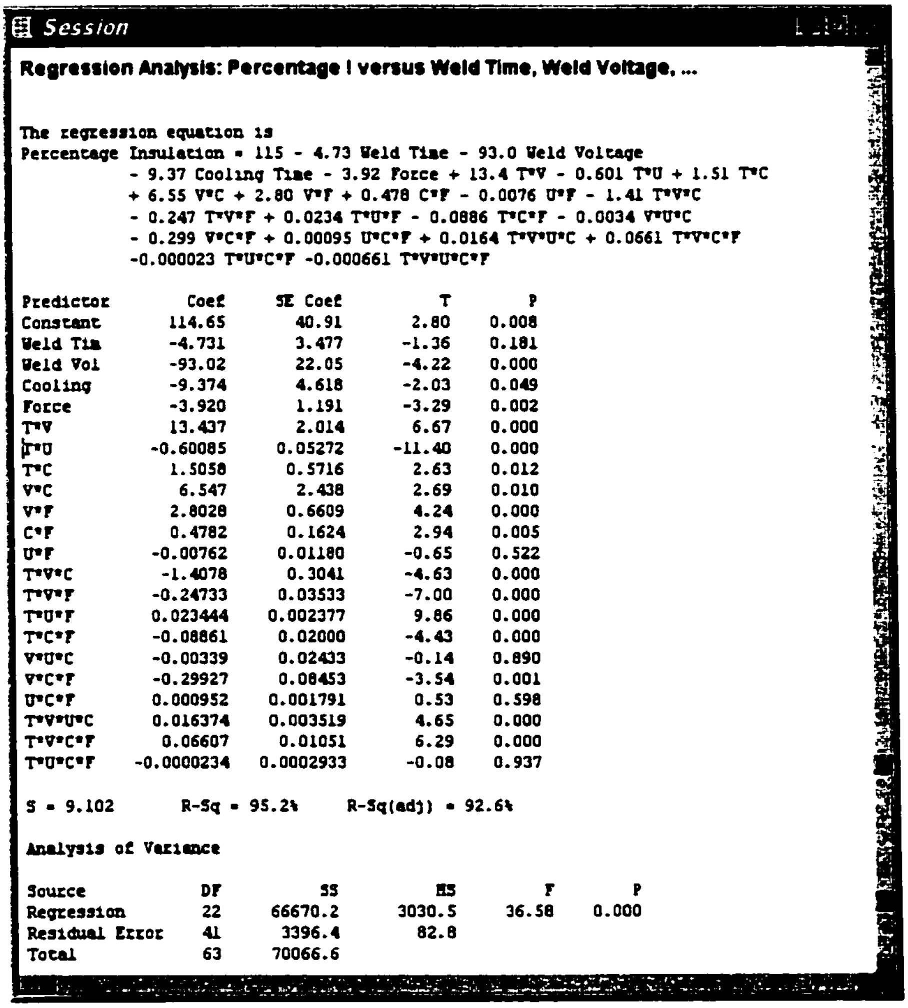
= 92.6%. In addition, the model may be over specified as indicated by the difference between R^2 and R^2 (adjusted) and the fact that five interaction effects were not statistically significant. This difference was larger then in the case with the pull strength regression however it was small enough to retain the five terms in the model.

Figure 5.12 –Regression Analysis – Percent Insulation Removed



Regression Analysis: Percentage I versus Weld Time, Weld Voltage, ...

```
The regression equation is
Percentage Insulation = 115 - 4.73 Weld Time - 93.0 Weld Voltage
           - 9.37 Cooling Time - 3.92 Force + 13.4 T*V - 0.601 T*U + 1.51 T*C
           + 6.55 V*C + 2.80 V*F + 0.478 C*F - 0.0076 U*F - 1.41 T*V*C
           - 0.247 T*V*F + 0.0234 T*U*F - 0.0886 T*C*F - 0.0034 V*U*C
           - 0.299 V*C*F + 0.00095 U*C*F + 0.0164 T*V*U*C + 0.0661 T*V*C*F
           -0.000023 T*U*C*F -0.000661 T*V*U*C*F

Predictor        Coef      SE Coef          T        P
Constant       114.65        40.91       2.80    0.008
Weld Tim       -4.731        3.477      -1.36    0.181
Weld Vol       -93.02        22.05      -4.22    0.000
Cooling        -9.374        4.618      -2.03    0.049
Force          -3.920        1.191      -3.29    0.002
T*V            13.437        2.014       6.67    0.000
T*U          -0.60085      0.05272     -11.40    0.000
T*C            1.5058       0.5716       2.63    0.012
V*C             6.547        2.438       2.69    0.010
V*F            2.8028       0.6609       4.24    0.000
C*F            0.4782       0.1624       2.94    0.005
U*F          -0.00762      0.01180      -0.65    0.522
T*V*C         -1.4078       0.3041      -4.63    0.000
T*V*F        -0.24733      0.03533      -7.00    0.000
T*U*F        0.023444     0.002377       9.86    0.000
T*C*F        -0.08861      0.02000      -4.43    0.000
V*U*C        -0.00339      0.02433      -0.14    0.890
V*C*F        -0.29927      0.08453      -3.54    0.001
U*C*F        0.000952     0.001791       0.53    0.598
T*V*U*C      0.016374     0.003519       4.65    0.000
T*V*C*F       0.06607      0.01051       6.29    0.000
T*U*C*F    -0.0000234    0.0002933      -0.08    0.937

S = 9.102       R-Sq = 95.2%     R-Sq(adj) = 92.6%

Analysis of Variance

Source            DF          SS          MS         F        P
Regression        22     66670.2      3030.5     36.58    0.000
Residual Error    41      3396.4        82.8
Total             63     70066.6
```

The performance of the above regression model in charted in Figure 5.13. This graph shows the fitted values derived from the model in comparisons with the actual results from the first replication. As shown in the figure the model fairly accurately predicts the percent insulation removed when the values from each standard order treatment is plugged into the mathematical model developed.

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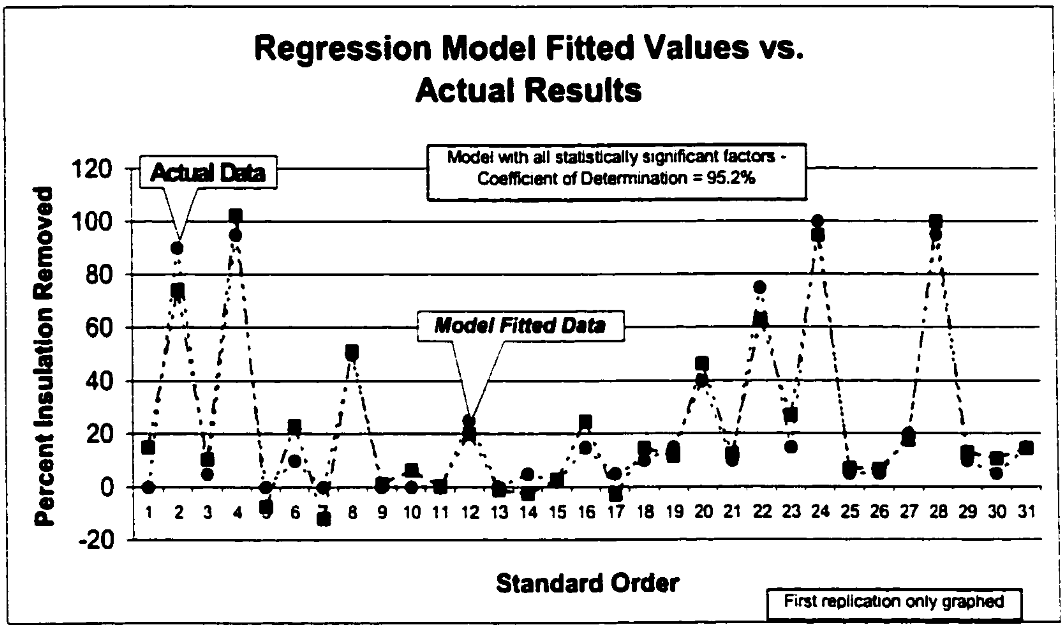
Figure 5.13 –Regression Model vs. Actual Results – Percent Insulation Removed



The above analysis resulted in a mathematical model of the process that was used in with 22 terms. The mathematical model (model #1) developed is listed in eqn. (5.1).

eqn. (5.2)

$$f_2(\underline{x}) = \text{percent insulation removed}(\%) = 115-4.73*T-93.0*V-9.37*C-3.92*F+13.4*T*V-0.601*T*U+1.51*T*C+6.55*V*C+2.8*V*F+0.478*C*F-0.0076*U*F-1.41*T*V*C-0.247*T*V*F+0.0234*T*U*F-0.0886*T*C*F-0.0034*V*U*C-0.299*V*C*F+0.00095*U*C*F+0.0164*T*V*U*C+0.0661*T*V*C*F-0.000023*T*U*C*F-0.000661*T*V*U*C*F$$

Where:

T is weld time in msec
V is weld voltage in volts
C is cooling time in msec
U is upslope in percentage
F is force in lbs.

A complete residual analysis was again performed to check the validity of the model assumptions. The model was checked to ensure the validity of the following assumptions; randomness (well dispersed

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residuals), constant variance, independence, normality and overall well behave distribution. However, the analysis was not reported in this dissertation due to the fact that the results of the model were to be used only for direction. The number of terms in the model (even at 10) and the significance of higher interaction effects led to the consideration of a second order non-linear model to describe percent insulation removed.

5.5 Central Composite Design I

As stated above the issues associated with model #1 led to the investigation into a second order non-linear mathematical model for both the pull strength and percent of insulation removed response variables. The new model was anticipated to be more computationally efficient through fewer terms and an overall better representation of the process. The new model was also developed to evaluate the true statistical significance of the higher interaction effects. In order to develop the new model it was decided that a central composite designed experiment would be developed and analyzed. Per Ramsier (1999) the central composite design is a widely used design for fitting second-order models. Ramsier (1999) also adds that the design consists of a 2^k factorial augmented by $2*k$ axial points as well as a center point. The distance of the axial points from the center point is ideally $(2k)^{1/4}$ where k is the number of factors. The additional axial points placed at optimal distance provide the benefit of augmenting the basic 2^k factorial design while maintaining the rotatability property of the design. This property allows for more uniform precision in model estimation.

The initial DOE provided insight in the central composite design developed for this process. Based on the results from the initial DOE it was decided to not include upslope as a factor in the next level of experimentation. Upslope was marginally statistically significant with respect to pull strength and was not significant with respect to percent insulation removed. Therefore the remaining factors were weld voltage, weld time, cooling time and weld force. This design was a 2^4 full factorial design with an optimal distance for the axial points from the center points equal to 2 (alpha=2). There were a total of $2^4=16$ treatments augmented by 8 axial points with 7 center points for a total of 31 runs. The factor levels were also adjusted in the central composite design to ensure that the axial point settings were capable values see Table 5.8. As

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stated above the same assessment method (response variables) were selected for the experiment.

Central Composite DOE Factors – Table 5.8

	Factor	*Lower Level (-1)*	*Higher Level (+1)*
A	Weld Voltage	1.6 volts	2.2 volts
B	Weld Time	4 msec	10 msec
C	Cooling Time	10 msec	20 msec
D	Weld Force	17.5 lbs (7.94kg)	35lbs (15.88kg)

The design represented a full resolution design meaning that effects were not confounded. This allowed for any statistically significant effects involving any main or interaction effect to be assigned only to that effect. Since the design was full resolution there was no defining relation or alias structure. The experiment had only one block run and no replications or repetitions for percentage of insulation and pull strength.

The standard order, treatments and the each joint quality assessment method (response variable) values for the entire run is shown in Table 5.9. The data matrix from the central composite 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 evaluated by pull testing the sample and determining the percent of insulation remaining. The experiment was first run as a full quadratic including all linear terms, interaction terms through 2-way, and all squared terms. The experimental results were then analyzed to draw conclusions.

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Table 5.9 – Central Composite Design Data Matrix

Std. Order	Weld Voltage	Weld Time	Cooling Time	Force	Point Type	Local Max Force	% Ins Removed
1	1.6	4	10	17.5	Factorial	7	0
2	2.2	4	10	17.5	Factorial	7.8	2
3	1.6	10	10	17.5	Factorial	8.4	5
4	2.2	10	10	17.5	Factorial	9.95	20
5	1.6	4	20	17.5	Factorial	6.3	0
6	2.2	4	20	17.5	Factorial	8.4	10
7	1.6	10	20	17.5	Factorial	7.45	17
8	2.2	10	20	17.5	Factorial	10.4	30
9	1.6	4	10	35	Factorial	10.85	5
10	2.2	4	10	35	Factorial	11.9	10
11	1.6	10	10	35	Factorial	9.25	15
12	2.2	10	10	35	Factorial	8.95	90
13	1.6	4	20	35	Factorial	10.25	10
14	2.2	4	20	35	Factorial	11.55	20
15	1.6	10	20	35	Factorial	10.4	25
16	2.2	10	20	35	Factorial	10.9	95
17	1.3	7	15	26.25	Axial	8.75	15
18	2.5	7	15	26.25	Axial	10.5	75
19	1.9	1	15	26.25	Axial	8.3	18
20	1.9	13	15	26.25	Axial	11.3	85
21	1.9	7	5	26.25	Axial	10.75	50
22	1.9	7	25	26.25	Axial	10.9	15
23	1.9	7	15	8.75	Axial	9.1	5
24	1.9	7	15	43.75	Axial	12.2	10
25	1.9	7	15	26.25	Center	9.95	18
26	1.9	7	15	26.25	Center	10.85	15
27	1.9	7	15	26.25	Center	9.6	18
28	1.9	7	15	26.25	Center	11.75	20
29	1.9	7	15	26.25	Center	10.25	18
30	1.9	7	15	26.25	Center	13	15
31	1.9	7	15	26.25	Center	10.25	15

A significant level of 5% (alpha=0.05) was used again to determine statistical significance. Statistical significance was interpreted throughout the analysis as being important in being able to predict the pull strength or percent of insulation remaining (depending on the response variable considered). The design was first analyzed with respect to pull strength of the weld (local maximum force). The analysis of variation (ANOVA) table in Figure 5.14 outlined that the model developed was significant from the F-test (p=0.008 which is < 0.05) and main effects were statistically significant from the F-test (p=0.049 which is

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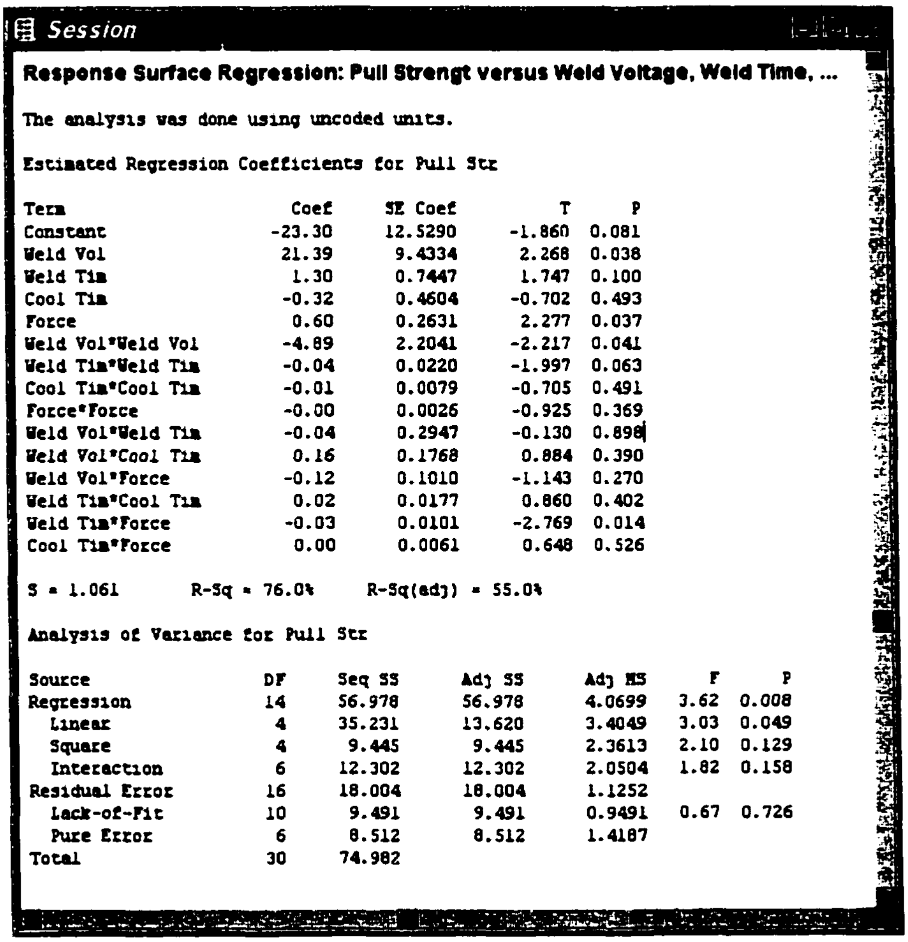
< 0.05). The main effects that were determined to be significant from the t-tests were weld voltage (p=0.038 which is < 0.05) and force (p=0.037 which is <.05). The ANOVA table also outlined that sets through 2-way interaction effects and the squared effects were not statistically significant from the F-test but weld voltage squared and weld time * force (both p=0.041 which is < 0.05) showed as being statistically significant from the t-test.

Figure 5.14 – Central Composite Design – Pull Strength



```
Response Surface Regression: Pull Strengt versus Weld Voltage, Weld Time, ...

The analysis was done using uncoded units.

Estimated Regression Coefficients for Pull Str

Term                     Coef   SE Coef        T      P
Constant               -23.30   12.5290   -1.860  0.081
Weld Vol                21.39    9.4334    2.268  0.038
Weld Tim                 1.30    0.7447    1.747  0.100
Cool Tim                -0.32    0.4604   -0.702  0.493
Force                    0.60    0.2631    2.277  0.037
Weld Vol*Weld Vol       -4.89    2.2041   -2.217  0.041
Weld Tim*Weld Tim       -0.04    0.0220   -1.997  0.063
Cool Tim*Cool Tim       -0.01    0.0079   -0.705  0.491
Force*Force             -0.00    0.0026   -0.925  0.369
Weld Vol*Weld Tim       -0.04    0.2947   -0.130  0.898
Weld Vol*Cool Tim        0.16    0.1768    0.884  0.390
Weld Vol*Force          -0.12    0.1010   -1.143  0.270
Weld Tim*Cool Tim        0.02    0.0177    0.860  0.402
Weld Tim*Force          -0.03    0.0101   -2.769  0.014
Cool Tim*Force           0.00    0.0061    0.648  0.526

S = 1.061      R-Sq = 76.0%    R-Sq(adj) = 55.0%

Analysis of Variance for Pull Str

Source            DF   Seq SS   Adj SS   Adj MS     F      P
Regression        14   56.978   56.978   4.0699  3.62  0.008
  Linear           4   35.231   13.620   3.4049  3.03  0.049
  Square           4    9.445    9.445   2.3613  2.10  0.129
  Interaction      6   12.302   12.302   2.0504  1.82  0.158
Residual Error    16   18.004   18.004   1.1252
  Lack-of-Fit     10    9.491    9.491   0.9491  0.67  0.726
  Pure Error       6    8.512    8.512   1.4187
Total             30   74.982
```

In order to obtain an understanding of the importance in each set of terms the above response surface analysis was re-run with a combination of sets of terms as shown in Table 5.10. The table showed that each set of terms as a group had a significant impact on the performance of the model. One pitfall in performing the response surface analysis however was that the interaction terms only included through 2-way interactions. This was a disadvantage since model #1 had suggested that the higher interaction effects were statistically significant. Also included in the table are the corresponding regression F-values for each

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analysis performed. As outlined by Vining (1998) the F-value is defined as the mean square error of the regression divided by the mean square error of the residuals. This value was compared to the critical F-value taken from the F-distribution based on the number of degrees of freedom in the regression, number of degrees of freedom in total and significant level (alpha) for each analysis. Statistical significance was defined as any case in which the regression F-value is greater than the critical F-value. This F-test is an indication of statistical significance and it takes into consideration the error in the regression versus the residuals as well as the degrees of freedom, as does the p-value. In each case the results mirrored the results reported above based on the p-value.

Table 5.10 – RS Analysis Performance Per Groups of Terms – Pull Strength

	Terms Included in Analysis			
	Full Quadratic	**Linear & Interaction**	**Linear & Squared**	**Linear**
Number of terms	4	1	1	2
R^2	76.0%	63.4%	59.6%	47.0%
R^2 (adjusted)	55.0%	45.1%	44.9%	38.8%
R^2 different	21.0%	18.3%	14.7%	8.2%
Reduction in R^2	0.0%	12.6%	16.4%	12.6%
Regression F-value	3.62	3.46	4.05	5.76
Regression p-value	0.008	0.009	0.004	0.002
F(critical)	2.03	2.16	2.27	2.69

The above analysis resulted in a second order non-linear mathematical model of the process with 4 terms. The mathematical model (model #2) developed is listed in eqn. (5.3).

eqn. (5.3) pull strength(lbs) = -23.30+21.39*weld voltage(volts)+0.60*force(lbs)-4.89*weld voltage^2(volts^2)-0.03*weld time(msec)*force(lbs)

The results did made logical sense and the model was simple however the performance was significantly worse than model #1. The analysis of variation (ANOVA) table from the analysis shown in Figure 5.14 listed a coefficient of determination, $R^2 = 76.0\%$ and R^2 (adjusted) = 55.0% in comparison with the R^2 = 86.2% from model #1. In addition, the model was over specified as analyzed above. There were a

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significant number of variables that could have been removed that were included in the analysis. This lower performance on fit of the model was hypothesized to be caused by the elimination of the marginally significant factor in model #1, upslope and by interaction effects higher than 2-way that were not included. Another potential area for error was experimental noise. Model #1 was developed, as reported above, with 10 replications. A complete residual analysis was performed to check the validity of the model assumptions. The model was checked to ensure the validity of the following assumptions; randomness (well dispersed residuals), constant variance, independence, normality and overall well behaved distribution.

To verify the constant variance assumption a plot of the residuals versus the fitted values and each of the regressors was performed as shown in Figure 5.15. The plot of the residuals versus the fitted values and of each regressor (weld voltage – Figure 5.16, weld force – Figure 5.17, voltage^2 - Figure 5.18, weld time * force – Figure 5.19) showed some signs of non-constant variance. The plots of the residuals versus each of the regressors showed signs that the variance may have been high toward the middle of the fitted values.

Figure 5.15 – Residuals vs. Fitted Values – Pull Strength

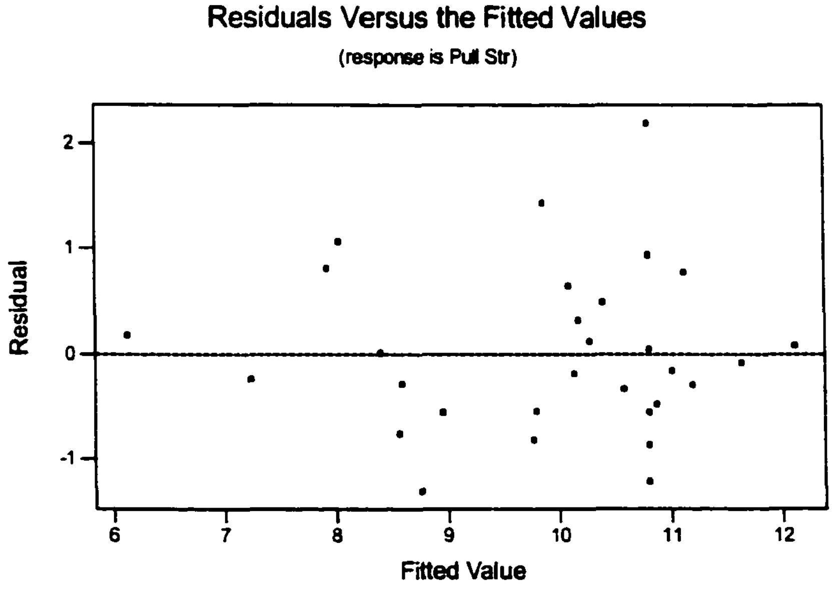

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Figure 5.16 – Residuals vs. Weld Voltage – Pull Strength

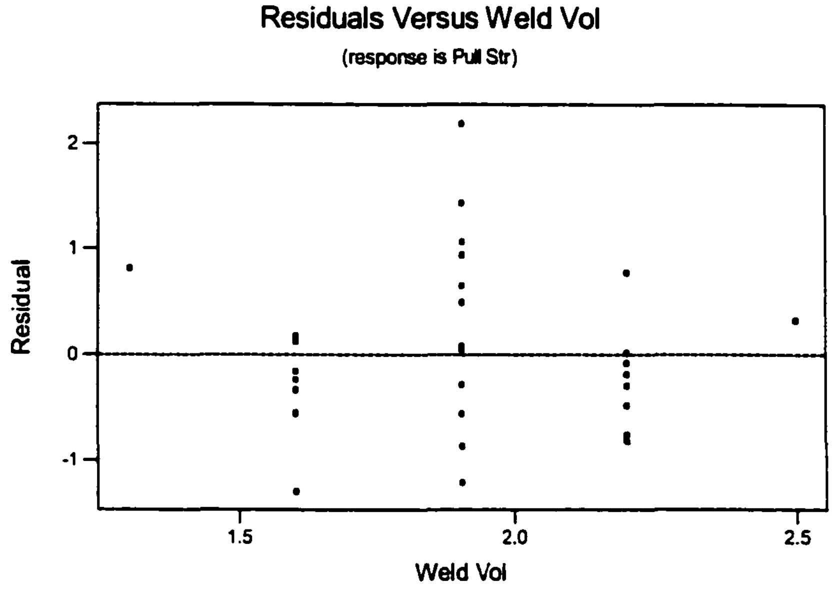

Figure 5.17 – Residuals vs. Weld Force – Pull Strength

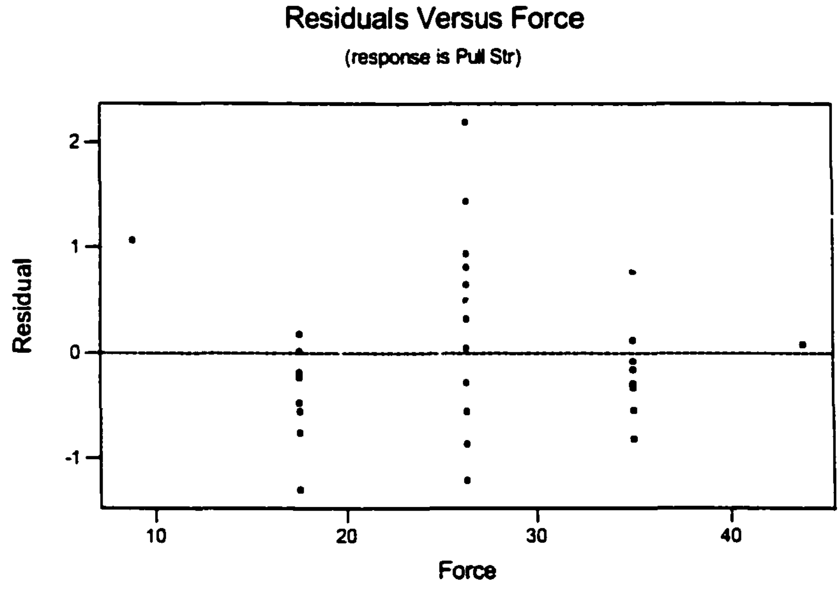

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Figure 5.18 – Residuals vs. Voltage^2 – Pull Strength

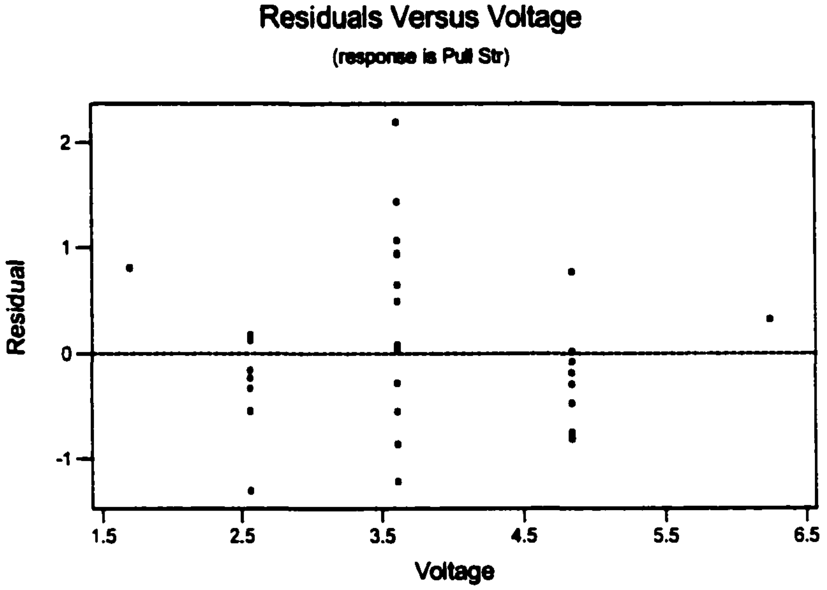
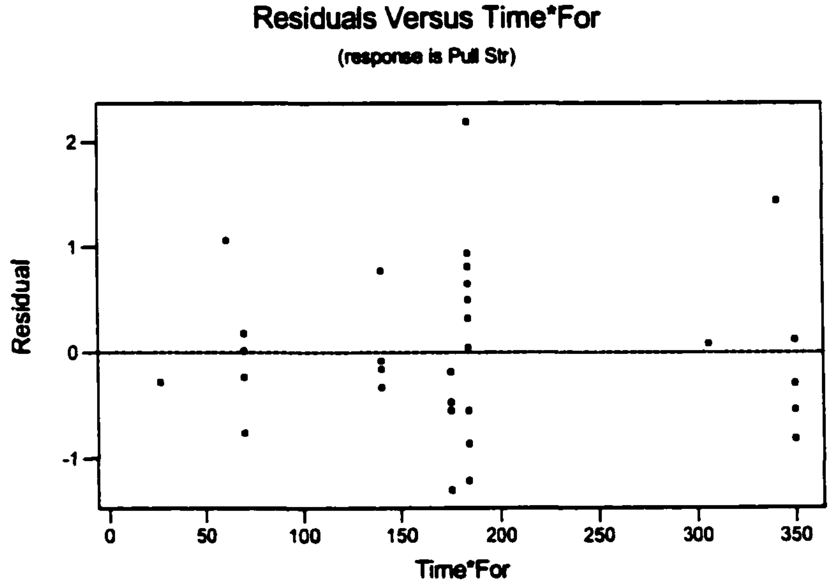


Figure 5.19 – Residuals vs. Weld Time * Force



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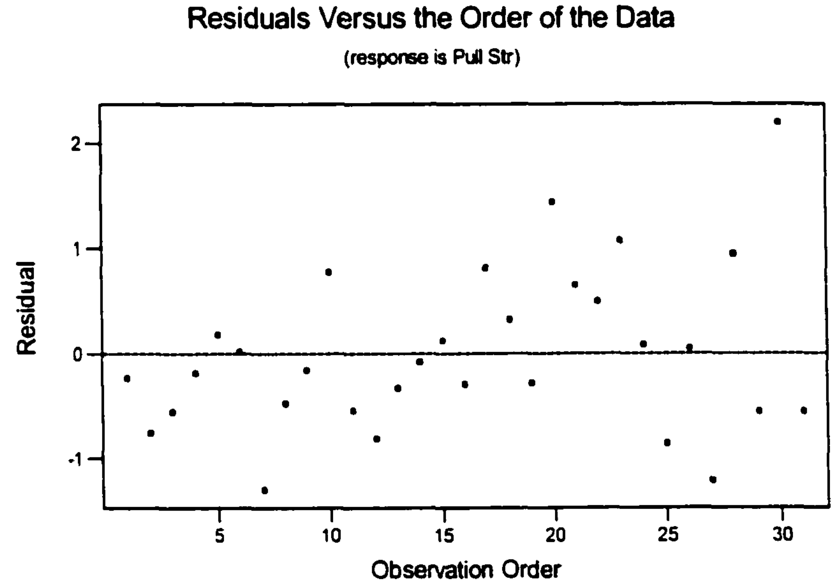
To verify the independence assumption a plot of the residuals versus the order of the data and was performed as shown in Figure 5.20. The plot of the residuals versus the order of the data showed a very slight sign of increasing residuals with increase observation order. However no other particular pattern existed and the points were well dispersed. The data was trending, slightly in a specific direction but it did not have any systematic effects. Since the issues were minimal, this plot substantiated the independence assumption.

Figure 5.20 – Residuals vs. Order – Pull Strength



To verify the residuals followed a well-behaved distribution a normal probability plot and a histogram of the residuals was performed as shown in Figure 5.21. The normal probability plot of the residual further confirmed that the residuals follow a normal distribution in Figure 5.22 by representing a straight line. The histogram plot showed that the residuals were normally distributed (bell-shaped) slightly skewed left. These two plots together illustrated that the residuals followed a well-behaved distribution.

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Figure 5.21 – Histogram – Pull Strength

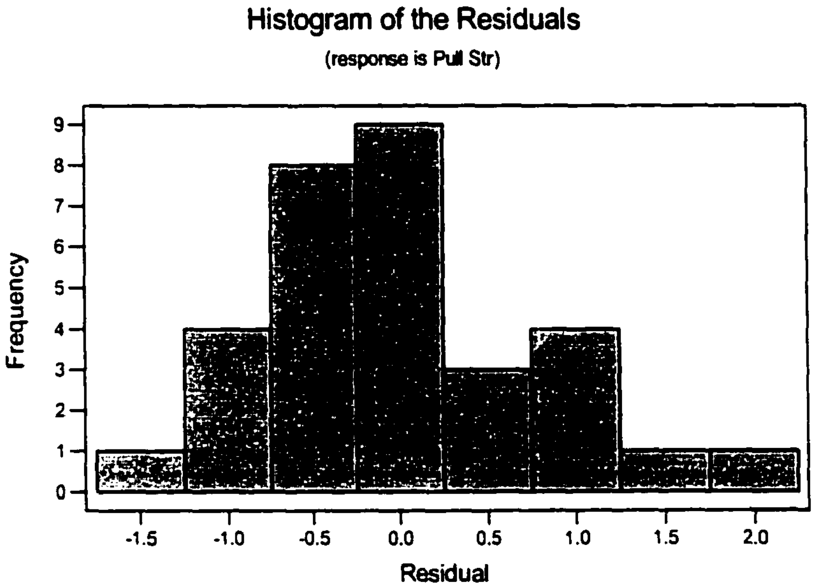
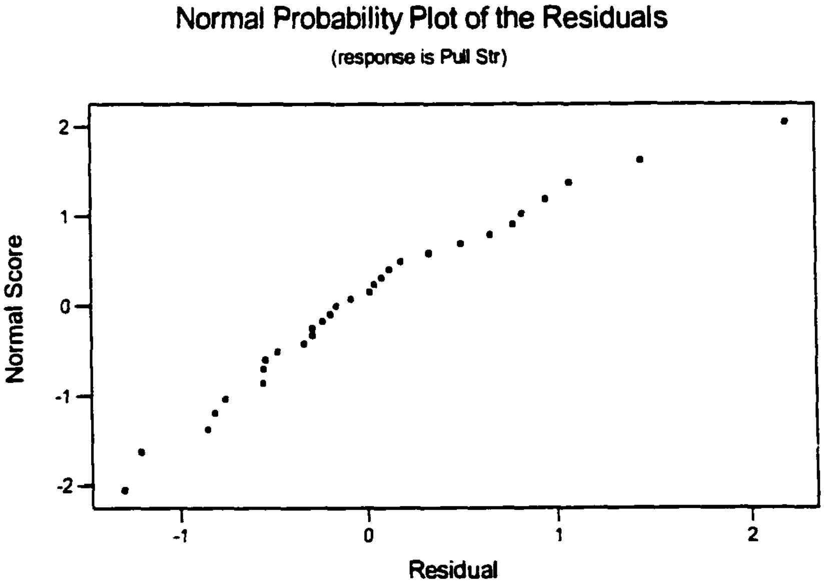


Figure 5.22 – Normal Probability Plot – Pull Strength



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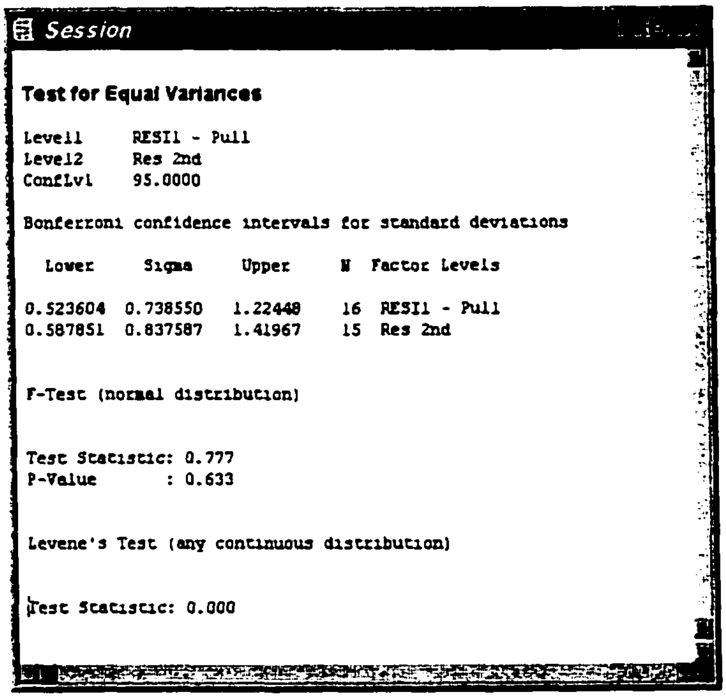
In order to determine if the non-constant variance reported above was significant a formal statistical test was performed. A Modified Levene Test was performed as described by Neter (1996) by analyzing the plots of the fitted values versus the residuals. A data matrix was created by ordering the residuals by increasing fitted values. This matrix was then divided into two distinct population samples. Since there were 31 runs the residuals for the first 16 fitted values were placed in the first population then the residuals for the last 15 fitted values were placed in the second population. These two populations were then analyzed to determine if the differences in their variances were statistically significant. A 5% significance level (alpha=0.05) was chosen to determine statistical significance. As shown in Figure 5.23 the difference in the variance was not statistically significant (p=0.997 which is > 0.05).

Figure 5.23 – Modified Levene Test



Test for Equal Variances

```
Level1     RESI1 - Pull
Level2     Res 2nd
ConfLvl    95.0000

Bonferroni confidence intervals for standard deviations

  Lower     Sigma     Upper     N  Factor Levels

0.523604  0.738550   1.22448    16  RESI1 - Pull
0.587851  0.837587   1.41967    15  Res 2nd


F-Test (normal distribution)


Test Statistic: 0.777
P-Value       : 0.633


Levene's Test (any continuous distribution)


Test Statistic: 0.000
```

The minimal difference between the residual populations is shown graphically in the box plot in Figure 5.24.

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Figure 5.24 – Modified Levene Box Plot

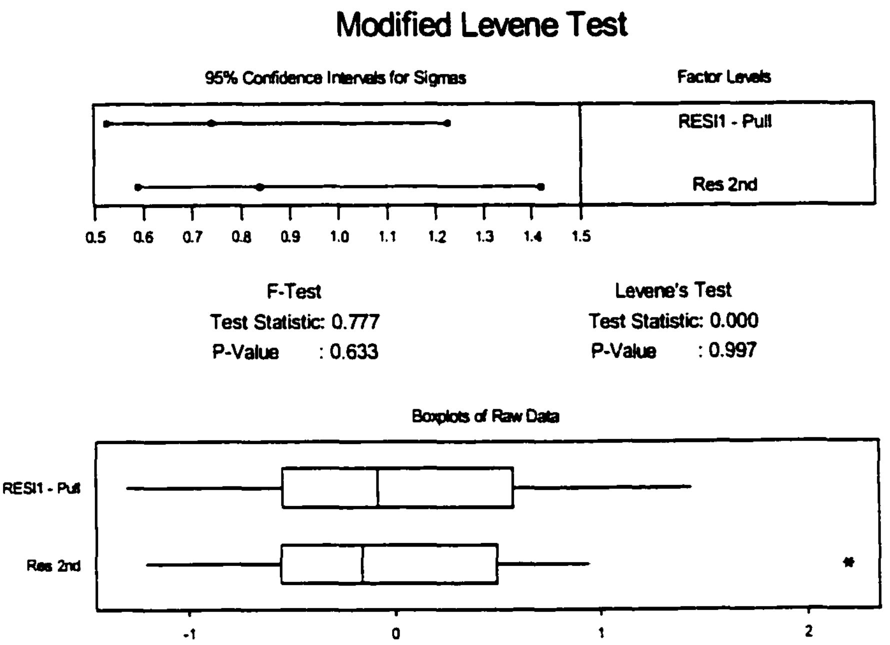
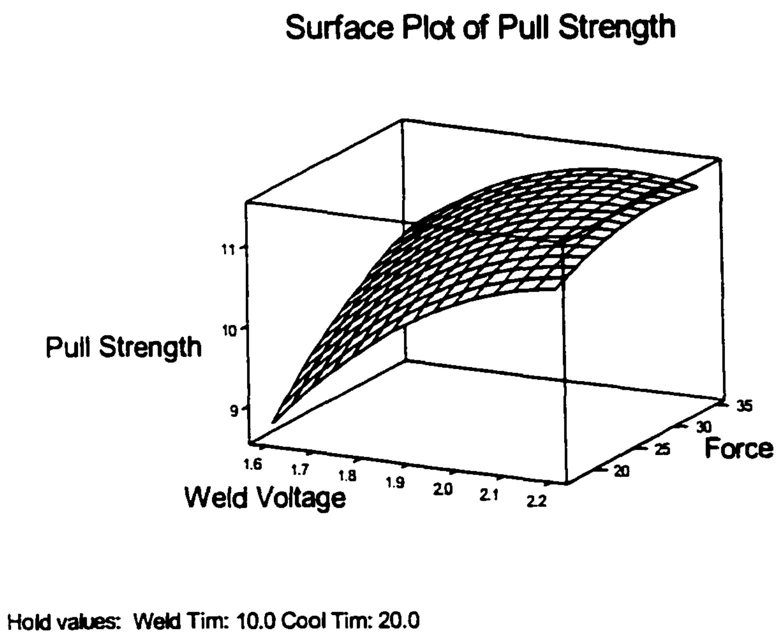


Figure 5.25 – Response Surface Plot – Pull Strength



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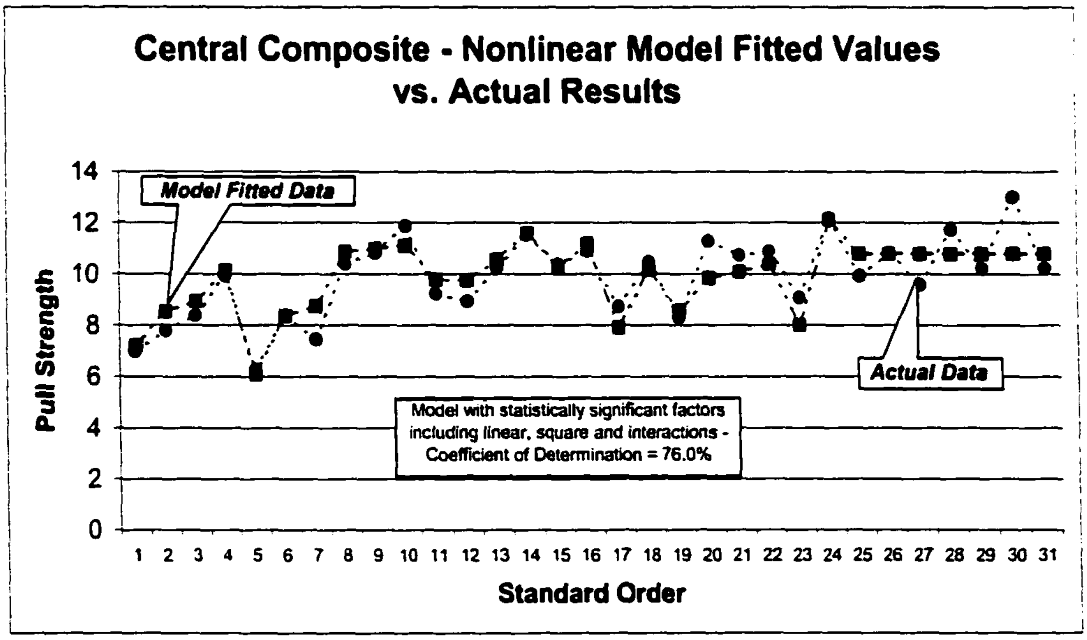
With the model assumptions verified, the performance was investigated further. The model confirmed the second order non-linear relationship that existed between some of the factors and the response variable. In the above analysis the primary significant factors in being able to predict pull strength were weld voltage and force. Figure 5.25 is a response surface plot that outlined the non-linear relationship between these variables. This figure and the model developed above indicated that the response variable pull strength is related to the square of the weld voltage. This makes intuitive sense in that the amount of voltage applied should have a large effect on the type and depth of bond created during the welding process.

The overall performance from the above central composite analysis and model #2 is charted in Figure 5.26. This graph shows the fitted values derived from the model in comparisons with the actual results from the entire run. As shown in the figure the model fairly adequately predicts the pull strength when the values for each standard order treatment are plugged into the mathematical model developed. The performance does degrade at the center points of the central composite design as indicated by standard order points 25-31.

Figure 5.26 – Non-linear Model vs. Actual Results – Pull Strength



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To explain the lower performance of the model in comparison with model #1 developed a series of regression analyses were performed. The regression analyses were performed with progressively removing sets of terms. The purpose of this analysis was to determine the impact of not including the 3 and 4-way interaction effects and from not including the main effect upslope. Table 5.11 shows the model performance with each group of terms respectively.

Table 5.11 - Regression Analysis Performance Per Groups of Terms – Pull Strength

	Terms				
	Full Quadratic Interactions through 4-Way	*Full Quadratic Interactions through 3-Way*	*Full Quadratic Interactions through 2-Way*	*Full Quadratic*	*Only Main Effects*
Number of Terms Statistically Significant	0	0	4	1	2
R^2	79.1%	79.1%	76.0%	59.6%	47.0%
R^2 (adjusted)	43.0%	47.7%	55.0%	44.9%	38.8%
R^2 different	36.1%	31.4%	21.0%	14.7%	8.2%
Reduction in R^2	0.0%	0.0%	3.1%	16.4%	29.0%
Regression F-value	2.19	2.52	3.62	4.05	5.76
Regression p-value	0.092	0.053	0.008	0.004	0.002
F(critical)	1.95	1.96	2.04	2.27	2.69

This analysis demonstrated that model #2 could be improved from an R^2 of 76.0% to 79.1% by the addition of 3-way effects. There was still a gap in performance in comparison with model #1 (R^2 of 86.2%) which was attributed to not including the main effect, upslope in the analysis and the potential of experimental noise. In addition, there were minimal number of terms that were statistically significant. This was caused by including all of the terms available in the analysis. While the purpose of the analysis was to determine the potential of the model, the additional insignificant terms hid the true significant terms. It was anticipated that when some of the insignificant terms were removed, the significant terms would become significant. Because of the issues listed above it was decided to re-run the central composite design of experiment for pull strength with upslope added as a factor and with two replications and to perform a progressive removal of insignificant terms find the best model available.

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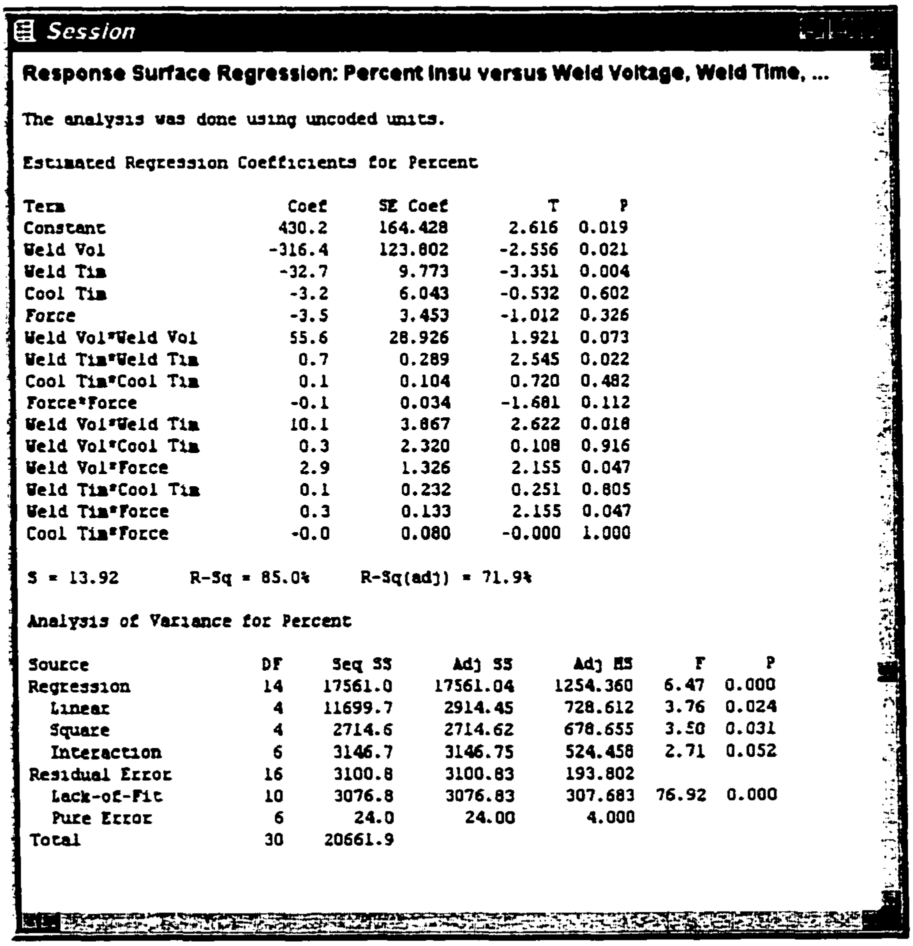
The design was then analyzed with respect to percent insulation removed. The analysis of variation (ANOVA) table in Figure 5.27 outlined that the model developed was significant from the F-test (p=0.000 which is < 0.05) and main effects were statistically significant from the F-test (p=0.024 which is < 0.05). The main effects that were determined to be significant from the t-tests were weld voltage (p=0.021 which is < 0.05) and time (p=0.004 which is <.05). The ANOVA table also outlined that sets of interaction effects through 2-way were not statistically significant form the F-test but weld voltage * time (p=0.018 which is < 0.05), weld voltage * force (p=0.047 which is <0.05) and time * force (p=0.047 which is < 0.05) were all statistically significant from the t-test. The squared effects were determined to be significant from the F-test (p=0.031 which is < 0.05), in particular time squared (p=0.022 which is < 0.05) from the t-test.

Figure 5.27 – Central Composite Design – Percent of Insulation Removed



Response Surface Regression: Percent Insu versus Weld Voltage, Weld Time, ...

```
The analysis was done using uncoded units.

Estimated Regression Coefficients for Percent

Term                      Coef   SE Coef        T      P
Constant                 430.2   164.428    2.616  0.019
Weld Vol                -316.4   123.802   -2.556  0.021
Weld Tim                 -32.7     9.773   -3.351  0.004
Cool Tim                  -3.2     6.043   -0.532  0.602
Force                     -3.5     3.453   -1.012  0.326
Weld Vol*Weld Vol         55.6    28.926    1.921  0.073
Weld Tim*Weld Tim          0.7     0.289    2.545  0.022
Cool Tim*Cool Tim          0.1     0.104    0.720  0.482
Force*Force               -0.1     0.034   -1.681  0.112
Weld Vol*Weld Tim         10.1     3.867    2.622  0.018
Weld Vol*Cool Tim          0.3     2.320    0.108  0.916
Weld Vol*Force             2.9     1.326    2.155  0.047
Weld Tim*Cool Tim          0.1     0.232    0.251  0.805
Weld Tim*Force             0.3     0.133    2.155  0.047
Cool Tim*Force            -0.0     0.080   -0.000  1.000

S = 13.92      R-Sq = 85.0%     R-Sq(adj) = 71.9%

Analysis of Variance for Percent

Source            DF    Seq SS     Adj SS     Adj MS      F      P
Regression        14   17561.0   17561.04   1254.360   6.47  0.000
  Linear           4   11699.7    2914.45    728.612   3.76  0.024
  Square           4    2714.6    2714.62    678.655   3.50  0.031
  Interaction      6    3146.7    3146.75    524.458   2.71  0.052
Residual Error    16    3100.8    3100.83    193.802
  Lack-of-Fit     10    3076.8    3076.83    307.683  76.92  0.000
  Pure Error       6      24.0      24.00      4.000
Total             30   20661.9
```

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In order to obtain an understanding of the importance in each set of terms the above response surface analysis was again re-run with a combination of sets of terms as shown in Table 5.12. The table showed that each set of terms as a group had a significant impact on the performance of the model. Not including higher than 2-way interaction effects again impaired the performance of the models.

Table 5.12 – RS Analysis Performance Per Groups of Terms – Percent Insulation Removed

	Terms Included in Analysis			
	Full Quadratic	**Linear & Interaction**	**Linear & Squared**	**Linear**
Number of terms	4	1	0	2
R^2	85.0%	71.9%	69.8%	56.6%
R^2 (adjusted)	71.6%	57.0%	58.8%	50.0%
R^2 different	13.4%	14.9%	11.0%	6.6%
Reduction in R^2	0.0%	13.1%	2.1%	15.3%
Regression F-value	6.47	5.11	6.34	8.49
Regression p-value	0.000	0.001	0.000	0.000
F(critical)	2.04	2.16	2.27	2.69

The analysis resulted in a second order non-linear mathematical model of the process with 6 terms. The mathematical model (model #2) developed is listed in eqn. (5.4).

eqn. (5.4) percent insulation removed(%) = 430.2-316.4•weld voltage(volts)-32.7•time(msec)+0.7•time^2(msec^2)+10.1•weld voltage(volts)•time(msec)+2.9•weld voltage(volts)•force(lbs)+0.3•time(msec)•force(lbs)

The results did made logical sense and the model was simple however the performance was worse than model #1. The analysis of variation (ANOVA) table from the analysis shown in Figure 5.27 listed a coefficient of determination, R^2 = 85.0% and R^2 (adjusted) = 71.9% in comparison with the R^2 = 95.2% from model #1. In addition, the model was over specified as analyzed above. There were a significant number of variables that could have been removed but were included in the analysis. As in the case with pull strength, this lower performance on fit of the model was hypothesized to be caused by the elimination of the marginally significant factor in the linear model, upslope and from not including the higher interaction effects.

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A complete residual analysis was again performed to check the validity of the model assumptions. The model was checked to ensure the validity of the following assumptions; randomness (well dispersed residuals), constant variance, independence, normality and overall well behave distribution.

To verify the constant variance assumption a plot of the residuals versus the fitted values and each of the regressors was performed as shown in Figure 5.28. The plot of the residuals versus the fitted values and of each regressor (weld voltage – Figure 5.29, weld time – Figure 5.30, time^2 - Figure 5.31, weld time * force – Figure 5.32, weld voltage * force - Figure 5.33, weld voltage * time – Figure 5.34) showed some signs of non-constant variance. No evidence of deviation from a constant variance is observed.

Figure 5.28 – Residuals vs. Fitted Values – Percent Insulation Removed

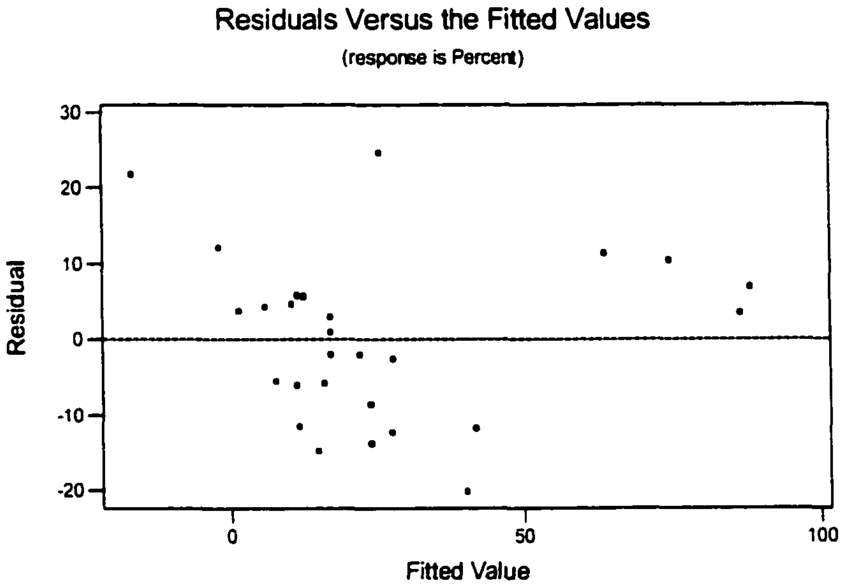

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Figure 5.29 – Residuals vs. Weld Voltage – Percent Insulation Removed

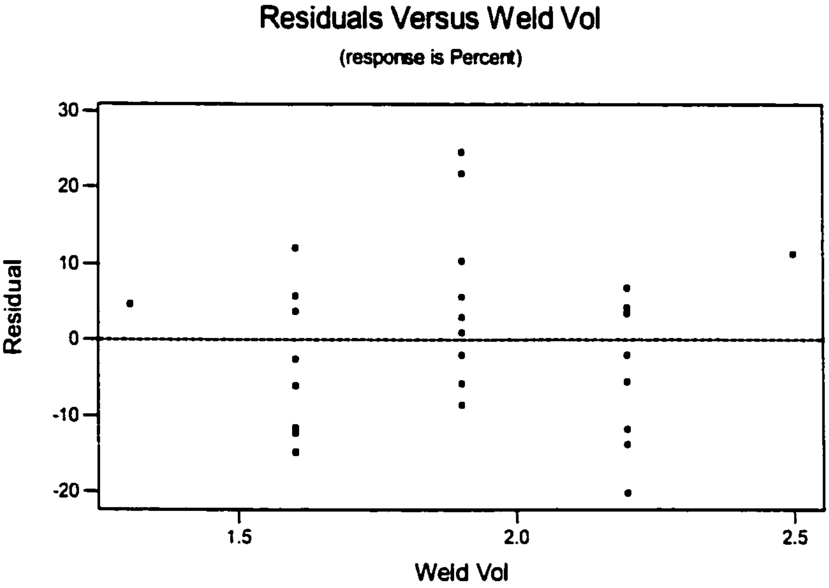

Figure 5.30 – Residuals vs. Weld Time – Percent Insulation Removed

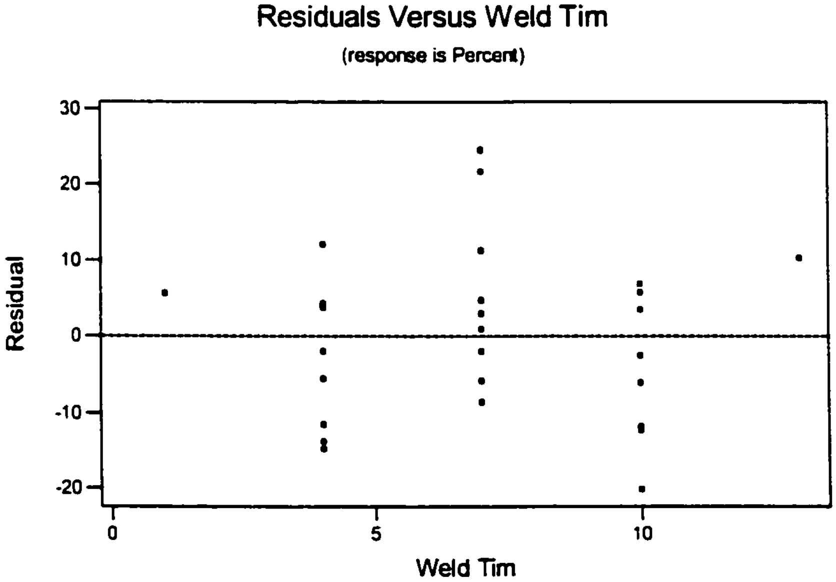

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Figure 5.31 – Residuals vs. Time^2 – Percent Insulation Removed

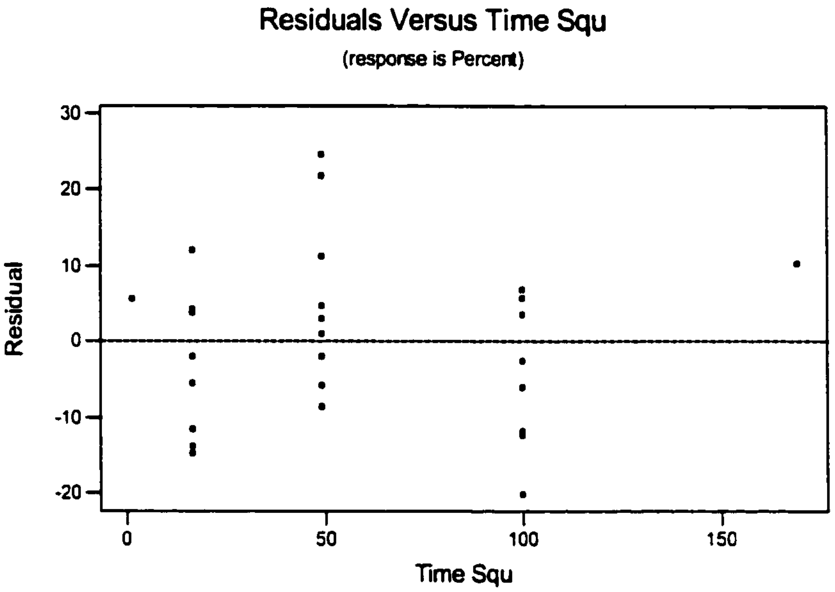

Figure 5.32 – Residuals vs. Weld Time * Force – Percent Insulation Removed

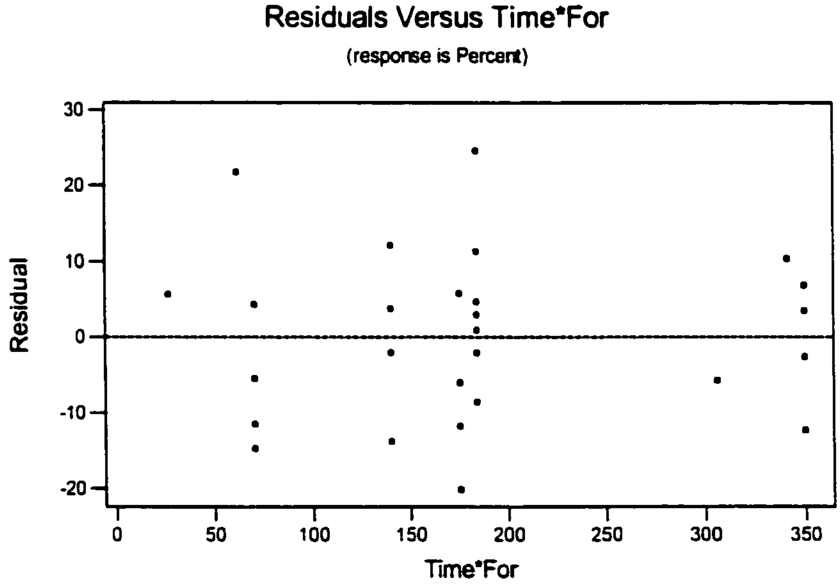

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Figure 5.33 – Residuals vs. Weld Voltage * Force – Percent Insulation Removed

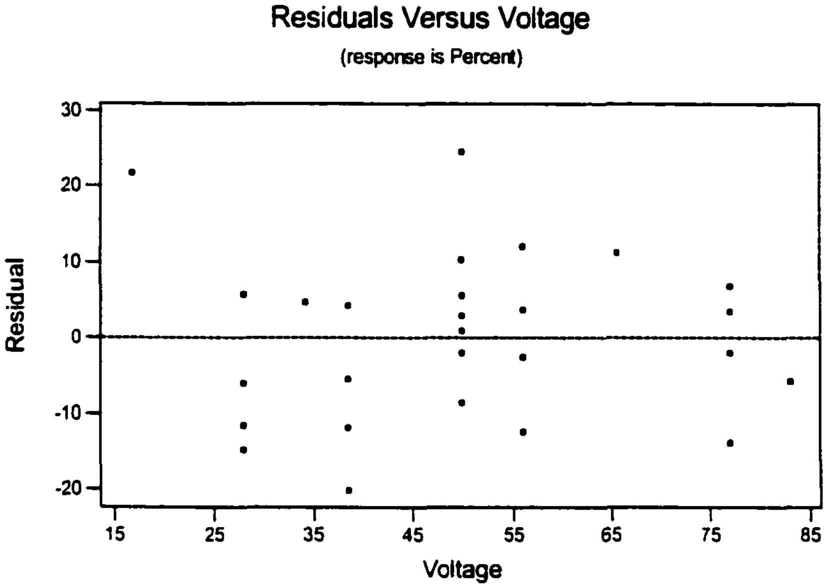
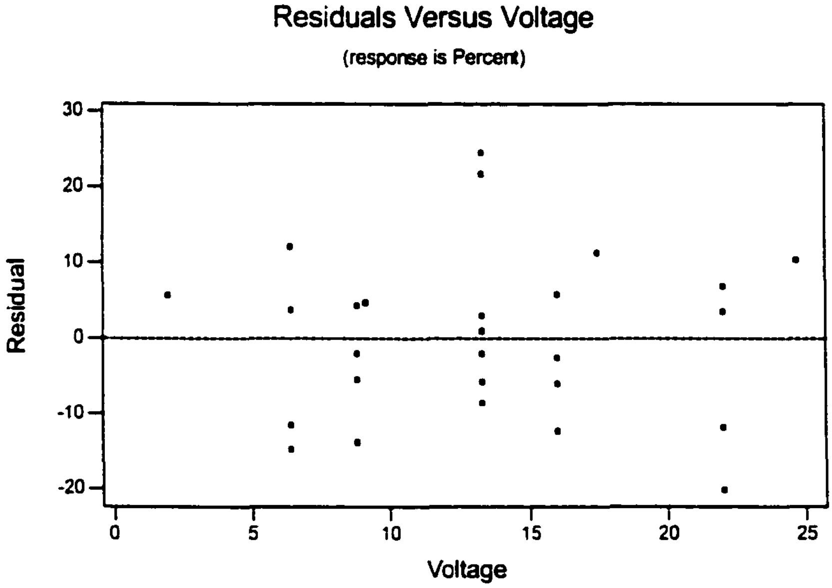


Figure 5.34 – Residuals vs. Weld Voltage * Time – Percent Insulation Removed



To verify the independence assumption a plot of the residuals versus the order of the data and was performed as shown in Figure 5.35. The plot of the residuals versus the order of the data showed a very

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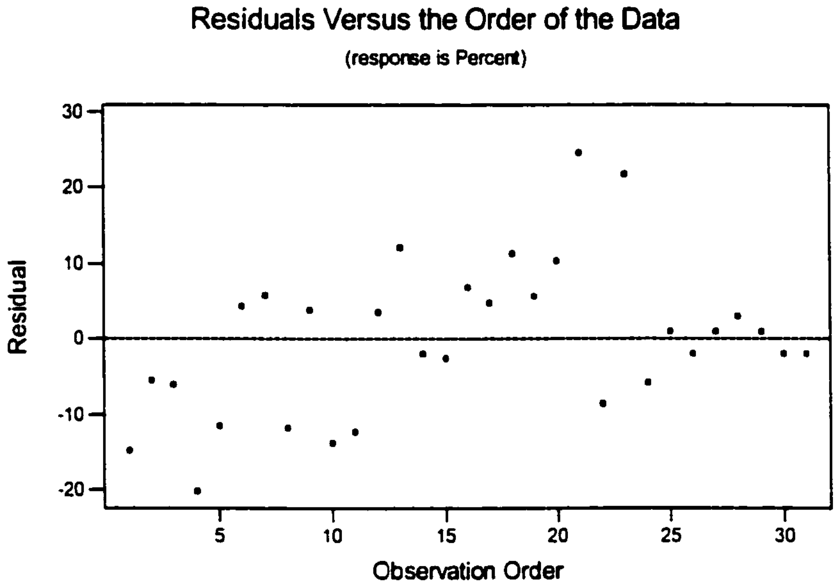
slight sign of increasing residuals with increase observation order. However no other particular pattern existed and the points were well dispersed. The data was trending, slightly in a specific direction and it did not have any systematic effects. Since the issues were minor, this plot substantiated the independence assumption.

Figure 5.35 – Residuals vs. Order – Pull Insulation Removed



To verify the residuals followed a well-behaved distribution a normal probability plot and a histogram of the residuals were performed as shown in Figure 5.36. The normal probability plot of the residual further confirmed that the residuals follow a normal distribution in Figure 5.37 by representing a straight line. The histogram plot showed that the residuals were normally distributed (bell-shaped). These two plots together illustrated that the residuals followed a well-behaved distribution.

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Figure 5.36 – Histogram – Percent on Insulation Removed

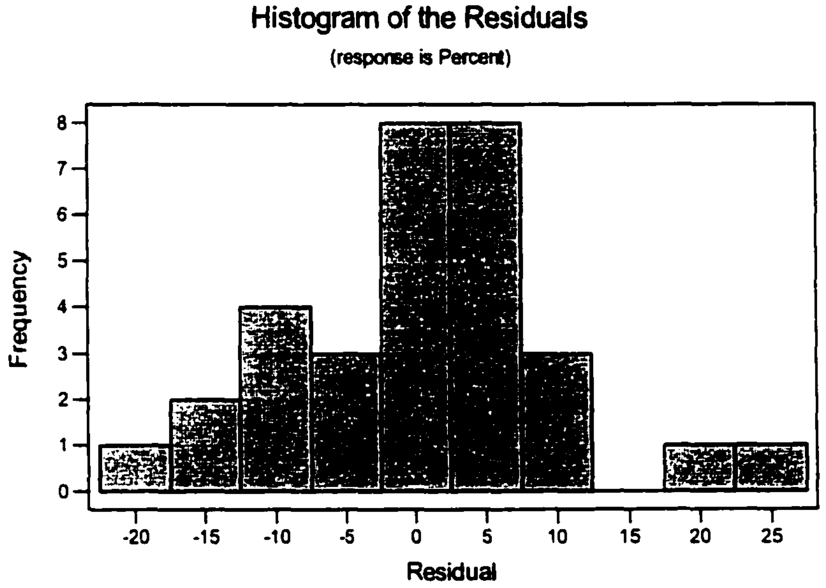
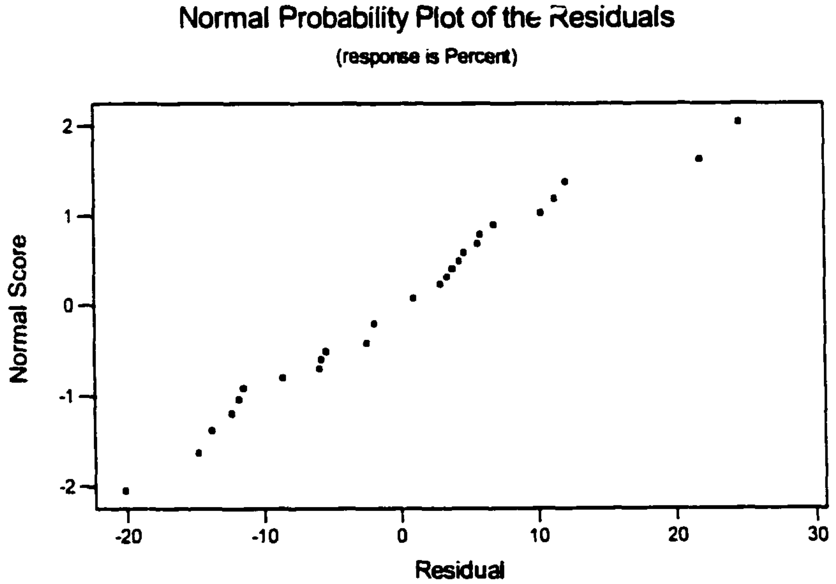


Figure 5.37 – Normal Probability Plot – Percent Insulation Removed



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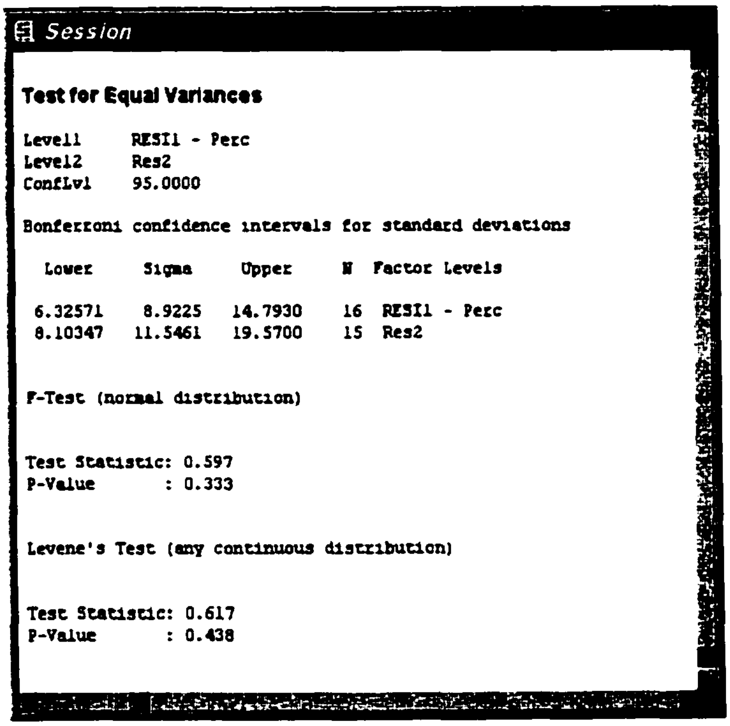
In order to determine if the non-constant variance reported above was significant, a formal statistical test was performed again. A Modified Levene Test was performed as described by Neter (1996) by analyzing the plots of the fitted values versus the residuals. A data matrix was created by ordering the residuals by increasing fitted values. This matrix was then divided into two distinct population samples. Since there were 31 runs the residuals for the first 16 fitted values were placed in the first population then the residuals for the last 15 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 chosen to determine statistical significance. As shown in Figure 5.38 the difference in the variance was not statistically significant (p=0.438 which is > 0.05).

Figure 5.38 – Modified Levene Test



Test for Equal Variances

```
Level1     RESI1 - Perc
Level2     Res2
ConfLvl    95.0000

Bonferroni confidence intervals for standard deviations

  Lower      Sigma     Upper     N  Factor Levels

 6.32571    8.9225   14.7930    16  RESI1 - Perc
 8.10347   11.5461   19.5700    15  Res2


F-Test (normal distribution)


Test Statistic: 0.597
P-Value       : 0.333


Levene's Test (any continuous distribution)


Test Statistic: 0.617
P-Value       : 0.438
```

The minimal difference between the residual populations is shown graphically in the box plot in Figure 5.39.

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Figure 5.39 – Modified Levene Box Plot

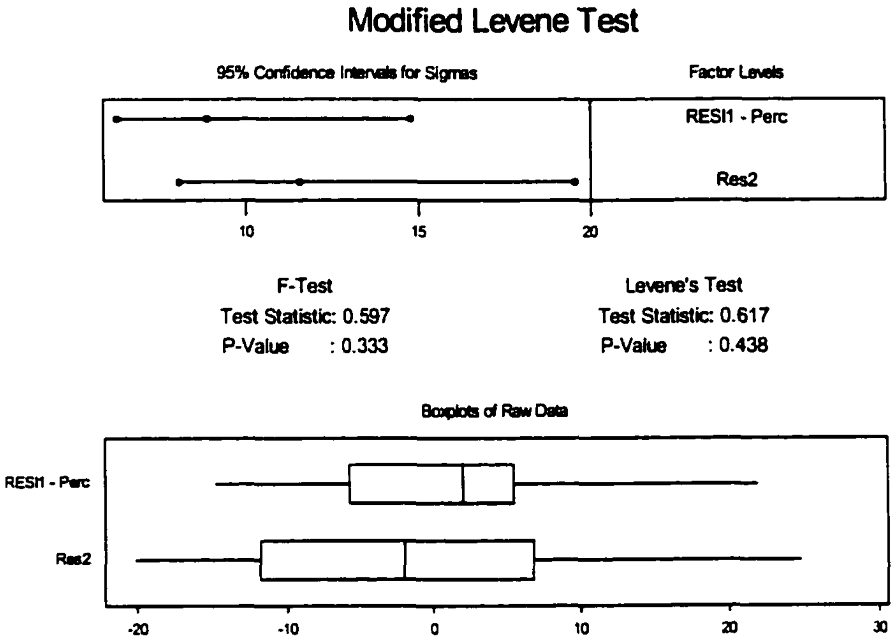
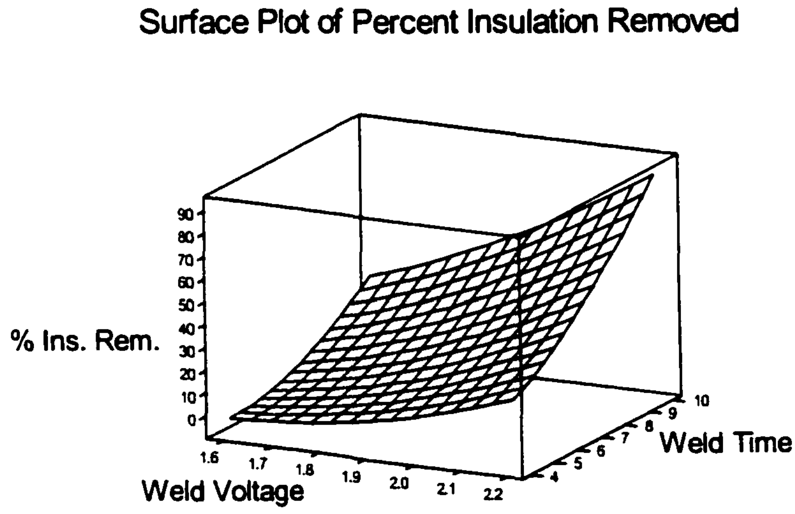


Figure 5.40 – Response Surface Plot – Percent of Insulation Removed



Hold values: Cool Tim: 20.0 Force: 35.0

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With the model assumptions verified, the performance was investigated further. The model confirmed the second order non-linear relationship that existed between some of the factors and the response variable. In the above analysis the primary significant factors in being able to predict percent of insulation removed were weld voltage and time. Figure 5.40 is a response surface plot that outlined the non-linear relationship between these variables. This figure and the model developed above indicated that the response variable pull strength is related to the square of the weld time. This makes intuitive sense in that the length of time the weld voltage is applied should have a large effect on the amount of insulation removed from the wire.

The overall performance from the above central composite analysis and model #2 is charted in Figure 5.41. This graph shows the fitted values derived from the model in comparisons with the actual results from the entire run. As shown in the figure the model fairly adequately predicts the percent insulation removed when the values from each standard order treatment are plugged into the mathematical model developed. In this particular case the performance did not degrade at the center points of the central composite design as indicated by standard order points 25-31.

To explain the lower performance of the model in comparison with the model #1 developed a series of regression analyses were performed. The regression analyses were performed with progressively removing sets of terms. The purpose of this analysis was to determine the impact not including the 3 and 4-way interaction effects and from not including the main effect upslope. Table 5.13 showed the model performance with each group of terms respectively. This analysis demonstrated that the current non-linear model could be improved from an R^2 of 85.0% to 89.1% by the addition of 3-way effects. There was still a gap in performance in comparison with linear model (R^2 of 95.2%) which was attributed to not including the main effect upslope and the sets of higher interaction effects in the analysis and the potential of experimental noise. In addition, there was minimal number of terms that were statistically significant. This was caused by including all of the terms available in the analysis.

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Figure 5-41 - Non-linear Model vs. Actual Results – Percent of Insulation Removed

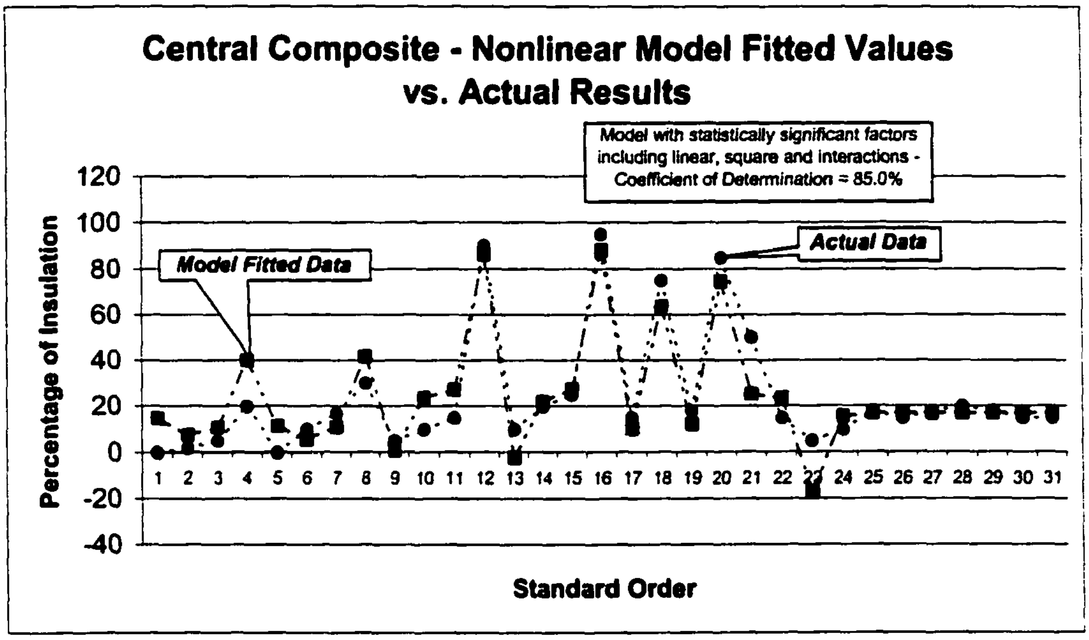

Table 5.13 - Regression Analysis Performance Per Groups of Terms – Percent Insulation Removed

	Terms				
	Full Quadratic Interactions through 4-Way	Full Quadratic Interactions through 3-Way	Full Quadratic Interactions through 2-Way	Full Quadratic	Only Main Effects
Number of Terms Statistically Significant	1	1	6	1	3
R^2	89.1%	89.1%	85.0%	69.8%	56.6%
R^2 (adjusted)	70.3%	72.8%	71.9%	58.8%	50.0%
R^2 different	18.8%	16.3%	13.1%	11.0%	6.6%
Reduction in R^2	0.0%	0.0%	4.1%	15.2%	28.4%
Regression F-value	4.74	5.46	6.47	6.34	8.49
Regression p-value	0.006	0.002	0.000	0.000	0.000
F(critical)	1.95	1.96	2.04	2.27	2.69

Again, while the purpose of the analysis was to determine the potential of the model, the additional insignificant terms hid the true significant terms as in the case with pull strength. It was anticipated that when some of the insignificant terms were removed, the significant terms would become significant. Because of the issues listed above it was decided to re-run the central composite design experiment for

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percent insulation removed also with two replications including upslope and to perform a progressive removal of insignificant terms find the best model available.

5.6 Central Composite Design II

As stated above, the issues associated with the first central composite design model #2 performance with respect to the pull strength and percent of insulation removed as a response variable, led to the development of an additional experiment. The next experiment performed was again a central composite design that included upslope as a factor in the design. Upslope was marginally statistically significant with respect to pull strength and not significant with respect to percent insulation removed in model #1 and for that reason was left out of the first central composite design. Upon review of the results it was decided to run another experiment including upslope. In addition, the significance of higher interaction effects and the effect of experimental noise was not quantified in the previous experiments. This design was a 2^5 full factorial design with an optimal distance for the axial points from the center points equal to 2.378 (alpha=2.378). There were a total of 2^5=32 treatments augmented by 10 axial points with 10 center points for a total of 52 runs for each replication. The factor levels were also adjusted in the central composite design to ensure that the axial point settings were capable values see Table 5.14. As stated above the same assessment methods (response variables) were selected for the experiment.

Table 5.14 - Central Composite DOE Factors

	Factor	*Lower Level (-1)*	*Higher Level (+1)*
A	Weld Voltage	1.6 volts	2.2 volts
B	Weld Time	4 msec	10 msec
C	Upslope	4 msec	10 msec
D	Cooling Time	10 msec	20 msec
E	Weld Force	17.5 lbs (7.94kg)	35lbs (15.88kg)

The design represented a full resolution design meaning that effects were not confounded. This allowed for any statistically significant effects involving any main or interaction effect to be assigned only to that effect. Since the design was full resolution there was no defining relation or alias structure. There was only one block run and no repetitions for either of the response variables. In order to minimize the effect of

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experimental noise and evaluate the improvement in the model, designs were performed with one and with two replications for both response variables.

The standard order, treatments and the each joint quality assessment method (response variable) values for the first replication is shown in Table 5.15. The data matrix from the central composite 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 evaluated by pull testing the sample and determining the percent of insulation remaining. The factorial design was then analyzed to draw conclusions.

Table 5.15 – Central Composite Design Data Matrix

Std Order	Weld Voltage	Weld Time	Upslope	Cooling Time	Force	Point Type	Local Max Force	% Ins Removed
1	1.6	4	20	20	17.5	Factorial	5	7.8
2	2.2	4	20	20	17.5	Factorial	15	12.7
3	1.6	10	20	20	17.5	Factorial	10	17.25
4	2.2	10	20	20	17.5	Factorial	90	13.55
5	1.6	4	30	20	17.5	Factorial	5	14.3
6	2.2	4	30	20	17.5	Factorial	25	13.95
7	1.6	10	30	20	17.5	Factorial	20	14.65
8	2.2	10	30	20	17.5	Factorial	85	12.7
9	1.6	4	20	30	17.5	Factorial	18	11.55
10	2.2	4	20	30	17.5	Factorial	15	8.15
11	1.6	10	20	30	17.5	Factorial	15	11.1
12	2.2	10	20	30	17.5	Factorial	85	17.1
13	1.6	4	30	30	17.5	Factorial	15	14.5
14	2.2	4	30	30	17.5	Factorial	17	13.45
15	1.6	10	30	30	17.5	Factorial	7	16.5
16	2.2	10	30	30	17.5	Factorial	85	14.25
17	1.6	4	20	20	35	Factorial	25	14.35
18	2.2	4	20	20	35	Factorial	48	21.3
19	1.6	10	20	20	35	Factorial	75	19.3
20	2.2	10	20	20	35	Factorial	60	16.5
21	1.6	4	30	20	35	Factorial	13	17.3
22	2.2	4	30	20	35	Factorial	18	19.8
23	1.6	10	30	20	35	Factorial	50	17.45
24	2.2	10	30	20	35	Factorial	60	17.8
25	1.6	4	20	30	35	Factorial	20	13.25
26	2.2	4	20	30	35	Factorial	30	14.55

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27	1.6	10	20	30	35	Factorial	35	20.1
28	2.2	10	20	30	35	Factorial	100	22.8
29	1.6	4	30	30	35	Factorial	35	18.7
30	2.2	4	30	30	35	Factorial	10	10.6
31	1.6	10	30	30	35	Factorial	45	17.95
32	2.2	10	30	30	35	Factorial	100	21.2
33	1.1902	7	25	25	26.25	Axial	20	15.7
34	2.6098	7	25	25	26.25	Axial	100	18.6
35	1.9	-0.098	25	25	26.25	Axial	15	11.6
36	1.9	14.098	25	25	26.25	Axial	80	20.2
37	1.9	7	13.17	25	26.25	Axial	50	16.4
38	1.9	7	36.83	25	26.25	Axial	23	18.3
39	1.9	7	25	13.17	26.25	Axial	35	18.85
40	1.9	7	25	36.83	26.25	Axial	45	19.4
41	1.9	7	25	25	5.5475	Axial	0	0
42	1.9	7	25	25	46.9525	Axial	40	23.1
43	1.9	7	25	25	26.25	Center	50	15.9
44	1.9	7	25	25	26.25	Center	50	16.95
45	1.9	7	25	25	26.25	Center	45	17.45
46	1.9	7	25	25	26.25	Center	40	15.6
47	1.9	7	25	25	26.25	Center	47	12.35
48	1.9	7	25	25	26.25	Center	45	14.7
49	1.9	7	25	25	26.25	Center	45	15.65
50	1.9	7	25	25	26.25	Center	45	16.35
51	1.9	7	25	25	26.25	Center	50	14
52	1.9	7	25	25	26.25	Center	42	16.8

A significant level of 5% (alpha=0.05) was used again to determine statistical significance. Statistical significance was interpreted throughout the analysis as being important in being able to predict the pull strength or percent of insulation remaining (depending on the response variable considered). The design was first analyzed with respect to pull strength of the weld (local maximum force). As in the case with the first central composite design two separate analyses were performed. The first analysis was a response surface analysis of the central composite design. This analysis was repeated for the same groups of terms that were established above. Table 5.16 shows the performance of the models developed with the one replication design and Table 5.17 shows the performance of the models developed with the two replication design.

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Table 5.16 - RS Analysis Performance Per Groups of Terms – Pull Strength 1 Replication

	Terms Included in Analysis			
	Full Quadratic	Linear & Interaction	Linear & Squared	Linear
Number of terms	1	0	2	2
R^2	72.8%	64.9%	64.4%	56.5%
R^2 (adjusted)	55.3%	50.3%	55.8%	51.7%
R^2 different	17.5%	14.6%	8.6%	4.8%
Reduction in R^2	0.0%	7.9%	8.4%	7.9%
Regression F-value	4.16	4.44	7.34	11.94
Regression p-value	0.000	0.001	0.000	0.000
F(critical)	1.78	1.87	2.02	2.40

Table 5.17 - RS Analysis Performance Per Groups of Terms – Pull Strength 2 Replications

	Terms Included in Analysis			
	Full Quadratic	Linear & Interaction	Linear & Squared	Linear
Number of terms	4	1	3	2
R^2	68.0%	59.6%	61.3%	52.9%
R^2 (adjusted)	60.3%	52.7%	57.1%	50.5%
R^2 different	7.7%	6.9%	4.2%	2.4%
Reduction in R^2	0.0%	8.4%	6.7%	8.4%
Regression F-value	8.84	8.65	14.73	21.98
Regression p-value	0.000	0.001	0.000	0.000
F(critical)	1.67	1.76	1.92	2.30

The performance from the new model decreased from the model developed in the first central composite design and well as in the model #1. It was concluded that the main difference in model #1 and model #2 performance for pull strength was due to not including significant interaction effects higher than 2-way. For this reason the regression analysis was performed again with the selected group of terms outlined above. This analysis was performed to determine the model potential that includes all available terms including all main effects, full quadratic as well as interaction set effects through 5-way. The analysis was performed and the performance of the models developed with the one replication design as shown in Table 5.18 and the performance of the models developed with the two replication design as shown in Table 5.19.

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Table 5.18 - Regression Analysis Performance Per Groups of Terms – Pull Strength – 1 Replication

	Terms					
	Full Quadratic Interactions through 5-Way	*Full Quadratic Interactions through 4-Way*	*Full Quadratic Interactions through 3-Way*	*Full Quadratic Interactions through 2-Way*	*Full Quadratic*	*only Main Effects*
Number of Terms Statistically Significant	1	1	5	1	2	2
R^2	89.0%	87.5%	84.4%	72.8%	64.4%	56.5%
R^2 (adjusted)	62.7%	60.2%	62.1%	55.3%	55.8%	51.7%
R^2 different	26.3%	27.3%	22.3%	17.5%	8.6%	4.8%
Reduction in R^2	0.0%	1.5%	3.1%	11.6%	8.4%	4.8%
Regression F-value	3.38	3.20	3.78	4.16	7.43	11.94
Regression p-value	0.007	0.008	0.001	0.000	0.000	0.000
F(critical)	1.65	1.65	1.68	1.78	2.02	2.40

Table 5.19 - Regression Analysis Performance Per Groups of Terms – Pull Strength – 2 Replications

	Terms					
	Full Quadratic Interactions through 5-Way	*Full Quadratic Interactions through 4-Way*	*Full Quadratic Interactions through 3-Way*	*Full Quadratic Interactions through 2-Way*	*Full Quadratic*	*only Main Effects*
Number of Terms Statistically Significant	17	10	10	4	3	2
R^2	86.3%	85.6%	82.8%	68.0%	61.3%	52.9%
R^2 (adjusted)	78.9%	78.2%	75.7%	60.3%	57.1%	50.5%
R^2 different	7.4%	7.4%	7.1%	7.7%	4.2%	2.4%
Reduction in R^2	0.0%	0.7%	2.8%	14.8%	6.7%	15.1%
Regression F-value	11.71	11.55	11.69	8.83	14.73	21.98
Regression p-value	0.000	0.000	0.000	0.000	0.000	0.000
F(critical)	.54	1.54	1.57	1.67	1.92	2.30

When including all available terms the new model results improved over model #1. This analysis was performed to determine the potential of the model. The tables above also show the incremental improvement in the model by sets of interaction effects. The analysis with 2 replications also showed more terms that were statistically significant. This phenomenon was attributed to the reduction in experimental noise due to the additional replication. While the model presented offered substantial insight into the potential of the model, there was still a significant difference between R^2 and R^2 (adjusted). This was an indication that the model was over specified and that the optimum number of terms were not included. In order to develop the optimum model the terms with the highest p-values were progressively removed and the regression was re-run. This process was repeated until the difference between R^2 and R^2 (adjusted) was

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not reduced any further. The elimination of some terms actually reduced R^2, however if the corresponding increase in R^2 (adjusted) compensated for the decrease such that the difference in the two values was reduced, the term was still eliminated. This process was performed on both the designs with 1 and 2 replications to determine the optimum models for each design. Table 5.20 shows the summary of the regression analysis for pull strength optimized models with 1 and 2 replications as well as the optimized models from the first central composite design and the initial DOE.

Figure 5.20 – Summary of Optimized Regression Models for Pull Strength

	Central Composite Design II	*Central Composite Design II*	*Central Composite Design I*	*Initial DOE*
Design Number	#3	#3	#2	#1
Number of Replications	2	1	1	10
Number of Terms Statistically Significant	31	27	14	25
R^2	85.8%	86.3%	76.0%	86.2%
R^2 Lower 95th CI	82.9%	83.4%	74.3%	82.6%
R^2 Upper 95th CI	88.7%	89.2%	77.7%	89.8%
R^2 (adjusted)	79.7%	71.0	55.0%	85.0%
R^2 different	6.1%	15.3%	21.0%	1.2%
Regression F-value	14.02	5.62	5.62	73.21
Regression p-value	0.000	0.0000	0.008	0.000
F(critical)	1.56	1.71	2.04	1.54

The optimized central composite design with two replications approaches the performance of the model #1. Model #1 did have better performance with fewer terms. The complete analysis was performed for both of the central composite II designs however only the design with 2 replications was reported because it was the model that was retained for optimization. Listed in Figure 5.42 is the regression analysis for the central composite design II with 2 replications.

The analysis of variation (ANOVA) outlined that the model developed was significant from the F-test ($p=0.000$ which is < 0.05) and listed a coefficient of determination, $R^2 = 85.8\%$ and R^2 (adjusted) = 79.7% as also outlined above. The model also outlined that 5 additional variables could be removed because of statistical significance however when these variable were attempted to be removed the performance of the model was reduced.

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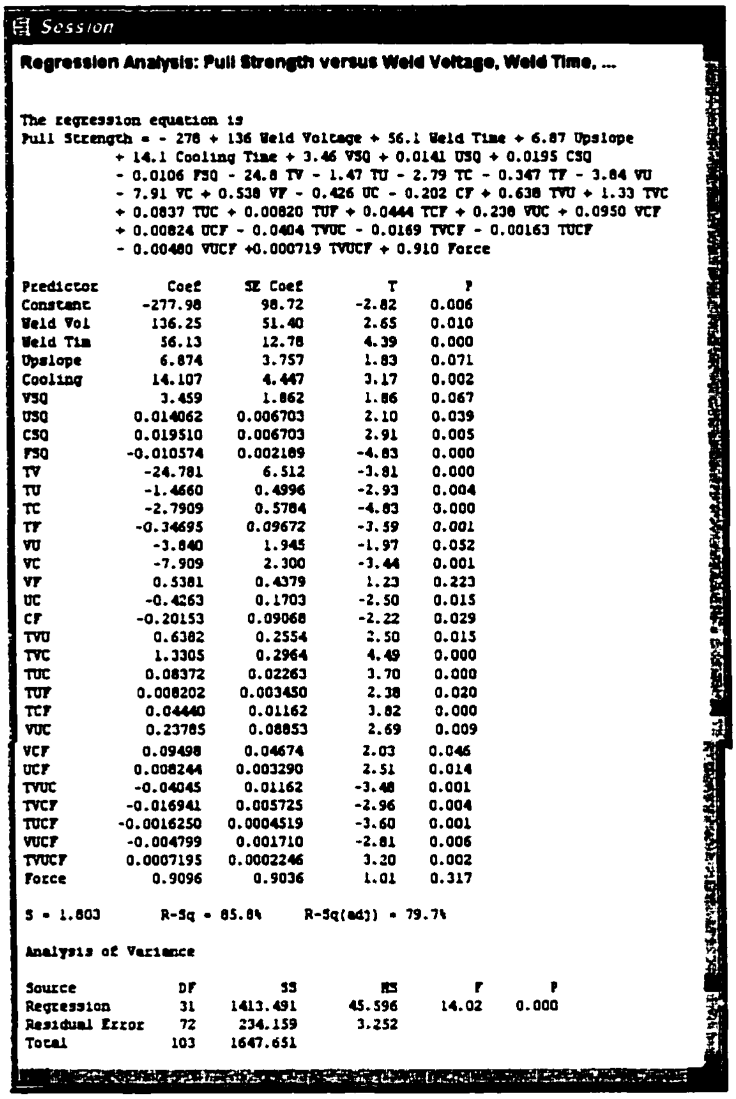
Figure 5.42 - Central Composite Design – Pull Strength



Regression Analysis: Pull Strength versus Weld Voltage, Weld Time, ...

```
The regression equation is
Pull Strength = - 278 + 136 Weld Voltage + 56.1 Weld Time + 6.87 Upslope
           + 14.1 Cooling Time + 3.46 VSQ + 0.0141 USQ + 0.0195 CSQ
           - 0.0106 FSQ - 24.8 TV - 1.47 TU - 2.79 TC - 0.347 TF - 3.84 VU
           - 7.91 VC + 0.538 VF - 0.426 UC - 0.202 CF + 0.638 TVU + 1.33 TVC
           + 0.0837 TUC + 0.00820 TUF + 0.0444 TCF + 0.238 VUC + 0.0950 VCF
           + 0.00824 UCF - 0.0404 TVUC - 0.0169 TVCF - 0.00163 TUCF
           - 0.00480 VUCF +0.000719 TVUCF + 0.910 Force

Predictor         Coef      SE Coef         T        P
Constant       -277.98        98.72     -2.82    0.006
Weld Vol        136.25        51.40      2.65    0.010
Weld Tim         56.13        12.78      4.39    0.000
Upslope          6.874        3.757      1.83    0.071
Cooling         14.107        4.447      3.17    0.002
VSQ              3.459        1.862      1.86    0.067
USQ           0.014062     0.006703      2.10    0.039
CSQ           0.019510     0.006703      2.91    0.005
FSQ          -0.010574     0.002189     -4.83    0.000
TV             -24.781        6.512     -3.81    0.000
TU             -1.4660       0.4996     -2.93    0.004
TC             -2.7909       0.5784     -4.83    0.000
TF            -0.34695      0.09672     -3.59    0.001
VU              -3.840        1.945     -1.97    0.052
VC              -7.909        2.300     -3.44    0.001
VF              0.5381       0.4379      1.23    0.223
UC             -0.4263       0.1703     -2.50    0.015
CF            -0.20153      0.09068     -2.22    0.029
TVU             0.6382       0.2554      2.50    0.015
TVC             1.3305       0.2964      4.49    0.000
TUC            0.08372      0.02263      3.70    0.000
TUF           0.008202     0.003450      2.38    0.020
TCF            0.04440      0.01162      3.82    0.000
VUC            0.23785      0.08853      2.69    0.009
VCF            0.09498      0.04674      2.03    0.046
UCF           0.008244     0.003290      2.51    0.014
TVUC          -0.04045      0.01162     -3.48    0.001
TVCF         -0.016941     0.005725     -2.96    0.004
TUCF        -0.0016250    0.0004519     -3.60    0.001
VUCF         -0.004799     0.001710     -2.81    0.006
TVUCF        0.0007195    0.0002246      3.20    0.002
Force           0.9096       0.9036      1.01    0.317

S = 1.803       R-Sq = 85.8%     R-Sq(adj) = 79.7%

Analysis of Variance

Source            DF         SS         MS         F        P
Regression        31   1413.491     45.596     14.02    0.000
Residual Error    72    234.159      3.252
Total            103   1647.651
```

The analysis resulted in a mathematical model of the process with 31 terms. The mathematical model (model #3) developed is listed in eqn. (5.5).

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eqn. (5.5) pull strength(lbs) = -278+136*V+56.1*T+6.87*U+14.1*C+3.46*VSQ+ 0.0141*USQ +0.0195*CSQ-0.0106*FSQ-24.8*T*V-1.47*T*U-2.79*T*C-0.347*T*F-3.84*V*U-7.91*V*C+ 0.538*V*F-0.426*U*C-0.202*C*F+0.638*T*V*U+1.33*T*V*C +0.0837*T*U*C+0.00820*T*U*F+0.0444*T*C*F+0.238*V*U*C+0.0950*V*C*F+0.00824*U*C*F- 0.0404*T*V*U*C-0.0169*T*V*C*F-0.00163*T*U*C*F-0.00480*V*U*C*F+0.000719*T*V*U*C*F+0.910*F

Where: T is weld time in msec
V is weld voltage in volts
C is cooling time in msec
U is upslope in percentage
F is force in lbs.
SQ is any of the above terms squared

The results did made logical sense and the model was similar to the previous response surface results in that the voltage term was squared however there were additional terms that were squared as well. A complete residual analysis was again performed to check the validity of the model assumptions. The model was checked to ensure the validity of the following assumptions; randomness (well dispersed residuals), constant variance, independence, normality and overall well behave distribution. These results were not shown in this dissertation due to the fact that they displayed similar results as the models above.

The design was then analyzed with respect to percent insulation removed. The first analysis was a response surface analysis of the central composite design. This analysis was repeated for the same groups of terms that were established above. Table 5.21 shows the performance of the models developed with the one replication design and Table 5.22 shows the performance of the models developed with the two replication design.

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Table 5.21 - RS Analysis Performance Per Groups of Terms – % Insulation Removed 1 Replication

	Terms Included in Analysis			
	Full Quadratic	Linear & Interaction	Linear & Squared	Linear
Number of terms	5	3	2	3
R^2	87.4%	81.9%	65.4%	66.7%
R^2 (adjusted)	79.2%	74.4%	72.2%	63.1%
R^2 different	8.2%	7.5%	-6.8%	3.6%
Reduction in R^2	0.0%	5.5%	16.5%	15.2%
Regression F-value	10.70	10.88	10.63	18.46
Regression p-value	0.000	0.000	0.000	0.000
F(critical)	1.78	1.87	2.02	2.40

Table 5.22 - RS Analysis Performance Per Groups of Terms – % Insulation Removed 2 Replications

	Terms Included in Analysis			
	Full Quadratic	Linear & Interaction	Linear & Squared	Linear
Number of terms	7	4	3	3
R^2	86.5%	81.0%	70.8%	65.3%
R^2 (adjusted)	83.2%	77.8%	67.6%	63.5%
R^2 different	3.3%	3.2%	3.2%	1.8%
Reduction in R^2	0.0%	5.5%	10.2%	15.7%
Regression F-value	26.59	25.09	22.51	36.91
Regression p-value	0.000	0.000	0.000	0.000
F(critical)	1.67	1.76	1.92	2.30

The performance from the new model increased from the model developed in the first central composite design and decreased from model #1. It was concluded that the main difference in model #1 and model #2 performance for percent of insulation removed was due to not including significant interaction effects higher than 2-way. For this reason the regression analysis was performed again with the selected group of terms outlined above. This analysis was performed to determine the model potential that includes all available terms including all main effects, full quadratic as well as interaction set effects through 5-way. The analysis was performed and the performance of the models developed with the one replication design as shown in Table 5.23 and the performance of the models developed with the two replication design as shown in Table 5.24.

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Table 5.23 - Regression Analysis Performance Per Groups of Terms – % Insulation Rem. – 1 Replication

	Terms					
	Full Quadratic Interactions through 5-Way	*Full Quadratic Interactions through 4-Way*	*Full Quadratic Interactions through 3-Way*	*Full Quadratic Interactions through 2-Way*	*Full Quadratic*	*only Main Effects*
Number of Terms Statistically Significant	6	10	7	5	2	3
R^2	98.3%	98.2%	95.6%	87.4%	64.4%	56.5%
R^2 (adjusted)	94.3%	94.1%	89.3%	79.2%	55.8%	51.7%
R^2 different	4.0%	4.1%	6.3%	8.2%	8.6%	4.8%
Reduction in R^2	0.0%	0.1%	2.6%	8.2%	23.0%	30.9%
Regression F-value	24.51	24.32	15.25	10.70	7.43	11.94
Regression p-value	0.000	0.000	0.000	0.000	0.000	0.000
F(critical)	1.65	1.65	1.68	1.78	2.02	2.40

Table 5.24 - Regression Analysis Performance Per Groups of Terms – % Insulation Rem. – 2 Replications

	Terms					
	Full Quadratic Interactions through 5-Way	*Full Quadratic Interactions through 4-Way*	*Full Quadratic Interactions through 3-Way*	*Full Quadratic Interactions through 2-Way*	*Full Quadratic*	*only Main Effects*
Number of Terms Statistically Significant	22	18	15	7	3	3
R^2	97.7%	97.6%	95.0%	86.5%	70.8%	65.3%
R^2 (adjusted)	96.5%	96.3%	93.0%	83.2%	67.6%	63.5%
R^2 different	1.2%	1.3%	2.0%	3.3%	3.2%	1.8%
Reduction in R^2	0.0%	0.1%	2.6%	8.5%	15.7%	21.2%
Regression F-value	79.86	78.0	46.43	26.59	22.51	36.91
Regression p-value	0.000	0.000	0.000	0.000	0.000	0.000
F(critical)	1.53	1.54	1.57	1.67	1.92	2.30

When including all available terms the new model results improved over the model #1. This analysis was performed to determine the potential of the model. The tables above also show the incremental improvement in the model by sets of interaction effects. The analysis with 2 replications also showed more terms that were statistically significant. This phenomenon was attributed to the reduction in experimental noise due to the additional replication. While the model presented offered substantial insight into the potential of the model there was still a significant difference between R^2 and R^2 (adjusted) as was in the case of the pull strength table above. The same progressive regression analysis was performed as above to outline the optimum model for percent insulation removed. Table 5.25 shows the summary of the

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regression analysis for percent insulation removed optimized models with 1 and 2 replications as well as the optimized models from the first central composite design and initial DOE.

Figure 5.25 – Summary of Optimized Regression Models for Percent Insulation Removed

	Central Composite Design II	*Central Composite Design II*	*Central Composite Design I*	*Initial DOE*
Design Number	#3	#3	#2	#1
Number of Replications	2	1	1	2
Number of Terms Statistically Significant	31	31	14	22
R^2	97.6%	98.1%	85.0%	95.2%
R^2 Lower 95th CI	80.0%	80.5%	74.3%	82.6%
R^2 Upper 95th CI	100.0%	89.2%	62.7%	80.6%
R^2 (adjusted)	96.5%	100.0%	100.0%	100.0%
R^2 different	1.1%	3.1%	13.1%	2.6%
Regression F-value	89.78	31.3	6.47	36.58
Regression p-value	0.000	0.000	0.000	0.000
F(critical)	1.56	1.67	2.04	1.71

The optimized central composite design with two replications is better than the performance of model #1 and offers the model with the highest R^2 value. The complete analysis was performed for both of the central composite II designs however only the design with 2 replications was reported because it was the model that was retained for optimization. Listed in Figure 5.43 is the regression analysis for the central composite design II with 2 replications.

The analysis of variation (ANOVA) outlined that the model developed was significant from the F-test ($p=0.000$ which is < 0.05) and listed a coefficient of determination, $R^2 = 97.6\%$ and R^2 (adjusted) = 96.5% as also outlined above. The model also outlined that 3 additional variables could be removed because of statistical significance however when these variable were attempted to be removed the performance of the model was reduced.

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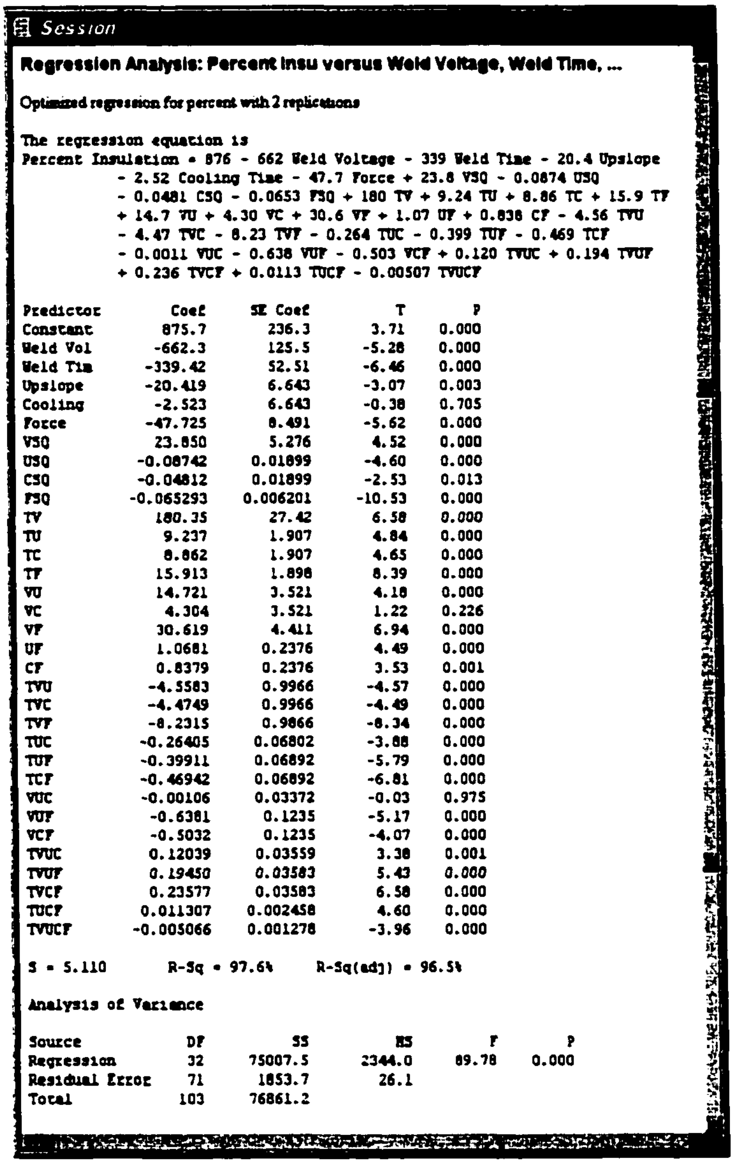
Figure 5.43 - Central Composite Design – Percent Insulation Removed



Regression Analysis: Percent Insu versus Weld Voltage, Weld Time, ...

Optimized regression for percent with 2 replications

```
The regression equation is
Percent Insulation = 876 - 662 Weld Voltage - 339 Weld Time - 20.4 Upslope
           - 2.52 Cooling Time - 47.7 Force + 23.8 VSQ - 0.0874 USQ
           - 0.0481 CSQ - 0.0653 FSQ + 180 TV + 9.24 TU + 8.86 TC + 15.9 TF
           + 14.7 VU + 4.30 VC + 30.6 VF + 1.07 UF + 0.838 CF - 4.56 TVU
           - 4.47 TVC - 8.23 TVF - 0.264 TUC - 0.399 TUF - 0.469 TCF
           - 0.0011 VUC - 0.638 VUF - 0.503 VCF + 0.120 TVUC + 0.194 TVUF
           + 0.236 TVCF + 0.0113 TUCF - 0.00507 TVUCF

Predictor        Coef     SE Coef        T       P
Constant        875.7       236.3     3.71   0.000
Weld Vol       -662.3       125.5    -5.28   0.000
Weld Tim      -339.42       52.51    -6.46   0.000
Upslope       -20.419       6.643    -3.07   0.003
Cooling        -2.523       6.643    -0.38   0.705
Force         -47.725       8.491    -5.62   0.000
VSQ            23.850       5.276     4.52   0.000
USQ          -0.08742     0.01899    -4.60   0.000
CSQ          -0.04812     0.01899    -2.53   0.013
FSQ         -0.065293    0.006201   -10.53   0.000
TV             180.35       27.42     6.58   0.000
TU              9.237       1.907     4.84   0.000
TC              8.862       1.907     4.65   0.000
TF             15.913       1.898     8.39   0.000
VU             14.721       3.521     4.18   0.000
VC              4.304       3.521     1.22   0.226
VF             30.619       4.411     6.94   0.000
UF             1.0681      0.2376     4.49   0.000
CF             0.8379      0.2376     3.53   0.001
TVU           -4.5583      0.9966    -4.57   0.000
TVC           -4.4749      0.9966    -4.49   0.000
TVF           -8.2315      0.9866    -8.34   0.000
TUC          -0.26405     0.06802    -3.88   0.000
TUF          -0.39911     0.06892    -5.79   0.000
TCF          -0.46942     0.06892    -6.81   0.000
VUC          -0.00106     0.03372    -0.03   0.975
VUF           -0.6381      0.1235    -5.17   0.000
VCF           -0.5032      0.1235    -4.07   0.000
TVUC          0.12039     0.03559     3.38   0.001
TVUF          0.19450     0.03583     5.43   0.000
TVCF          0.23577     0.03583     6.58   0.000
TUCF         0.011307    0.002458     4.60   0.000
TVUCF       -0.005066    0.001278    -3.96   0.000

S = 5.110       R-Sq = 97.6%     R-Sq(adj) = 96.5%

Analysis of Variance

Source            DF         SS         MS         F        P
Regression        32    75007.5     2344.0     89.78    0.000
Residual Error    71     1853.7       26.1
Total            103    76861.2
```

The analysis resulted in a mathematical model of the process with 31 terms. The mathematical model (model #3) developed is listed in eqn. (5.5).

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eqn. (5.6)

$$\text{percent insulation removed}(\%) = 876-662*V-339*T-20.4*U-2.52*C-47.7*F+23.8*VSQ-0.0874*USQ-0.0481*CSQ-0.0653*FSQ+180*T*V+9.24*T*U+8.86*T*C+15.9*T*F+14.7*V*U+4.30*V*C+30.6*V*F+1.07*U*F+0.838*C*F-4.56*T*V*U-4.47*T*V*C-8.23*T*V*F-0.264*T*U*C-0.399*T*U*F-0.469*T*C*F-0.0011*V*U*C-0.638*V*U*F-0.503*V*C*F+0.120*T*V*U*C+0.194*T*V*U*F+0.236*T*V*C*F+0.0113*T*U*C*F-0.00507*T*V*U*C*F$$

Where:
T is weld time in msec
V is weld voltage in volts
C is cooling time in msec
U is upslope in percentage
F is force in lbs.
SQ is any of the above terms squared

The results did made logical sense but the model differed to the previous response surface results in that the time term was not squared and there were additional terms that were squared as well. A complete residual analysis was again performed to check the validity of the model assumptions. The model was checked to ensure the validity of the following assumptions; randomness (well dispersed residuals), constant variance, independence, normality and overall well behave distribution. These results were not shown in this dissertation due to the fact that they displayed similar results as the models above.

The apparent reason for the significance of higher order interactions with both pull strength and percent insulation removed is the nature of the physics of the process. Furthermore, the equation for thermal energy, eqn. (3.2) in the Appendix expresses a relationship between voltage squared, time, contact resistance and thermal energy. In addition, weld time and upslope are directly proportional and cooling time is inversely proportional to thermal energy. Also, force is inversely proportional to contact resistance. This means that all of the controllable predictor values used in this study are physically linked and are expected to have a high degree of cross-correlation, with sets of higher interaction effects being statistically significant. Quantifying the amount of cross-correlation and using these values to re-specify the model is another opportunity for future investigation.

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In order to further analyze the effect of the second replication a study was performed to compare the 95% confidence interval on the fitted values for both the response variables. The 95% confidence intervals were calculated for each fitted value for the design with 1 replication and with 2 replications. The confidence band (difference between upper and lower confidence interval) was also calculated. These values are shown in Table 5.26. As expected the confidence band in the design with 2 replications was significantly narrower. The narrower confidence band further increased the legitimacy of the regression model #3 for pull strength.

Table 5.26 – Central Composite Design II Confidence Intervals – Pull Strength

1 Replication					*2 Replication*			
Lower 95% CI	Fitted Value	Upper 95% CI	Confidence Band		Lower 95% CI	Fitted Value	Upper 95% CI	Confidence Band
3.5	7.2	10.9	7.4		5.7	7.9	10.1	4.4
8.3	12.0	15.7	7.4		10.9	13.1	15.3	4.4
11.7	15.4	19.1	7.4		14.4	16.7	19.0	4.6
9.3	13.0	16.7	7.4		10.7	13.0	15.3	4.6
8.2	11.9	15.6	7.4		9.4	11.6	13.8	4.4
10.7	14.4	18.1	7.4		12.0	14.2	16.4	4.4
11.1	14.8	18.5	7.4		12.9	15.2	17.4	4.6
8.9	12.6	16.3	7.4		9.4	11.7	14.0	4.6
6.5	10.6	14.6	8.1		8.2	10.5	12.9	4.7
3.6	7.6	11.7	8.1		5.8	8.2	10.5	4.7
7.3	11.3	15.4	8.1		8.2	10.6	13.0	4.8
12.8	16.9	20.9	8.1		14.1	16.5	18.9	4.8
10.6	14.7	18.8	8.1		12.5	14.9	17.3	4.7
8.1	12.1	16.2	8.1		10.1	12.5	14.8	4.7
11.3	15.4	19.4	8.1		13.8	16.2	18.6	4.8
9.6	13.7	17.8	8.1		12.5	14.9	17.3	4.8
10.8	14.5	18.2	7.4		11.7	13.9	16.1	4.4
18.4	22.1	25.8	7.4		20.2	22.4	24.6	4.4
17.5	21.2	24.9	7.4		17.6	19.9	22.2	4.6
13.9	17.6	21.3	7.4		14.0	16.3	18.6	4.6
15.5	19.2	22.9	7.4		16.5	18.7	20.9	4.4
15.7	19.4	23.1	7.4		18.3	20.5	22.7	4.4
13.6	17.3	21.0	7.4		15.8	18.1	20.4	4.6
14.7	18.4	22.1	7.4		17.5	19.8	22.1	4.6
10.0	14.1	18.2	8.1		13.0	15.3	17.7	4.7
11.3	15.4	19.5	8.1		12.7	15.1	17.4	4.7
16.1	20.2	24.3	8.1		18.4	20.8	23.2	4.8
19.8	23.9	27.9	8.1		21.6	24.0	26.4	4.8
14.3	18.3	22.4	8.1		16.1	18.4	20.8	4.7
8.2	12.2	16.3	8.1		9.7	12.1	14.4	4.7

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15.3	19.4	23.4	8.1		16.4	18.8	21.2	4.8
18.5	22.6	26.6	8.1		19.9	22.3	24.7	4.8
13.4	15.3	17.2	3.7		14.6	16.5	18.4	3.8
14.7	16.5	18.4	3.7		15.9	17.8	19.7	3.8
10.5	12.4	14.2	3.7		10.9	12.0	13.2	2.3
17.6	19.4	21.3	3.7		17.6	18.8	19.9	2.3
13.1	14.9	16.8	3.7		14.3	16.2	18.1	3.8
15.1	16.9	18.8	3.7		16.6	18.5	20.4	3.8
15.8	19.1	22.3	6.6		16.4	18.3	20.2	3.8
15.4	18.7	21.9	6.6		16.1	18.0	19.9	3.8
1.2	4.5	7.8	6.6		2.4	4.3	6.2	3.8
14.8	18.1	21.4	6.6		15.6	17.5	19.3	3.8
15.0	15.9	16.9	1.9		14.7	15.4	16.1	1.4
15.0	15.9	16.9	1.9		14.7	15.4	16.1	1.4
15.0	15.9	16.9	1.9		14.7	15.4	16.1	1.4
15.0	15.9	16.9	1.9		14.7	15.4	16.1	1.4
15.0	15.9	16.9	1.9		14.7	15.4	16.1	1.4
15.0	15.9	16.9	1.9		14.7	15.4	16.1	1.4
15.0	15.9	16.9	1.9		14.7	15.4	16.1	1.4
15.0	15.9	16.9	1.9		14.7	15.4	16.1	1.4
15.0	15.9	16.9	1.9		14.7	15.4	16.1	1.4
15.0	15.9	16.9	1.9		14.7	15.4	16.1	1.4

The above analysis was repeated for percent insulation removed as shown in Table 5.27. Again, as expected the confidence band in the design with 2 replications was significantly narrower. The narrower confidence band further increased the legitimacy of the regression model #3 for percent insulation removed.

Table 5.27 - Central Composite Design II Confidence Intervals – Percent Insulation

1 Replication					2 Replication			
Lower 95% CI	Fitted Value	Upper 95% CI	Confidence Band		Lower 95% CI	Fitted Value	Upper 95% CI	Confidence Band
-4.9	6.4	17.6	22.5		-0.6	5.7	12.1	12.7
9.7	21.1	32.6	23.0		11.5	18.0	24.5	12.9
-3.3	9.0	21.3	24.6		4.0	11.0	17.9	13.8
76.8	89.2	101.5	24.6		84.4	91.3	98.3	13.9
-6.4	4.8	16.1	22.5		-1.1	5.2	11.5	12.7
11.5	23.0	34.5	23.0		19.7	26.2	32.6	12.9
4.5	16.7	29.0	24.6		9.4	16.3	23.2	13.8
72.2	84.5	96.9	24.6		79.7	86.7	93.6	13.9
9.3	20.5	31.8	22.5		15.6	22.0	28.3	12.7

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4.2	15.7	27.2	23.0		7.5	14.0	20.4	12.9
2.2	14.4	26.7	24.6		7.2	14.1	21.0	13.8
74.9	87.2	99.6	24.6		77.5	84.4	91.4	13.9
3.7	15.0	26.2	22.5		8.8	15.1	21.4	12.7
10.2	21.7	33.2	23.0		16.9	23.4	29.8	12.9
-7.7	4.6	16.9	24.6		-3.1	3.8	10.7	13.8
70.4	82.8	95.1	24.6		76.3	83.2	90.1	13.9
14.2	25.4	36.7	22.5		19.1	25.4	31.8	12.7
39.3	50.8	62.3	23.0		43.7	50.1	56.6	12.9
63.4	75.7	88.0	24.6		68.0	74.9	81.8	13.8
49.5	61.8	74.2	24.6		56.7	63.6	70.6	13.9
4.4	15.7	26.9	22.5		10.1	16.4	22.8	12.7
9.8	21.3	32.8	23.0		15.5	22.0	28.4	12.9
34.6	46.9	59.2	24.6		39.8	46.7	53.7	13.8
46.4	58.8	71.1	24.6		49.4	56.3	63.2	13.9
14.1	25.4	36.6	22.5		21.4	27.7	34.0	12.7
24.5	36.0	47.4	23.0		29.3	35.8	42.2	12.9
22.3	34.6	46.9	24.6		27.6	34.5	41.4	13.8
89.1	101.5	113.8	24.6		94.6	101.6	108.5	13.9
22.8	34.0	45.2	22.5		28.5	34.8	41.1	12.7
-0.1	11.4	22.8	23.0		3.5	10.0	16.4	12.9
32.0	44.3	56.6	24.6		39.9	46.8	53.7	13.8
88.1	100.4	112.7	24.6		93.6	100.5	107.4	13.9
13.3	22.8	32.3	19.0		18.0	23.4	28.7	10.7
83.3	92.8	102.3	19.0		87.0	92.4	97.7	10.7
-2.0	3.9	9.7	11.7		0.9	4.1	7.4	6.6
81.5	87.3	93.1	11.7		84.3	87.6	90.8	6.6
31.4	40.9	50.4	19.0		34.2	39.6	44.9	10.7
18.2	27.7	37.2	19.0		22.3	27.6	33.0	10.7
25.5	35.0	44.5	19.0		31.1	36.5	41.8	10.7
31.1	40.6	50.1	19.0		36.4	41.7	47.1	10.7
-8.5	1.0	10.5	19.0		-4.3	1.1	6.4	10.7
25.1	34.6	44.1	19.0		29.3	34.6	40.0	10.7
42.0	45.6	49.2	7.1		43.8	45.8	47.9	4.0
42.0	45.6	49.2	7.1		43.8	45.8	47.9	4.0
42.0	45.6	49.2	7.1		43.8	45.8	47.9	4.0
42.0	45.6	49.2	7.1		43.8	45.8	47.9	4.0
42.0	45.6	49.2	7.1		43.8	45.8	47.9	4.0
42.0	45.6	49.2	7.1		43.8	45.8	47.9	4.0
42.0	45.6	49.2	7.1		43.8	45.8	47.9	4.0
42.0	45.6	49.2	7.1		43.8	45.8	47.9	4.0
42.0	45.6	49.2	7.1		43.8	45.8	47.9	4.0
42.0	45.6	49.2	7.1		43.8	45.8	47.9	4.0

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6.0 MULTI-OBJECTIVE OPTIMIZATION

With the three models developed and confirmed, the next step was to utilize the models to perform a multi-objective optimization so that the ideal process parameters could be selected. These ideal parameters are the levels that allow the achievement of the optimum pull strength and percent insulation removed results simultaneously. The 3 models developed each represented the objective functions (or independent variables) in the optimization while the specific levels of their terms represented the dependent variables. Two different mathematical programming methodologies were used to establish the optimization on the regression based model, the weighting method and goal programming. For model #3, a response surface optimizer was also used to perform the non-linear optimization.

6.1 Weighting Method on Model #1

The weighting method is a multi-objective optimization method that develops a set of non-dominated solutions as described by Labadie et al. (1992). In the weighting method weights, w_i are assigned to the objective functions, $f_k(\underline{x})$ to provide a relative importance value to the functions. The products of the weights times the objective is maximized by finding the optimum parameters to achieve the maximization as outlined in eqn. (6.1).

eqn. (6.1) $$\max f(\underline{x}) = \Sigma\, w_k * f_k(\underline{x})$$

The problem described in this dissertation was set-up in Microsoft Excel® as a maximization problem described in eqn. (6.1). The two objective functions (eqn. (6.2 and 6.3)) were taken from model #1 developed above.

eqn. (6.2) $$\begin{aligned}&f_1(\underline{x}) = \text{pull strength(lbs)} = -103+12.0*T+49.9*V-0.591*U-1.08*C+3.44*F-5.83*T*V-\\&0.354*T*F+0.638*V*C-1.46*V*F+0.0511*U*C+0.0130*U*F+0.0372*C*F+\\&0.0477*T*V*U+0.176*T*V*F-0.00260*T*U*C+0.00161*T*U*F-0.00046*T*C*F-\\&0.0150*V*U*C+0.00619*V*U*F-0.0211*V*C*F-0.00110*U*C*F+\\&0.00045*T*V*U*C-0.00265*T*V*U*F+0.000275*T*V*C*F+0.000031*T*V*U*C*F\end{aligned}$$

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eqn. (6.3) $f_2(\underline{x})$ = percent insulation removed(%) = $115-4.73*T-93.0*V-9.37*C-3.92*F+13.4*T*V-0.601*T*U+1.51*T*C+6.55*V*C+2.8*V*F+0.478*C*F-0.0076*U*F-1.41*T*V*C-0.247*T*V*F+0.0234*T*U*F-0.0886*T*C*F-0.0034*V*U*C-0.299*V*C*F+0.00095*U*C*F+0.0164*T*V*U*C+0.0661*T*V*C*F-0.000023*T*U*C*F-0.000661*T*V*U*C*F$

Where: T is weld time in msec
V is weld voltage in volts
C is cooling time in msec
U is upslope in percentage
F is force in lbs.

The weights were varied to determine the set of non-dominated solutions however the base weights were established so that pull strength was twice as important as percent of insulation removed ($w_1=2$, $w_2=1$). These particular values of the weights were assigned because it was determined that while it is desirable to have as much of the insulation removed as possible the only real requirement of an acceptable part is one that has a good weld in at least one location. The amount of insulation removed is related to this but the pull strength is the ultimate indication that a satisfactory weld had occurred. For that reason it was established that the pull strength of the weld is of higher importance than percent of insulation removed. Once the problem was set up, Microsoft Excel Solver® was used to arrive at a solution. For model #1 the Microsoft Excel Solver® uses the simplex method with bounds on the variables implemented by John Watson and Dan Fylstra, Frontline Systems, Inc. For models #2 and #3 the Microsoft Excel Solver® uses the Generalized Gradient (GRG2) non-linear optimization code developed by Leon Lasdon, University of Texas at Austin and Allan Warren, Cleveland State University. The sum in eqn. (6.1) was set as the target cell and the process parameters for weld voltage, weld force, cooling time, upslope and weld time were set up as the cells to be varied. Listed in Table 6.1 are the constraints that were coded into the problems.

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Table 6.1 – Weighting Method Constraints

Value	*Constraint*
Weld Voltage	1.2 <= x <= 2.4
Weld Force	0 <= x <= 100
Weld Time	2 <= x <= 22
Cooling Time	0 <= x <= 30
Upslope	0 <= x <= 50
Pull Strength	0 < x <= 21.4
Percent Insulation Removed	0 <= x <= 100

The constraints were based on the feasibility section lobe curves and from realistically feasible extensions from those limits as well as the limits used in the designed experiments. The limits on the weld voltage and time are the approximate physical limits in the amount of heat that can be transferred through the terminal before blowing out on the higher end and are the minimum level voltages required to perform a weld on the lower end. These values were taken off of the lobe curve. The weld force is the reasonable limits that are attainable by the weld head and sustainable by the part. This limit was a substantial extension from the designed experiment values. The cooling time and upslope were reasonable extensions from the limits used in the designed experiments. The pull strength was the allowable limits of the pull strength of the wire alone. The 21.4lbs (9.71kg) upper limit is the 3σ limit on the wire tensile strength. The solver converged on one non-dominated solution, which was a feasible set outlined in the trials performed. Model #1 optimum results for both the independent and dependent variables are listed in Table 6.2.

Table 6.2 – Weighting Method Optimum Solution – Model #1

Weld Voltage	*Weld Time*	*Weld Force*	*Cooling Time*	*Upslope*	*Predicted Pull Strength*	*Predicted Percent Insulation Removed*
2.4volts	10.6msec	28lbs (12.70kg)	29msec	1%	21.4 lbs (9.71kg)	100%

6.2 Goal Programming on Model #1

The goal programming method is also a multi-objective optimization method that develops a set of non-dominated solutions as described by Labadie et al. (1992). In the goal programming method weights, w_i

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are also assigned to the difference in an particular objective functions $F_i(\underline{x})$ and its prescribed target T_i, to provide a relative importance value to the functions. The products of the weights times the absolute value of the objective function minus the target is minimized by finding the optimum parameters to achieve the minimization as outlined in eqn. (6.4).

eqn. (6.4) $\min \Sigma\, w_i * | F_i(\underline{x}) - T_i |$

The difference between the objective function and the target is often described as the deviation, d_i. If the objective function is above the target the absolute value of the deviation is d_i^+. If the objective function is below the target the absolute value of the deviation is d_i^-. With these definitions of deviations eqn. (6.4) can be re-written as eqn. (6.5).

eqn. (6.5) $\min \Sigma\, w_i * (d_i^+ + d_i^-)$

The problem described in this dissertation was set-up in Microsoft Excel® as a minimization problem described in eqn. (6.5). The two objective functions (eqn. (6.2 and 6.3)) were taken from model #1 developed above. The weights were varied to determine the set of non-dominated solutions however the base weights were established the same as was done in the weighting method above. The target for pull strength was set at the upper 3σ limit of the wire tensile strength, 21.4lbs (9.71kg). The target for the percent of insulation removed was set at 100%. Once the problem was set up, Microsoft Excel Solver® was used again to arrive at a solution. The sum in eqn. (6.5) was set as the target cell and the process parameters for weld voltage, weld force, cooling time, upslope and weld time were set up as the cells to be varied. The same constraints were coded into the problem as in the weighting method.

The solver converged on one non-dominated solution, which was a feasible set outlined in the trials performed. The optimum solution provided a $\Sigma\, w_i * (d_i^+ + d_i^-) = 0.0$. The optimum results for both the independent and dependent variables were similar to those obtained with the weighting method and are listed in Table 6.3.

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Table 6.3 – Goal Programming Optimum Solution – Model #1

Weld Voltage	*Weld Time*	*Weld Force*	*Cooling Time*	*Upslope*	*Predicted Pull Strength*	*Predicted Percent Insulation Removed*
2.4volts	10.1msec	29lbs (13.16kg)	30msec	1%	21.4 lbs (9.71kg)	100%

6.3 Weighting Method on Model #2

The weighting method was also used as a multi-objective non-linear optimization method to develop a set of non-dominated solutions from the non-linear models. The problem was again set-up in Microsoft Excel® as a maximization problem described in eqn. (6.1). The two objective functions (eqn. (6.6 and 6.7)) were taken from model #2 developed above.

eqn. (6.6) $f_1(\underline{x})$ = pull strength(lbs) = -23.30+21.39•weld voltage(volts)+0.60•force(lbs)-4.89•weld voltage^2(volts^2)-0.03•weld time(msec)•force(lbs)

eqn. (6.7) $f_2(\underline{x})$ = percent insulation removed(%) = 430.2-316.4•weld voltage(volts)-32.7•time(msec)+0.7•time^2(msec^2)+10.1•weld voltage(volts)•time(msec)+2.9•weld voltage(volts)•force(lbs)+0.3•time(msec)•force(lbs)

The weights were again varied to determine the set of non-dominated solutions however the base weights remained the same (w_1=2, w_2=1). Once the problem was set up, Microsoft Excel Solver® was again used to arrive at a solution. The sum in eqn. (6.1) was set as the target cell referencing the new objective functions and the process parameters for weld voltage, weld force and weld time were set up as the cells to be varied. The constraints were the same that was used in Table 6.1. The solver converged on one non-dominated solution, which was a feasible set outlined in the trials performed. Model #2 optimum results for both the independent and dependent variables are listed in Table 6.4.

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Table 6.4 – Weighting Method Optimum Solution – Model #2

Weld Voltage	*Weld Time*	*Weld Force*	*Predicted Pull Strength*	*Predicted Percent Insulation Removed*
2.2volts	**6msec**	**50lbs (22.69kg)**	**21.4 lbs (9.71kg)**	**100%**

6.4 Goal Programming on Model #2

The goal programming method was also used as a multi-objective optimization method to develop a set of non-dominated solutions based on model #2.

The non-linear problem was set up in Microsoft Excel® as a minimization problem in the same manner as the regression model described in eqn. (6.5). The two objective functions (eqn. (6.6 and 6.7)) were again taken from model #2 developed above. The weights were again varied to determine the set of non-dominated solutions however the base weights were established the same as was done in the weighting method above. The same targets used with model #1 for pull strength and percent insulation removed were used with model #2. Once the problem was set up, Microsoft Excel Solver® was used again to arrive at a solution. The sum in eqn. (6.5) referencing the new objective functions was set as the target cell and the process parameters for weld voltage, weld force and weld time were set up as the cells to be varied. The same constraints were coded into the problem as in the weighting method.

The solver converged on one non-dominated solution, which was a feasible set outlined in the trials performed. The optimum solution provided a $\Sigma\, w_i * (d_i^+ + d_i^-) = 1.0$. The optimum results for both the independent and dependent variables were similar to those obtained with the weighting method and are listed in Table 6.5.

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Table 6.5 – Goal Programming Optimum Solution – Model #2

Weld Voltage	*Weld Time*	*Weld Force*	*Predicted Pull Strength*	*Predicted Percent Insulation Removed*
2.2volts	5.6msec	50lbs (22.69kg)	21.8 lbs (9.89kg)	99.8%

6.5 Response Surface Optimization on Model #2

The final multi-objective response surface non-linear optimization method used was the response surface optimizer available in the statistical software application, Minitab®. Minitab's Response Surface Optimizer® allows for the identification of the combination of variable settings that jointly optimize a set of response variables based on response surface methodology. Joint optimization must satisfy the requirements for both of the responses in the set. The overall desirability, D is a measure of how well the combined goals of both of the responses have been met. Minitab® calculates an optimal solution and develops a plot. The optimal solution serves as a starting point for the plot.

The response optimizer was setup as a maximization problem for both response variables simultaneously. The range for response variable pull strength was set at a minimum of 0 to a target of 21.4lbs (0-9.71kg) with a weight of 2. The range for the response variable percent insulation removed was set at a minimum of 0 to a target of 100% with a weight of 1. The criteria / justification for the range of the response variables are the same as in the previous two methods reviewed. The optimizer was run with the results plotted in Figure 6.1.

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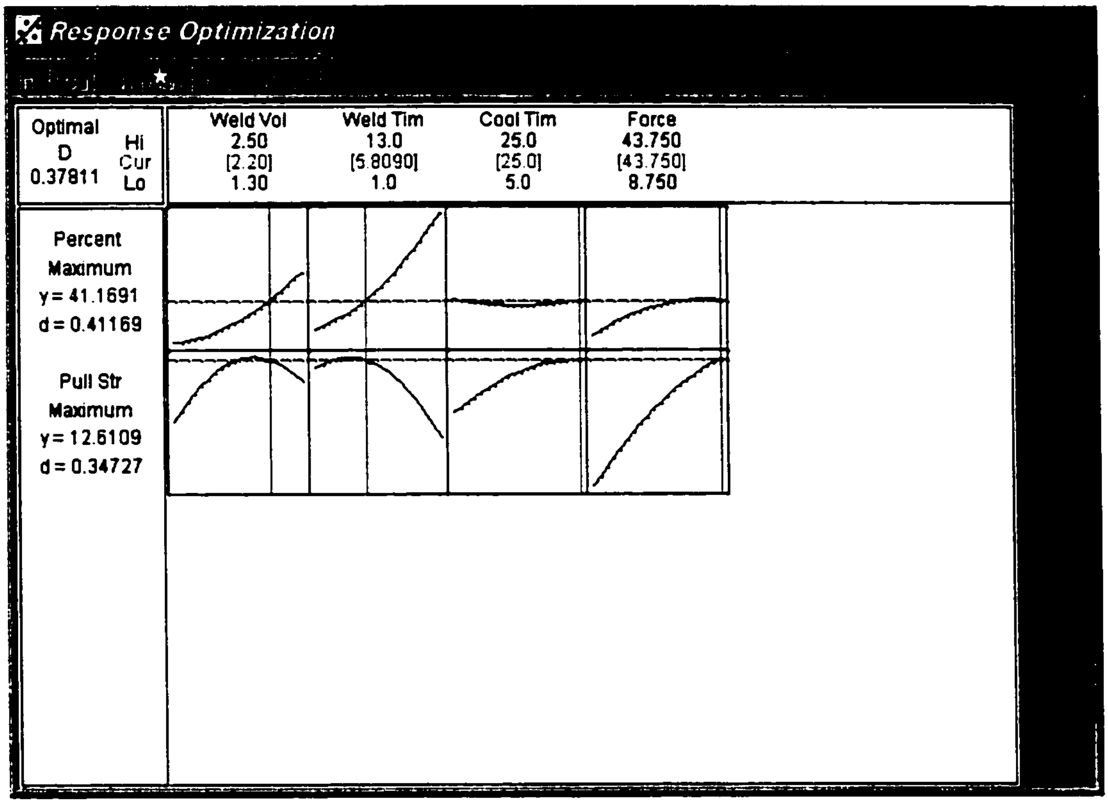
Figure 6.1 – Response Optimizer Plot – Model #2



The results are lower then obtained in the first two methods because the weld force was limited to 43.75lbs (19.85kg) as the upper limit in the design space outlined by the central composite designed experiment. In the first two optimizations the weld force was extended beyond the DOE design space to the approximate feasible limit. The optimum results for both the independent and dependent variables are listed in Table 6.6.

Table 6.6 – Response Surface Optimization Solution – Model #2

Weld Voltage	*Weld Time*	*Cool Time*	*Weld Force*	*Predicted Pull Strength*	*Predicted Percent Insulation Removed*
2.2volts	5.8msec	25msec	43.75lbs (19.85kg)	12.6lbs (5.72kg)	41.2%

All of the three response surface non-linear optimization methods used produced similar results except for the response surface optimization because of the design space limitation on weld force. Each method also produced a solution that was feasible in the set of trials performed.

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6.6 Weighting Method on Model #3

The weighting method was also used as a multi-objective non-linear optimization method to develop a set of non-dominated solutions from model #3. The problem was again set-up in Microsoft Excel® as a maximization problem described in eqn. (6.1). The two objective functions (eqn. (6.8 and 6.9)) were taken from model #3 developed above.

eqn. (6.8)

$$f_1(\underline{x}) = \text{pull strength(lbs)} = -278+136*V+56.1*T+6.87*U+14.1*C+3.46*VSQ+0.0141*USQ+0.0195*CSQ-0.0106*FSQ-24.8*T*V-1.47*T*U-2.79*T*C-0.347*T*F-3.84*V*U-7.91*V*C+0.538*V*F-0.426*U*C-0.202*C*F+0.638*T*V*U+1.33*T*V*C+0.0837*T*U*C+0.00820*T*U*F+0.0444*T*C*F+0.238*V*U*C+0.0950*V*C*F+0.00824*U*C*F-0.0404*T*V*U*C-0.0169*T*V*C*F-0.00163*T*U*C*F-0.00480*V*U*C*F+0.000719*T*V*U*C*F+0.910*F$$

eqn. (6.9)

$$f_2(\underline{x}) = \text{percent insulation removed(\%)} = 876-662*V-339*T-20.4*U-2.52*C-47.7*F+23.8*VSQ-0.0874*USQ-0.0481*CSQ-0.0653*FSQ+180*T*V+9.24*T*U+8.86*T*C+15.9*T*F+14.7*V*U+4.30*V*C+30.6*V*F+1.07*U*F+0.838*C*F-4.56*T*V*U-4.47*T*V*C-8.23*T*V*F-0.264*T*U*C-0.399*T*U*F-0.469*T*C*F-0.0011*V*U*C-0.638*V*U*F-0.503*V*C*F+0.120*T*V*U*C+0.194*T*V*U*F+0.236*T*V*C*F+0.0113*T*U*C*F-0.00507*T*V*U*C*F$$

Where:
T is weld time in msec
V is weld voltage in volts
C is cooling time in msec
U is upslope in percentage
F is force in lbs.
SQ is any of the above terms squared

The weights were again varied to determine the set of non-dominated solutions however the base weights remained the same ($w_1=2$, $w_2=1$). Once the problem was set up, Microsoft Excel Solver® was again used to arrive at a solution. The sum in eqn. (6.1) was set as the target cell referencing the new objective functions and the process parameters for weld voltage, weld force and weld time were set up as the cells to be varied. The constraints were the same that was used in Table 6.1. The solver converged on one non-

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dominated solution, which was a feasible set outlined in the trials performed. The model #3 optimum results for both the independent and dependent variables are listed in Table 6.7.

Table 6.7 – Weighting Method Optimum Solution –Model #3

Weld Voltage	*Weld Time*	*Weld Force*	*Cooling Time*	*Upslope*	*Predicted Pull Strength*	*Predicted Percent Insulation Removed*
2.1volts	16.1msec	28lbs (12.70kg)	4msec	0%	21.4 lbs (9.71kg)	100%

6.7 Goal Programming on Model #3

The goal programming method was also used as a multi-objective optimization method to develop a set of non-dominated solutions based on model #3.

The non-linear problem was set up in Microsoft Excel® as a minimization problem in the same manner as described in eqn. (6.5). The two objective functions (eqn. (6.8 and 6.9)) were again taken model #3 developed above. The weights were again varied to determine the set of non-dominated solutions however the base weights were established the same as was done in the weighting method above. The same targets used with model #1 for pull strength and percent insulation removed were used with model #3. Once the problem was set up, Microsoft Excel Solver® was used again to arrive at a solution. The sum in eqn. (6.5) referencing the new objective functions was set as the target cell and the process parameters for weld voltage, weld force and weld time were set up as the cells to be varied. The same constraints were coded into the problem as in the weighting method.

The solver converged on one non-dominated solution, which was a feasible set outlined in the trials performed. The optimum solution provided a $\Sigma w_i * (d_i^+ + d_i^-) = 0.0$. The optimum results for both the independent and dependent variables were similar to those obtained with the weighting method and are listed in Table 6.8.

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Table 6.8 – Goal Programming Optimum Solution – Model #3

Weld Voltage	*Weld Time*	*Weld Force*	*Cooling Time*	*Upslope*	*Predicted Pull Strength*	*Predicted Percent Insulation Removed*
2.1volts	9.0msec	28.4lbs (12.89kg)	3.1msec	0%	21.4 lbs (9.71kg)	100%

As shown in Table 6.9, the optimization results from all of the models produced very similar results for the predicted responses except for the response surface optimizer method because of the design limits on force. All values presented are in the feasible region for process parameters. The fact that the optimum responses are very similar for different models and methods validates the analysis. The results from the models with a lack of satisfactory statistical fit alone could be brought into question. That fact that the similar results were obtained from subsequent models, with better goodness of fit, as indicated by the R^2 values, increased the confidence in the results.

Table 6.9 – Optimization Summary

Optimization Method	*Optimized Weld Voltage*	*Optimized Weld Time*	*Optimized Weld Force*	*Optimized Cooling Time*	*Optimized Upslope*	*Predicted Pull Strength*	*Predicted Percent Insulation Removed*
Weighting Method Model #1	2.4volts	10.6msec	28lbs (12.70kg)	29msec	1%	21.4 lbs (9.71kg)	100%
Goal Programming Model #1	2.4volts	10.1msec	29lbs (13.16kg)	30msec	1%	21.4 lbs (9.71kg)	100%
Weighting Method Model #2	2.2volts	6msec	50lbs (22.69kg)	-	-	21.4 lbs (9.71kg)	100%
Goal Programming Model #2	2.2volts	5.6msec	50lbs (22.69kg)	-	-	21.8 lbs (9.89kg)	99.8%
Response Optimizer Model #2	2.2volts	5.8msec	43.75lbs (19.85kg)	25msec	-	12.6lbs (5.72kg)	41.2%
Weighting Method Model #3	2.1volts	16.1msec	28lbs (12.70kg)	4msec	0%	21.4 lbs (9.71kg)	100%
Goal Programming Model #3	2.1volts	9.0msec	28.4lbs (12.89kg)	3.1msec	0%	21.4 lbs (9.71kg)	100%

To confirm the above results additional microjoining experiments were conducted at the optimized process settings provided by the goal programming analysis on model #3. These settings were chosen because they represented the results from the model with the best statistical fit. Pull strength and percent insulation removed were measured, the average pull strength for the trials was 20.9lbs (9.48kg) with a standard deviation of 1.1lbs (0.49kg). The results of these experiments are shown in the histogram in Figure 6.2. In

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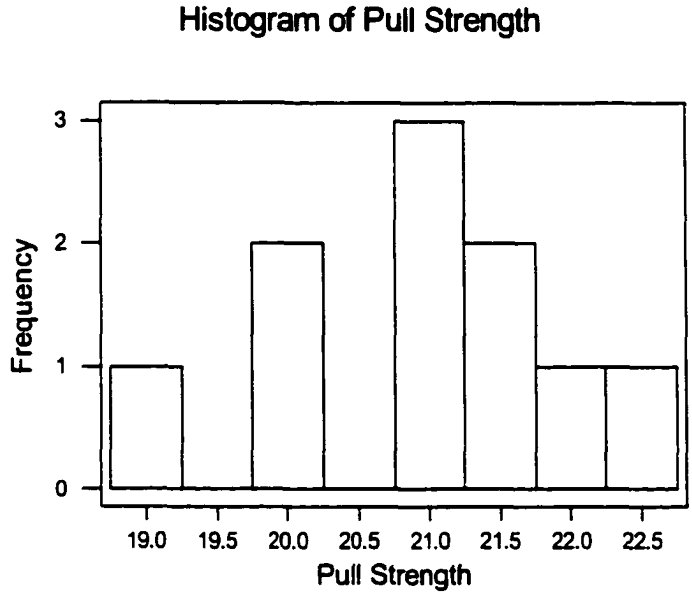
addition, in each of the trials performed, 100% of the insulation was removed. These results provide a validation of the modeling and optimization process.

Figure 6.2 - Histogram of Pull Strength Values



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7.0 DISCUSSION OF RESULTS

Microjoining

The application studied was for a specific terminal design, magnet wire diameter and magnet wire insulation. Microjoining was chosen for this study based on the specific requirements of this project. The joint quality assessment methods chosen represented satisfactory methods to evaluate the quality of the joint based on variability, ease of use, time involved in performing the evaluation and equipment available. However, a significant amount of variability remained in the response results. This is especially the case in the fringe areas of the lobe curve. Variation increased at the extreme process parameter settings. For most of the assessment methods, as you moved further away from the optimum operation point it became more difficult to repeat the results. This is a topic for future investigation. That is to establish the robustness of the solution.

For the purposes of this study the controlled process parameters were weld voltage, weld force, upslope and weld time of the welding pulse, as well as cooling time between the seating pulse and welding pulse. These variables were shown to be sufficient for the case of microjoining process, to establish a process that fulfilled the requirements established in the scope of the research and for the models as outlined by the models developed in the statistical analysis.

Response Surface Methodology

The traditional practice in designed experiments is to assume that interaction effects of higher order than 2-way interactions are not statistically significant and squared terms are rarely included. In the statistical analysis section of this dissertation it was shown that interaction effects as high as 5-way and squared terms could be statistically significant in microjoining of magnet wire. This is a significant finding, since there were only two other documented studies that addressed welding designed experiment interaction effects (Gould and Lehman (1994 & 1997) and Salter and Doherty (1981)). These studies followed traditional practice and did not analyze higher order interaction effects in detail. Gould and Lehman (1994 & 1997)

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considered main, 2-way interaction effects and did not include interactions higher than 2-way or squared effects. Gould and Lehman (1994 & 1997) showed that 2-way interaction effects significantly affected the quality of resistance spot welds. However, this work was not carried beyond the 2-way effects or extended to squared terms. Salter and Doherty (1981) expanded the notion in an arc welding application in which a three-factor interaction effect was considered statistically significant and included it in a mathematical model. Salter's results corroborate the findings of this dissertation that it is important to include higher order interaction effects. Not taking interaction effects beyond two factor interactions into account has been the normal course of action that has been taken in the majority of welding designed experiments. Although Salter and Doherty (1981) included an interaction effect higher than two factor, they failed to evaluate the performance of the mathematical model in detail and merely evaluated the significance of terms and proposed a model.

Listed in Table 7.1 is the performance of the models developed in this study by the terms that were included.

Table 7.1 – Model Performance by Terms

Model	*Terms Included in Model*	*Percent Insulation Removed R^2*	*Percent Insulation Removed R^2 (adjusted)*	*Pull Strength R^2*	*Pull Strength R^2 (adjusted)*
Model #3	Linear, Interactions through 5-way and Statistically Significant Squared Terms	97.6%	96.5%	85.8%	79.7%
Model #1	Linear and Interactions through 5-way	95.2%	92.6%	86.2%	85.0%
Model #2	Linear, Interactions through 2-way and Statistically Significant Squared Terms	85.0%	71.9%	76.0%	55.0%
Gould	Linear and Interactions through 2-way	81.0%	77.8%	59.6%	52.7%

All previous documented work would have stopped with a model performance of $R^2 = 81.0\%$ for percent insulation removed and $R^2 = 59.6\%$ for pull strength. With this type of model performance, there would be lower confidence in the results attained through the optimization because of the models lack of goodness of fit. Because of this lack of goodness of fit from the model, the use of designed experiments in welding would be a questioned. It is believed that this may be a significant factor in why designed experiments are

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The apparent reason for the significance of higher order interactions in microjoining, as outlined in the statistical analysis, is the nature cross-correlation of process parameters caused by the physics of the process. This cross-correlation from the physics of the process is explained from the equation for thermal energy. Quantifying the amount of cross-correlation and using this information to re-specify the model is another opportunity for future investigation.

Optimization

Three separate optimization methods were applied to the various models developed in the multi-objective non-linear optimization section of this dissertation. The similar results from the different optimization methods further confirmed the results of the analysis. The models having a better goodness of statistical fit increased the confidence in the results obtained.

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8.0 CONCLUSIONS

The dissertation research achieves significant contributions to the state-of-the art in microjoining of magnet wire in three distinct areas;

1. The use of response surface methodology based non-linear design of experiment techniques in the development of a welding process.
2. The integration of non-linear mathematical programming optimization techniques to prescribe the optimum welding process.
3. The development of the microjoining product/process in terminating magnet wire without prior removal of the insulation.

A microjoining design and process has been developed to join 0.65mm diameter, copper magnet wire with polyesterimide over-coated polyamideimide insulation to tin plated brass terminals without prior removal of the insulation of the wire. This design and process was developed through the application of response surface methodology to develop a representative mathematical model. This mathematical model was then optimized to determine the optimum process parameter values. This work resulted in the following important advancements:

Response Surface Methodology

1. When evaluating welded 0.65mm diameter, copper magnet wire with polyesterimide over-coated polyamideimide insulation, the pull strength of the weld in a response surface analysis is dependent on a non-linear square relationship with the weld voltage and weld time. Mathematical models were developed to model pull strength and percent insulation removed that included linear, squared and interaction terms through 5 factors. These models had a maximum coefficient of determination of 86.3% for pull strength and 98.1% for percent insulation removed. The results of included higher order interaction and squared terms and has advanced the potential for understanding of mathematical modeling of the welding process. These procedures are hypothesized to be transferable to other welding processes.

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Optimization

2. Three non-linear, multi-objective programming methods (weighting method, goal programming and response surface optimization) were applied to the mathematical models developed. These methods provided similar optimum process settings for welding 0.65mm diameter, copper magnet wire with polyesterimide over-coated polyamideimide insulation to tin plated brass terminals without prior removal of the insulation of the wire. The similar predicted response results from the models, especially the models with better statistical goodness of fits, increased the confidence in the optimum process settings established.

Microjoining

3. A microjoining design and process has been developed to join 0.65mm diameter, copper magnet wire with polyesterimide over-coated polyamideimide insulation to tin plated brass terminals without prior removal of the insulation of the wire.

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APPENDIX

THE DEVELOPMENT OF THE MICROJOINING PRODUCT/PROCESS

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1.0 APPENDIX OVERVIEW

The purpose of the appendix is to outline the application base for the development of response surface methodologies to microjoining of magnet wire without prior removal of insulation. As stated above the development of a specific application is required to perform the analysis that constitutes the focus of the dissertation research. The development of the microjoining magnet wire product/process will serve as this application.

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2.0 MICROJOINING IGNITION COIL TERMINAL / MAGNET WIRE PROJECT

2.1 Scope

As stated above, a number of other technologies were investigated in the work proceeding this research. Microjoining was selected for investigation based on the particulars of the product and process and thus constitutes the scope of this dissertation research. The considerations in choosing this technology valued the product design, existing process performance, company history and the process and product goals. This section of the dissertation reviews the application of microjoining techniques to a specific ignition coil – primary coil circuit terminal to magnet wire joint. The dissertation reviews the experiments performed and the results of the product and process findings enabling successful termination of the magnet wire without prior removal of the insulation. The research then builds on the development of the feasibility experimentation in the main body of the dissertation to develop a non-linear mathematical model using design of experiment methods. Listed below are the process and product specific goals that defined the scope of the project. With alternate goals and in other circumstances one of the other investigated process technologies might have been chosen.

2.2 Product Goals

In defining the scope of the work to be performed, a number of product specific goals were established. The goals centered on establishing a replacement process for soldering that did not lead to a major redesign of the product. Listed below are the product goals that were established to guide the research:

1. Any changes to the product/process would be transparent to the exterior appearance of the ignition coil and thus transparent to the customer.
2. Any changes should not effect the ignition coil electrical parameters or performance.
3. The change should reduce the overall material cost and improve the product's durability and/or reliability.
4. The product changes would pose a solution that was environmental and safety friendly with respect to recycleability, hazardous materials and ventilation.

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2.3 Process Goals

In defining the scope of the work to be performed a number of process goals were also established. Listed below are the process goals that were established to guide the research:

1. The cycle time would not be increased in searching for a replacement to soldering.
2. The process reliability was to be increased (less downtime) while the process robustness was also increased to minimize the variation.
3. The process developed was to also be environmental and safety friendly with respect to recycleability, hazardous materials and ventilation.

2.4 Microjoining

Microjoining offers many product benefits as a potential solution to the joining of magnet wire. As outlined by Riches (1994), magnet wire is difficult to join primarily because it is difficult to remove insulation and the high electrical and thermal conductivity copper hinders the generation of heat required at the joint interfaces. Listed below are the product benefits of using microjoining:

1. Microjoining also offers the advantage of being a replacement to most soldering applications with little redesign required and with an improvement in joint integrity.
2. The clamping force performed by the electrodes often can compensate for product assembly issues where tight tolerances of proximity between parent materials are difficult to achieve.
3. In most case microjoining offers an environmentally friendly process by not requiring flux, solvents, lead-based products, etc.
4. Microjoining can serve as a potential material cost reduction in that there is not a need for a third joining material like solder.

On the process side, microjoining has many benefits as well. Listed below are the process benefits of using microjoining:

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1. In most cases microjoining processes can be set up to improve cycle time and overall process efficiency and reliability in comparisons with soldering.
2. The HF (high frequency) inverter welding equipment specifically offers many advantages as pointed out by Ely (1997). The HF inverter can perform advanced program schedules (dual pulsing), can be operated in current, voltage and power modes, offers complete control over current, time (including upslope and downslope), energy and power and it is very repeatable. The mode and advanced program schedules are very important when welding magnet wire. The dual pulse can be used as first proposed by Riches (1994) where the first pulse breaks through the insulation and the second pulse actually performs the weld. Riches (1994) also points out that this idea has not been widely investigated but the notion is expanded in this paper.

While many of the different process technologies outlined above meet some of the product and process goals, a solution involving microjoining, on this specific project, met all of them. For that reason microjoining was chosen as the technology to pursue.

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3.0 EXPERIMENTAL DETAILS

3.1 Materials

The material used during the experiment was production magnet wire and prototype terminals (lead frames). The magnet wire was 0.65mm enameled round copper magnet wire with 0.0295mm of polyesterimide over-coated polyamideimide insulation. The terminals were prototype lead frames that were 0.8mm thick, 2680R yellow brass (65Cu-35Zn) w/ 3-5µ tin plating in widths of 2.5mm and 3.3mm.

3.2 Equipment

Samples were welded on a Unitek Equipment 2kHz HF (high frequency) inverter weld controller. The HF inverter welder offers flexibility in the ability to control many different potential factors. The welder used a Unitek Series 180 Thin-Line dual 100lb (45.4kg) weld head configured for parallel gap welding. The electrode configuration/design consisted off two different materials. A tungsten electrode (0.094inch (2.39mm) diameter with an offset tip) was the electrode used on one side of the weld head. On the other side of the weld head a copper electrode (0.25inch (6.35mm) diameter shank) was used. For pull testing results an Ametek EZ250 tensile test machine was used. For evaluating contact resistance an AEMC model 5600 micro ohmmeter was used. For dimensional measurements of the sectioned welds a Browne and Sharpe CMM (coordinate measuring machine) with ram optics package and a video capture card was used to take the measurements and capture the images electronically.

3.3 Welding Procedure

Trials were conducted to find the feasible process control limits. As outlined above the HF inverter welder has the capability of controlling power, current or voltage. The choice of which variable to control is based on two governing the equations, eqn (3.1) ohm's law and eqn. (3.2) the equation for thermal energy.

eqn. (3.1) $V=I*R$ or $P=V*I$

Where V is voltage, I is current, R is contact resistance and P is power

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eqn. (3.2) $H=(V^2 \cdot T)/R$

Where V is voltage, T is time, R is contact resistance and H is thermal energy

Resistance can be influenced by varying the electrode force and is a derived (dependent) variable. Voltage control was chosen as the mode of operation because it provides the best control when the contact resistance varies. A wide range of contact resistance was anticipated during the process as the terminal is folded over the wire, the terminal is seated, the insulation is broken through and the part is welded.

The feasible process control limits were found by determining the lobe curve for the process. Voltage and time were varied for the selected force levels and the welds were classified as either good or bad per the definitions for joint quality assessment. These results were then plotted on a graph of voltage versus time for a selected force level. Each point on each graph was annotated as to whether it produced a good weld or a bad weld. The contour line, called a lobe curve, which connects all of the good welds, constituted the region of process parameters which would produce a good weld. This process was repeated for both seating the terminal and welding the parent metals.

Specifically not addressed in the dissertation were the effects of variation in tin plating, material consistency, contamination (dirt, debris, oils), weld squeeze and hold time, condition of the electrodes, consistency in positioning of the part and dimensional repeatability of the parts used. A decision was made not to include these variables based on the work by Lynch and Duff (2001) for the same ignition coil terminal design, from the situation surrounding the materials and environment and from the performance during initial trials. Further investigations including some or all of these factors may lead to additional insights.

3.4 Joint Quality Assessment – Response Variables

A number of different joint quality assessment methods were evaluated. A visual evaluation was performed as an initial subjective rating. The joint was dismantled by peeling the terminal off of the copper wire. The materials were inspected and amount of copper remaining on the brass terminal, the depth of the indentation in the brass, the amount of insulation removed from the wire and the condition of the copper

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wire were noted. The amount of copper remaining on the brass terminal and the depth of the indentation was an indication of the level of solid state bond that had occurred. The amount of insulation removed from the wire and the condition of the wire provided an indication of insulation removal and joining of the copper to the brass. The base lobe curve of the welding process was established with this visual method and it was compared with some of the objective assessment methods below to aid in establishing the area of the process operating range. For the welds that turned out unsatisfactory (insufficient), there was not a noticeable amount of copper left on the brass terminal, there was not a significant indentation in the brass or there was still insulation remaining on the wire after dismantling the joint. The welds that were unsatisfactory because of excess voltage or time showed signs of expulsion during the process up to the point where the terminal blew out (cracks due to over heating). The welds that were satisfactory provided distinct indications that permitted a positive judgement to be made. The satisfactory welds had the insulation completely removed from the entire surface area of the wire in contact with the terminal. There was also a sizeable indentation in the brass terminal left by the imprint of the wire. Another indication of a satisfactory weld was the evidence of copper deposited in the terminal indentation and the condition of the wire surface showing indication of imperfections in areas that a bond was disrupted. These indications that a bond was disrupted were evident by small imperfections in the condition of the surface of the wire that were caused by a bond tearing material from the wire upon dismantling of the joint.

This visual method was expanded to include a continuous variable. The percentage of insulation removed from the surface of the wire was estimated by a visual inspection. This assessment method was developed when it was determined that whenever 100% of the insulation was removed the result was a satisfactory weld. This method, although dependent on subjective judgement, provided a means for placing a continuous, numerical value on the visual inspection.

Another assessment method was a pull strength test. The tensile test machine detailed above was setup with a gripper on the wire and on the other end a specially designed fixture that held the terminal captive while allowing the wire to move. The specimen was pulled at a rate of 50 mm/min, while monitoring the force, until the jointed failed in tension. The maximum force was then recorded. The local maximum force

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was defined as the force in which the joint initially failed. That is where the wire began to slip in the terminal or when the first cracking of the bond occurred as indicated by sound. The global maximum force was defined as the maximum force required to completely separate wire from the terminal. The local force was selected as the primary measure, since a failure was defined as the first failure of the joint. However, both values were recorded during the experimentation. The preliminary definition of a minimum acceptable weld was originally taken from Dawes (1980) and Riches (1994) as 25% of the wire's tensile strength. A sample set of the 0.65mm wire was pulled to determine an average tensile strength of 20.0lbs (9.08kg) leaving the preliminary target at 5.0lbs (2.27kg). The definition of an acceptable weld was reevaluated based on correlation of the pull strengths to the visual evaluation method above. The lobe graph of the visual evaluation method was transposed over the matrix of pull strength values to establish a guideline for acceptable welds in terms of force. This guideline was then compared with the preliminary target established from previous work to determine the target to be used through the balance of the research.

A third assessment method was based on the percentage of the round copper wire circumference that was joined to the brass. A joint was defined as an obvious solid state bond between the copper and brass as indicated by no distinct line at the joint. The area of no distinct line was an indication of where the solid state weld occurred. If a line (miniscule gap) was evident along a particular section of the circumference between the copper and brass it was considered not to be a satisfactory joint. To inspect the weld, the joint was potted in a clear, two-part epoxy, to maintain its rigidity. The specimen was then sectioned, polished and viewed with the CMM under 250X magnification. The length of the arc indicating a fusion weld on top of the wire was added to the length of the arc indicating a fusion weld on the bottom of the wire to make up the length of arc with a satisfactory welded. This length satisfactory welded was divided by the circumference of the 0.65mm wire to determine the percentage of wire circumference welded. A definition of an acceptable weld was based on correlation of this percentage to the visual evaluation method above. The lobe graph of the visual evaluation method was transposed over the percentage of circumference welded to establish a guideline for acceptable welds in terms of percentage of circumference. A minimum number of data points were taken with this method due to the lengthy process of preparing the samples.

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A fourth assessment method involved measuring the change in vertical diameter (height) of the wire after welding. The background on this evaluation method was that if the desired solid state bond occurred between the copper wire and the brass terminal the vertical diameter of the copper wire would be reduced. This reduction occurs because the part of the copper becomes liquidus and fuses with the brass thus reducing the amount of pure copper away from the heat-effected zone. This method was meant to be analogous to measuring the displacement of the weld head, which has been used often in industry. The specimen was prepared the same way as the third assessment prior to measuring. The diameter of the copper wire between the top and bottom joints was measured and subtracted from the original 0.65mm diameter to determine the reduction in diameter due to welding. This difference was divided by the original 0.65mm diameter to determine the percentage reduction diameter. The lobe graph of the visual evaluation method was used, as it was above to establish a guideline for acceptable welds in terms of percentage reduction in diameter. A minimum number of data points were taken with this method due to the lengthy process of preparing the samples.

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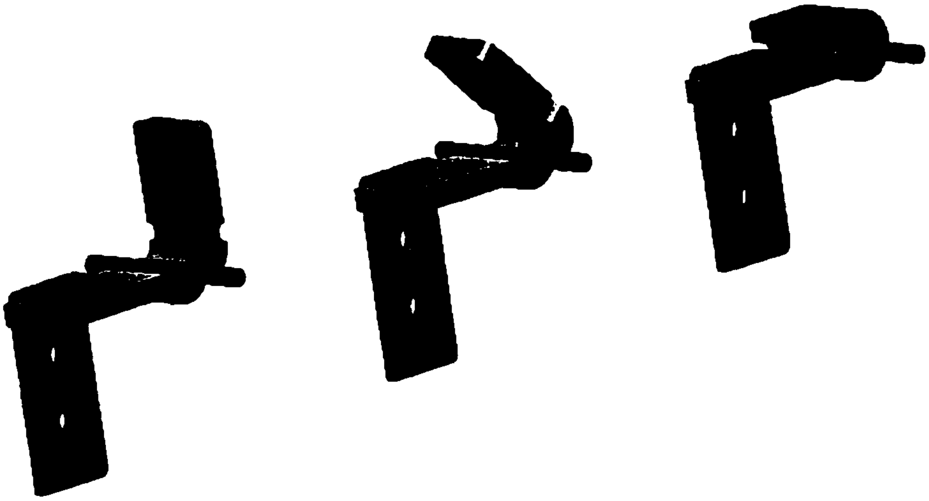
4.0 FEASIBILITY RESULTS

4.1 Product Design

The terminal product design that was developed, as part of the microjoining solution, was a derivative of the tag design introduced by Riches (1994) and the commutator welds (crimp welding) design discussed by Ely (1997). It became evident very early in the development that contacting the magnet wire directly with the electrodes was not going to provide a robust solution. The designs offered by Riches (1994) and Ely (1997) offered a potential process in which both electrodes would come in contact with only the brass terminals. A derivative of these designs was developed that could be implemented in an automated manufacturing process to form the terminal over the wire. The benefits of this type of design are that the wire becomes mechanically captured (crimped) once the terminal tab is folded over. The design is robust in that the folded over tab compensates for the wire position. Figure 4.1 shows the tab design with the wire lying in place. The three figures show the successive folding over of the tab and crimping of the wire.

Figure 4.1 – Fold Over Terminal Design



4.2 Process Design

The process design developed, started from the parallel gap welding method introduced by Ely (1997). The method was refined and altered to result in a complicated welding profile which served to accomplish the

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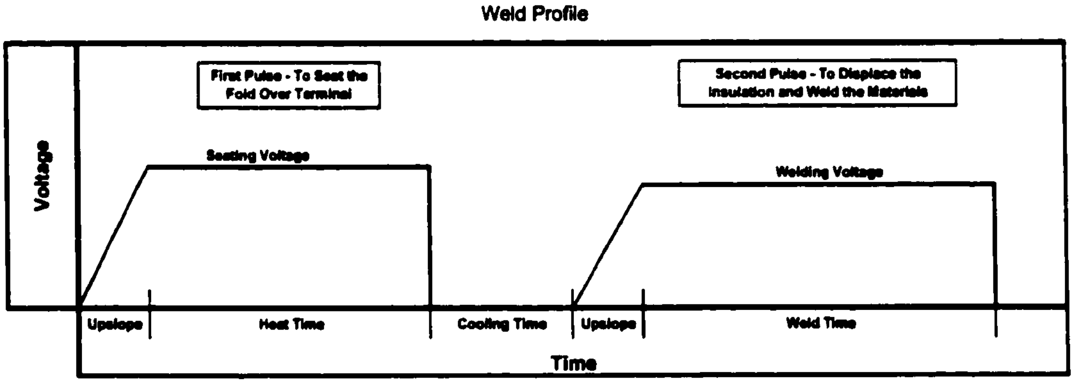
goal of joining the copper wire to the brass without prior removal of the wire insulation. The process design underwent a significant amount of trial and error resulting in a dual pulse profile. The idea was first presented by Riches (1994) but was expanded in this paper. The first pulse consisted of applying a force and voltage for a specified period of time to the specimen through the electrodes with the purpose of seating the terminal on the wire thus reducing contact resistance. This pulse is required in order to ensure the proper heat flow through the part by seating the terminal and beginning to displace the insulation on the wire.

The second pulse is applied with a similar clamp force and duration but at a lower voltage to displace the insulation and weld the materials. A graphic of a typical weld profile of the process is shown in Figure 4.2.

Figure 4.2 – Weld Profile



In addition to the force voltage and time outlined above each pulse had an upslope. Upslope is the time it allocated for the voltage to increase from zero to the specified value. There was also cooling time, which was the time between the first and second pules. The phenomena of the seating the terminal, heating the part, displacing the insulation and welding the two materials is depicted in Figure 4.3.

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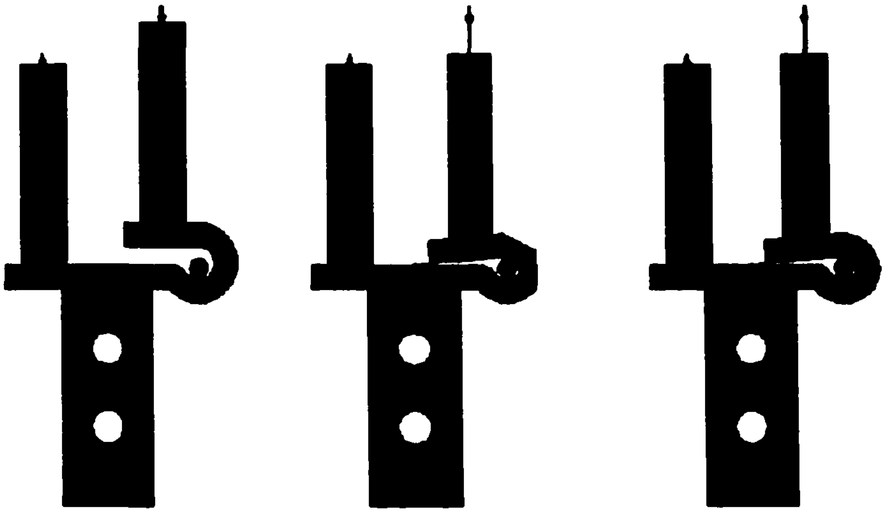
Figure 4.3 – Welding Process



The three stages in outlined in Figure 4.3 depict the process going from left to right. The lines with arrows in the figure outline the current and thus heat transfer path through the electrodes, terminal and eventually wire. In order to optimize the heat balance the electrode on the right (seating the terminal) was made from tungsten and the electrode on the left was copper. The first figure indicates the initial welding pulse that is applying the force and heat over time to seat the terminal over the wire. The second figure represents the second welding pulse in which heat is flowing through the part, along two paths, around the wire. During the weld time, in the second figure, heat is continuing to build up in the part while the force is being applied. The third figure represents the second pulse still but indicates the situation where the heat and force over time displaces the insulation around the wire. Once the insulation is displaced the contact resistance is instantaneously reduced as the copper wire makes contact with the brass terminal causing an electrical path for the current and thus heat to flow. The current flow through the terminal and wire is the current that actually welds brass terminal to the copper wire. An important insight is that the wire insulation does not melt, vaporize or burn but simply is displaced with the heat and force over time. Inspection under a microscope shows the insulation material collecting in the gaps under the folded over terminal outside of the wire.

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4.3 Feasibility Trial Results

The initial trials focused on determining a suitable electrode force to seat the brass terminal fold over tab and minimize contact resistance but not high enough to penetrate the brass terminal when welding the part. After a number of trials an electrode force of 24.0lbs (10.89kg) was settled on for all of the trials unless otherwise specified. This value minimized the contact resistance, but did not cause the part to stick to the electrode at the majority of the weld parameters that were investigated. The contact resistance was evaluated using the micro ohmmeter listed above to measure the resistance between each of the electrodes, the terminal and the wire. This total contact resistance was measured by connecting the four leads to each of the electrodes and measuring the resistance through the entire assembly.

The next set of trials centered on determining the weld profile for seating the brass terminal over the 0.65mm diameter magnet wire with polyesterimide over-coated polyamideimide insulation. This profile is labeled as first pulse in Figure 4.2. The voltage and the heat time were varied while documenting the results. The desired impact was that the terminal was seated over the wire with the portion of the terminal contacting the electrode deformed such that it was contacting the entire face of the electrode. This was the configuration that minimized contact resistance. If the face of the electrode did not contact the entire terminal the seat was considered to be insufficient because of its anticipated effect on contact resistance and overall heat transfer to the specimens. If the electrode displaced material in the terminal (electrode stuck in the part) the heat was considered excessive. This criterion was used on a range of parameters of voltage and heat time, as depicted in the lobe curve in Figure 4.4. A contour of the points classified as seated represent the lobe curve. As shown in Figure 4.4 and represented by the center of the largest area of the lobe curve, the optimum process setting was at a voltage of 2.6 volts and a heat time of 12 msec.

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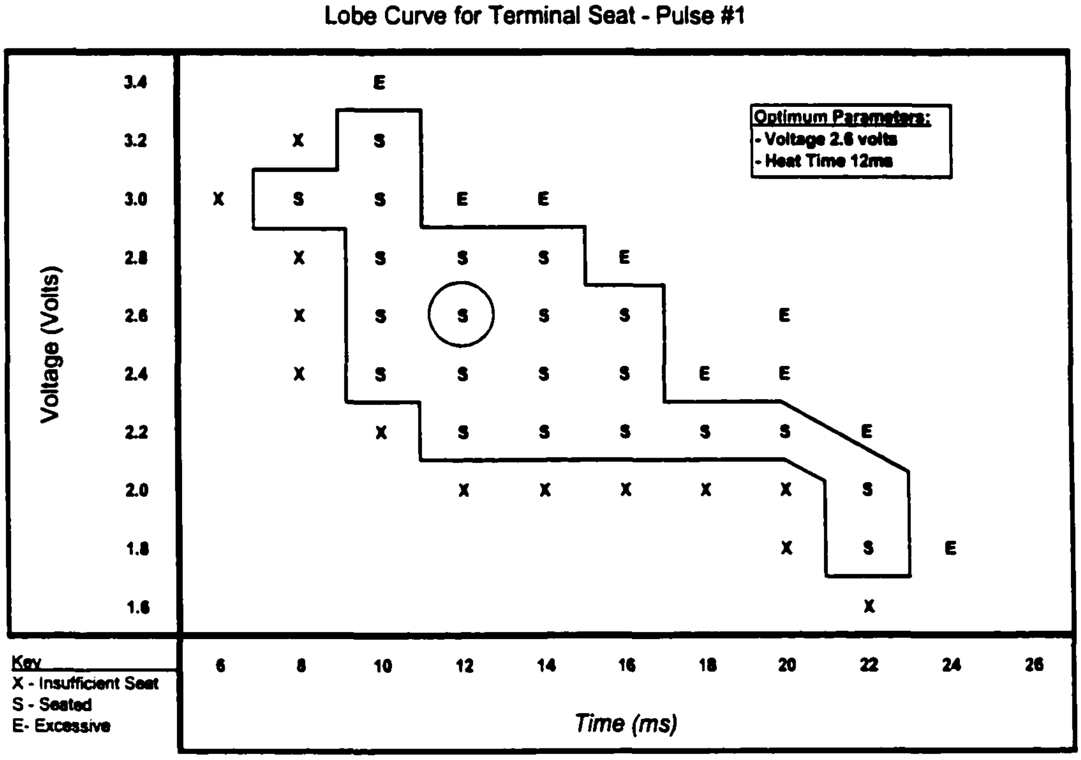
Figure 4.4 – Lobe Curve for Terminal Seat – Pulse #1



The size of the area enclosed by the lobe curve served as an indication that the seating process was robust in that small changes in the voltage or time would not effect the results. The upslope was set, per convention definitions, at one quarter of the heat time while the cooling time was set at 10 msec.

Trials were performed on the second pulse utilizing the visual evaluation outlined above in the joint quality assessment section above. The voltage and weld time for the second pulse were varied with each joint evaluated. The joints were evaluated based on the following criteria:

- if there was no evidence of copper on the brass terminal and if the indentation in the brass was minimal or if there was still insulation on the wire after the joint was peeled apart the weld was considered insufficient – see Figure 4.5 for an example
- if there was some copper observed on the brass terminal and if there was some indentation in the brass and the copper wire was smooth (no evidence of fusion) with the insulation partially removed it was classified as some evidence – see Figure 4.6 for an example

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- if there was a significant amount of copper on the brass terminal and the indentation in the brass was significant with the insulation completely removed and evidence on the surface of the wire a fusion had occurred it was considered as strong evidence – see Figure 4.7 for an example
- if there was expulsion the weld or if the terminal blew out (cracked) is was considered as excessive

Figure 4.5 – Insufficient Weld

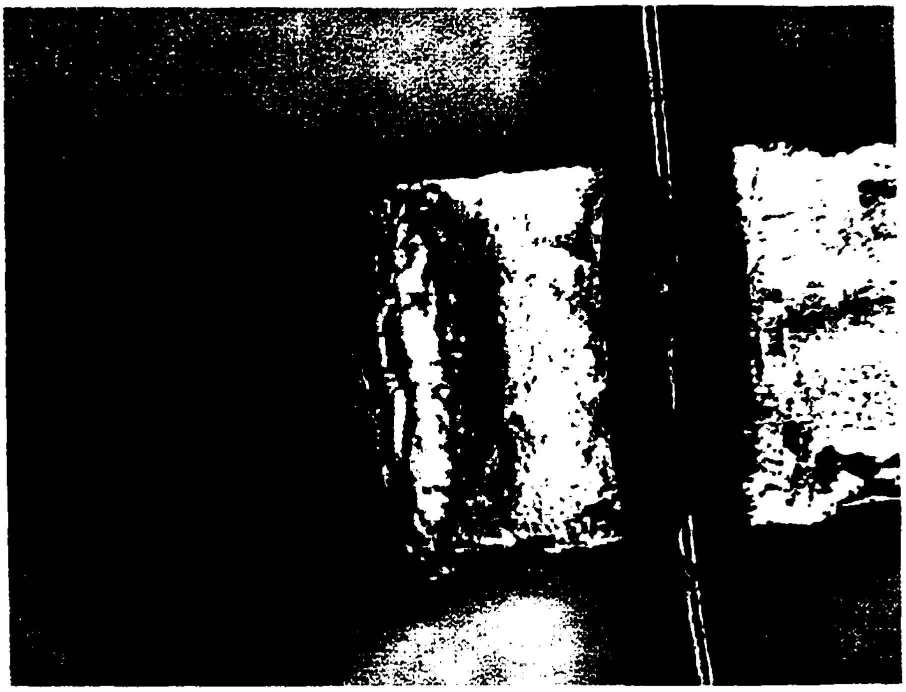

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Figure 4.6 – Some Evidence of Weld

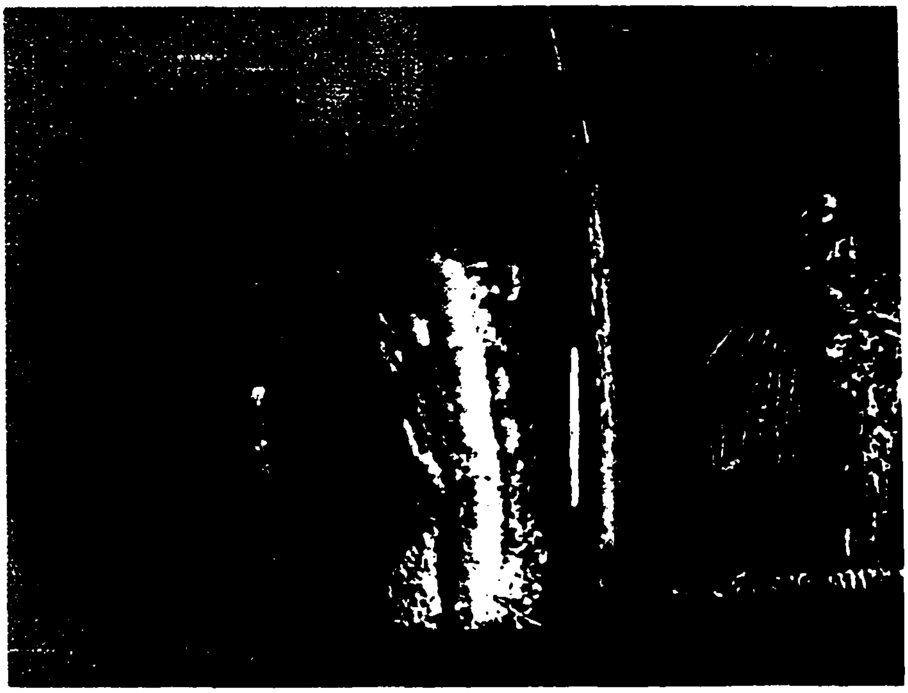

Figure 4.7 – Strong Evidence of Weld

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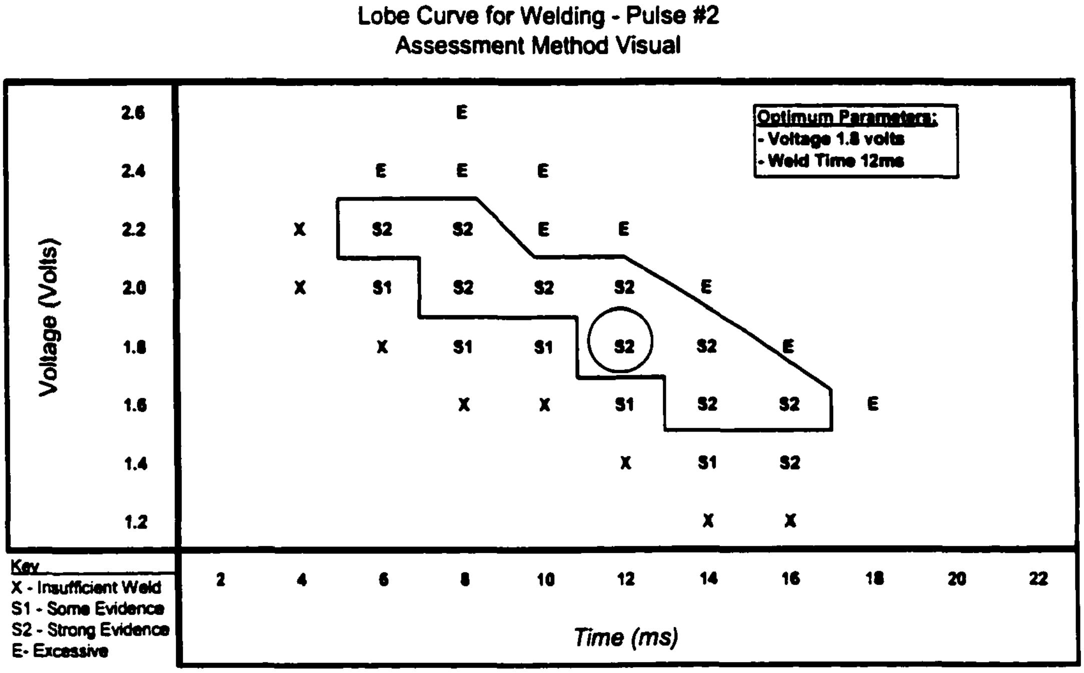
This criterion was used on a range of parameters of voltage and weld time, as depicted in the lobe curve in Figure 4.8.

Figure 4.8 – Lobe Curve for Welding – Pulse #2 Assessment Method Visual



This lobe curve was used throughout the balance of the study as the baseline process. This method was used to establish the acceptance criteria of the subsequent assessment methods, since the indication of an acceptable weld was known with the visual method. The areas around the edge of the lobe curve (fringe) were specifically targeted for evaluation. As shown in Figure 4.8 and represented by the center of the largest area of the lobe curve, the optimum process setting was at a voltage of 1.8 volts and a weld time of 12 msec. The upslope was set at one quarter of the heat time.

The since the method of evaluation was subjective it was anticipated that there was error in the results associated with individual interpretation of the above evidence. Even though precise definitions existed for the four different classifications of the weld, interpretation could lead to different results, especially along the fringe areas of the lobe curve. Results were not anticipated to vary significantly near the optimum process settings.

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While developing the lobe curves for the materials using the visual evaluation method it was noticed that the area outlined by the lobe curve was fairly narrow. This is an indication of lack of process robustness in that there is not a large difference between good welds and bad welds for selected process parameters. Small changes to process setting could effect the results in this area. After investigation it was determined that the area of good welds may be improved if the 2.5mm width of brass was increased to 3.3mm. The 3.3mm wide terminal allows for a larger range of heat to be transferred through the terminal and to the joint without blowing out on this particular design. The process of developing the lobe curves for terminal seating and welding was repeated for a terminal 3.3mm wide as shown in Figures 4.9 and 4.10. While the terminal seating lobe curve (Figure 4.9) offers a smaller area of acceptable welds, the terminal welding lobe curve (Figure 4.10) offers a substantially larger area. While the larger width of terminal offers the capability for a more robust process, 2.5mm terminals will be utilized in this research because of the current prototype design level and availability of test specimens.

The assessment method involving pull strength of the weld evaluated samples as described in the joint quality assessment section above. Based on prior work described above the preliminary acceptance criteria for a good weld set at 25% of the wire's tensile strength or 5.0lbs (2.27kg) for the 0.65mm wire used in this evaluation. This was the limit that was originally used when evaluating the samples. After trials were complete however it became apparent that 25% of the wire's tensile strength did not necessary indicate a good weld as shown by transposing the lobe graph for the visual evaluation method over the matrix of pull forces. It was determined while performing the trials that the strength of a good weld, offering a solid state bond between the brass terminal and copper wire, would be closer to 10.0lbs (4.54kg), as indicated by the fringe of the lobe curve see Figure 4.11. The lobe curve established from the visual evaluation method was overlaid on the pull strength data as shown in Figure 4.11.

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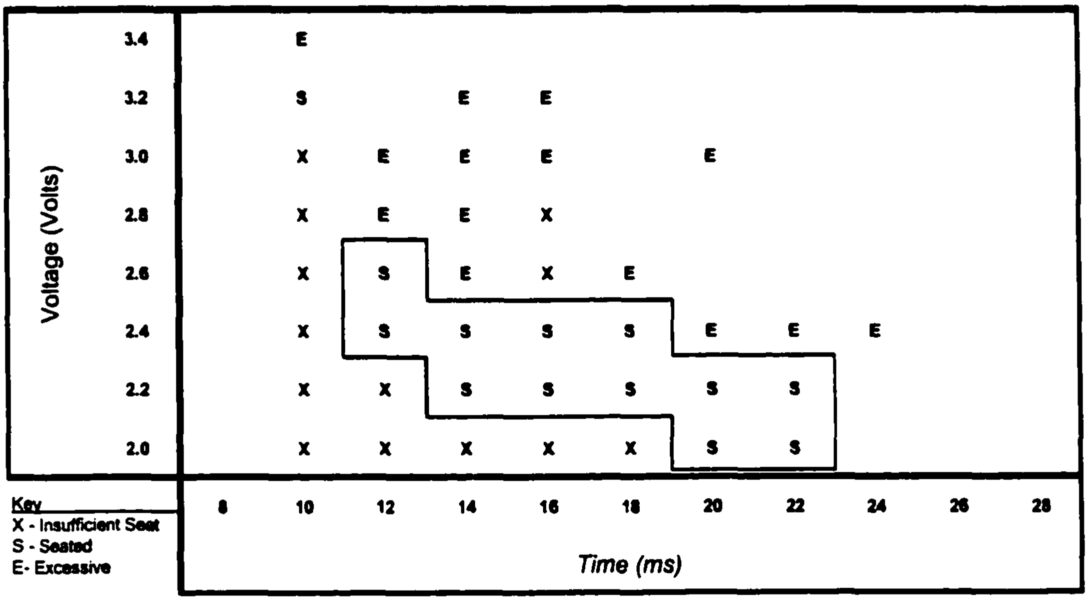
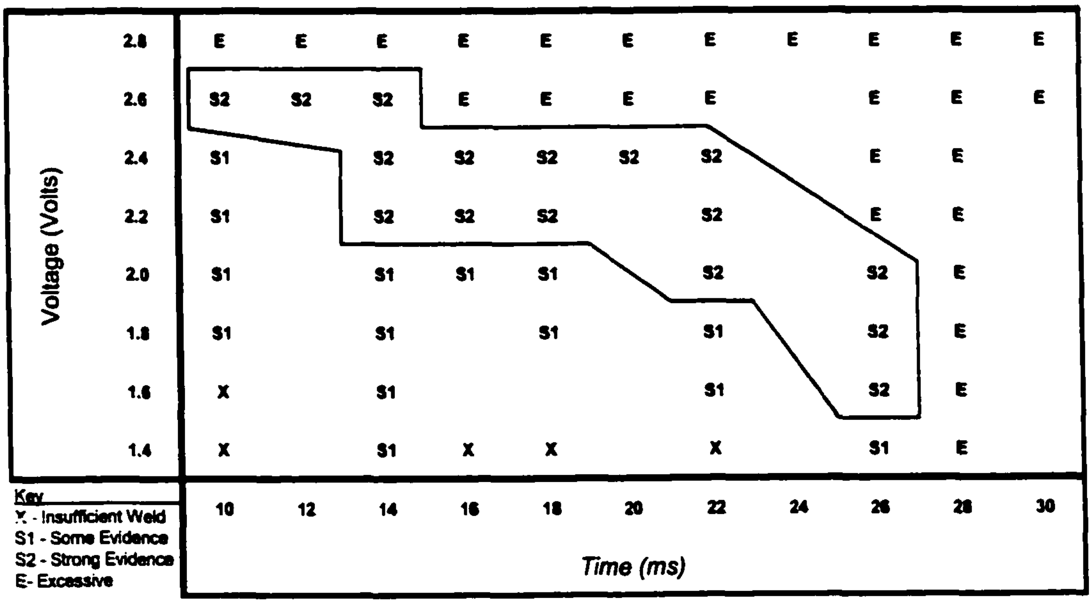
Figure 4.9 – Lobe Curve for Terminal Seat – 3.3mm Width – Pulse #1



Lobe Curve for Terminal Seat - 3.3mm Width - Pulse #1

Voltage (Volts)	8	10	12	14	16	18	20	22	24	26	28
3.4		E									
3.2		S		E	E						
3.0		X	E	E	E		E				
2.8		X	E	E	X						
2.6		X	S	E	X	E					
2.4		X	S	S	S	S	E	E	E		
2.2		X	X	S	S	S	S	S			
2.0		X	X	X	X	X	S	S			

Figure 4.10 – Lobe Curve for Welding – 3.3mm Width – Pulse #2 Assessment Method Visual



Lobe Curve for Welding - 3.3mm Width - Pulse #2
Assessment Method Visual

Voltage (Volts)	10	12	14	16	18	20	22	24	26	28	30
2.8	E	E	E	E	E	E	E	E	E	E	E
2.6	S2	S2	S2	E	E	E	E		E	E	E
2.4	S1		S2	S2	S2	S2	S2		E	E	
2.2	S1		S2	S2	S2		S2		E	E	
2.0	S1		S1	S1	S1		S2		S2	E	
1.8	S1		S1		S1		S1		S2	E	
1.6	X		S1				S1		S2	E	
1.4	X		S1	X	X		X		S1	E	

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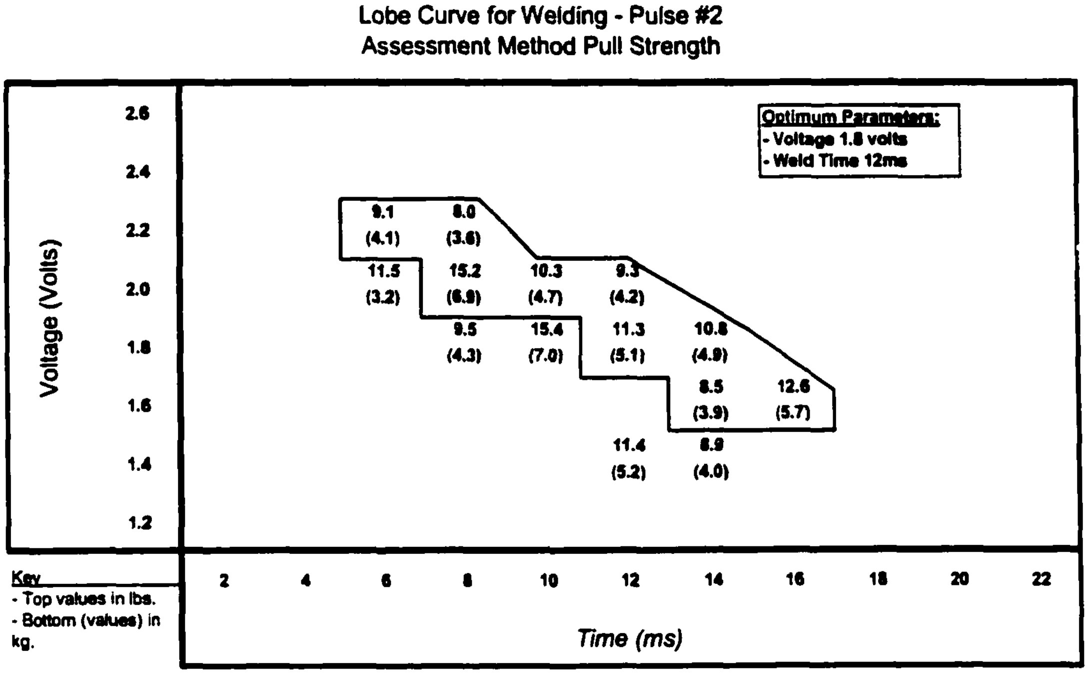
Figure 4.11 – Lobe Curve for Welding – Pulse #2 Assessment Method Pull Strength



While the fringe areas of the outlined visual evaluation method match up fairly well there are some definite inconsistencies between the two methods as outlined by values outside the lobe curve having higher pull strengths than values inside.

To evaluate these differences another lobe curve was developed in Figure 4.12 that displayed the standard deviations of the pull strength values outlined above. The magnitude and variation in the standard deviations indicated issues of repeatability not only with the measurement technique but with the process as well. This is evident by the fact that the standard deviations near the upper end of the lobe curve are the largest. Possible causes of measurement error can be attributed to the difficulty in recording the actual tensile force that causes the weld to fail. While pulling, the specimen's largest force is not always the force that causes initial failure of the joint (global versus local maximum forces). In many cases a local maximum force is witnessed which causes an initial failure of the joint (usually indicated by an initial cracking sound or the moving of the wire). This local failure was then followed by the global maximum force, which is the force that causes complete failure (complete wire separation from the terminal). Since

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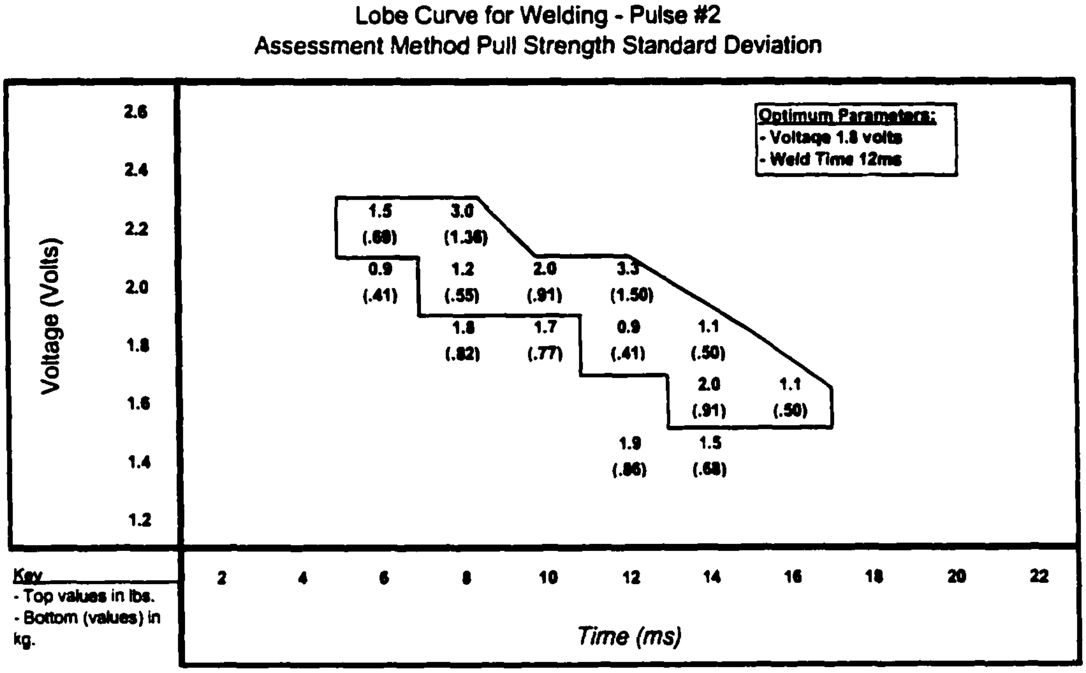
any failure of the joint could potentially effect electrical continuity of the part, the initial local maximum force was differentiated and used as the failure force. The differentiation of the local from global maximum force, through observation, is the main source of potential error in the measurement techniques for pull strengths. Both forces were documented however for comparison purposes.

Figure 4.12 – Lobe Curve for Welding – Pulse #2 Assessment Method Pull Strength Standard Deviation



Also for comparative purposes, the soldered joint from the existing design was analyzed for pull strength. The joint between the production ignition coil terminal and mechanically stripped 0.65mm copper magnet wire was soldered using 60Sn-40Pb solder on an automated soldering machine. The procedure for evaluating the soldered joints followed the same method for pull strength of the welded samples as described in the joint quality assessment section above. It was determined while performing the trials that the strength of the soldered joint was on average 15.9lbs (7.21kg). In all of the cases the wire failed prior to the actual joint. In every case the wire failed in the stripped region, in close proximity to the solder, in the heat-effected zone.

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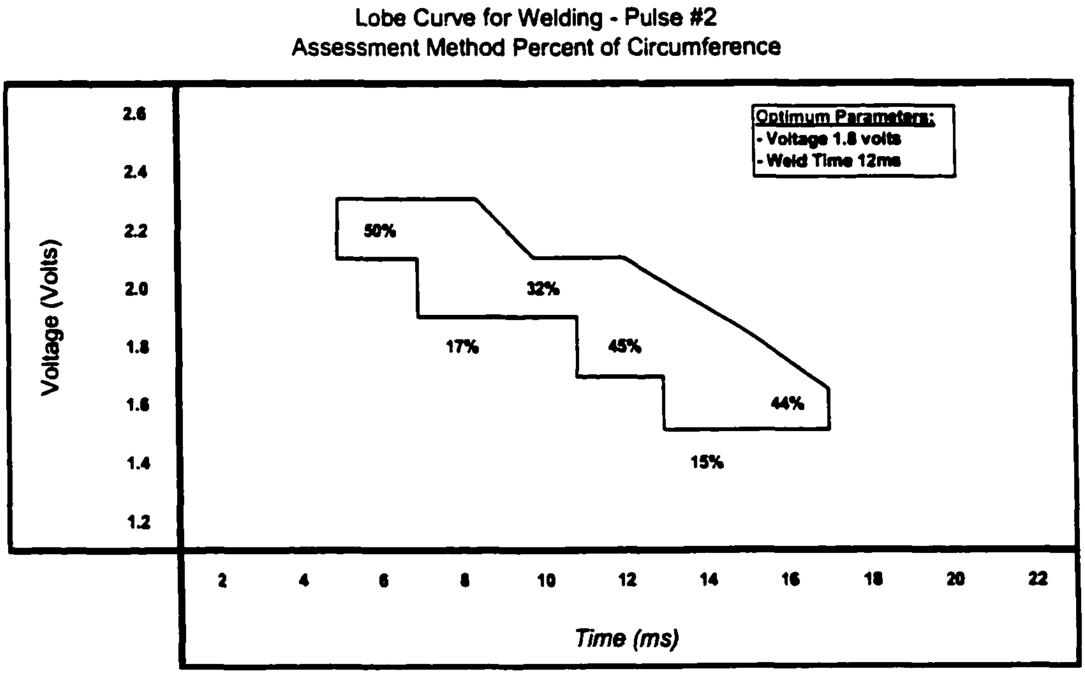
The assessment method involving percent of circumference, evaluated samples as described in the joint quality assessment section above. There were no prior documented standards for acceptable welds based on percentage of circumference located in the available literature. However, it was predicted that if a total of 20% (10% on the top of the weld and 10% on the bottom) of the circumference was contained within a solid state weld, the part would constitute a good weld. After trials were complete it was evident that the minimum acceptable percentage of circumference for an acceptable weld was closer to 30%. This value was determined by transposing the lobe graph for the visual evaluation method over the matrix of percentage of circumferences as shown in Figure 4.13. While there is some differentiation between good and bad parts as indicated by the lobe graph the repeatability of this assessment method was also in question.

Figure 4.13 – Lobe curve for Welding – Pulse #2 Assessment Method Percent of Circumference



The variability of this assessment method is increased due to the fact that there is a somewhat subjective process that needs to take place in differentiating if a line exist between the two materials. With the CMM and ram optics package at 250X magnification used it is very difficult to differentiate between a solid state

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bond and a line between the materials as shown in Figure 4.14, 4.15 and 4.16. This difficulty in differentiation effects the measurements made and affects the repeatability of the assessment method. The parts were viewed with under a microscope with a 400X magnification and it was much easier to evaluate the weld. Since the CMM available for use in the experimentation only had the capability to go to 250X magnification that is what was used for the evaluation in this research.

The assessment method involving percent reduction in diameter, evaluated samples as described in the joint quality assessment section above. There were no prior documented standards for acceptable welds based on percentage of circumference located in the available literature. However, it was predicted that if the diameter were reduced by 10% it would indicate that a fusion weld occurred and the part would constitute a good weld. After trials were complete it was evident that the minimum percent reduction in diameter for an acceptable weld was closer to 8%. This value was determined by transposing the lobe graph for the visual evaluation method over the matrix of percentage reduction in diameter as shown in Figure 4.17. Also, as in the case above while there is some differentiation between good and bad parts as indicated by the lobe graph the differentiation issues in recognizing the end of the copper wire also leads to repeatability issues.

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Figure 4.14 – Cross Section of the Weld

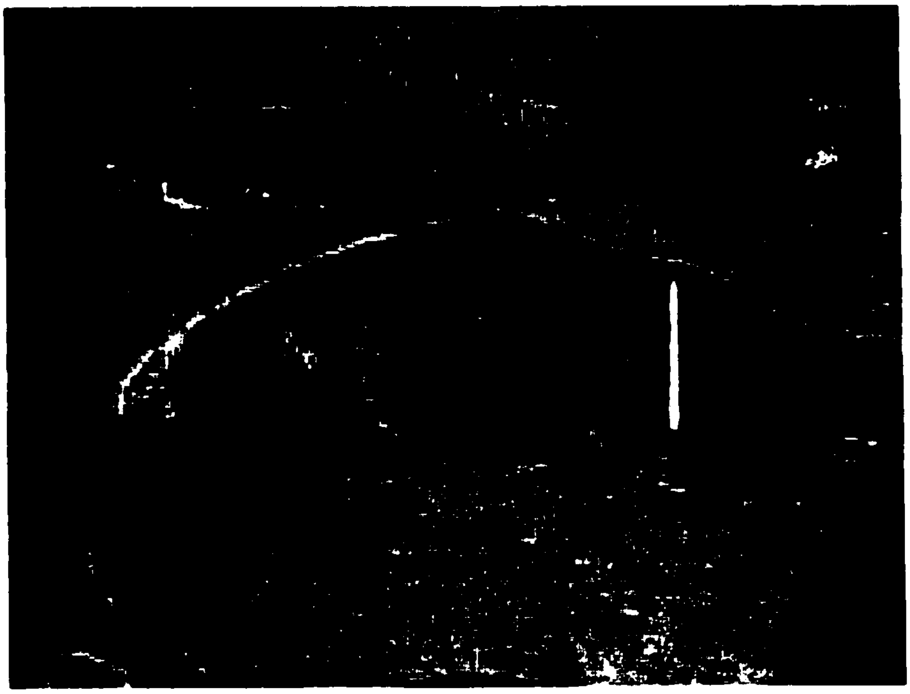

Figure 4.15 – Cross Section of the Weld

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Figure 4.16 – Cross Section of the Weld

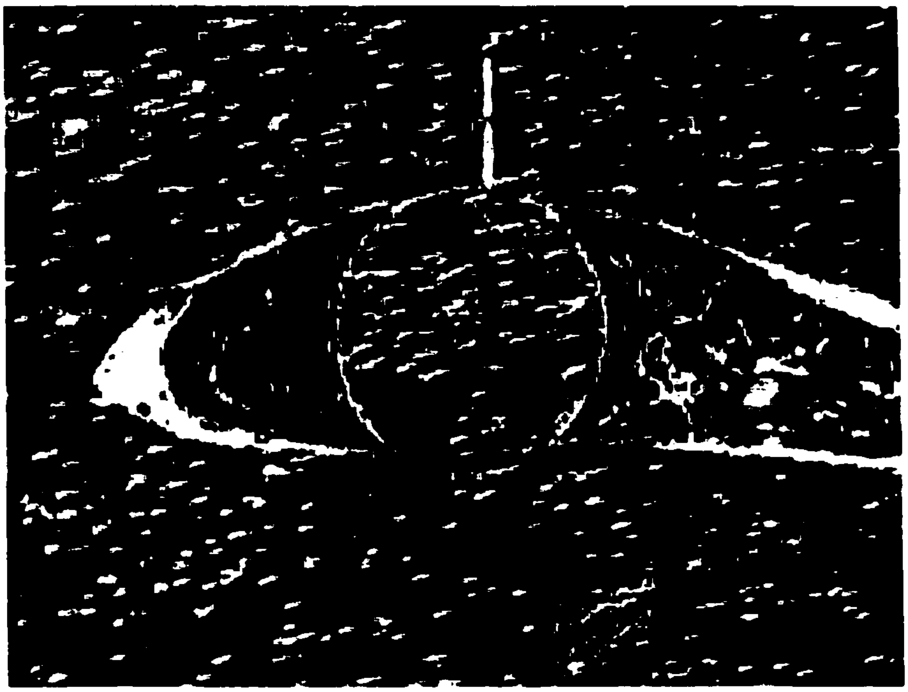
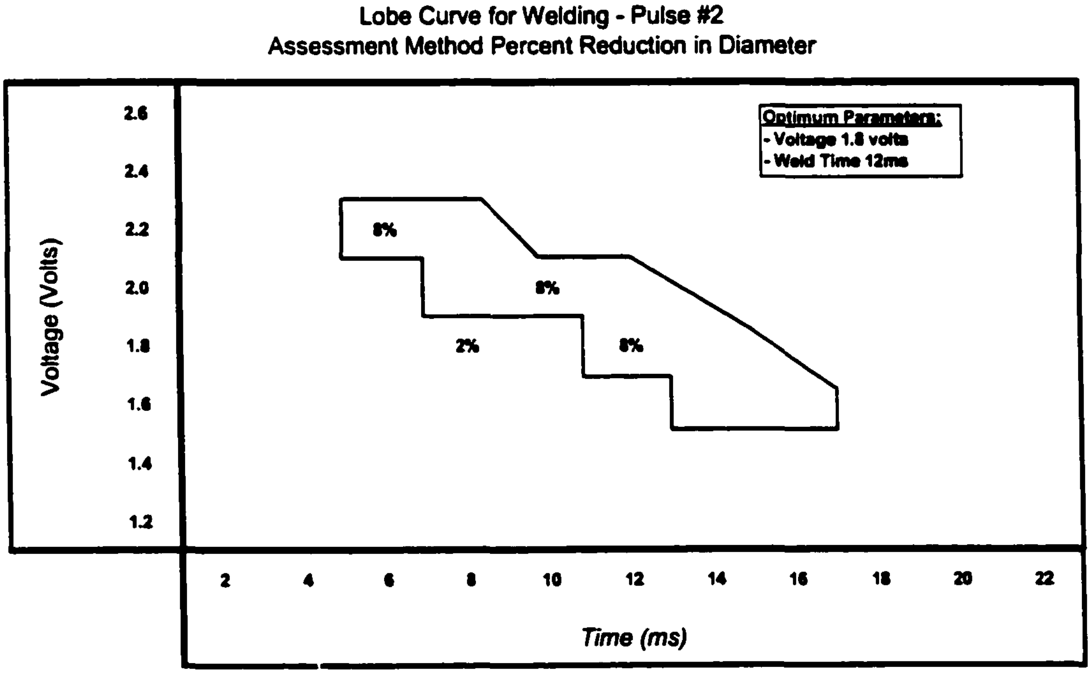


Figure 4.17 – Lobe Curve for Welding Pulse #2 Assessment Method Percent Reduction in Diameter



Lobe Curve for Welding - Pulse #2
Assessment Method Percent Reduction in Diameter

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The other constraint in both sectioning methods was the time required to properly prepare the samples. Each sample had to be potted in a clear two-part epoxy and cure to maintain its rigidity. The samples were then sectioned close to the middle of the terminal with a diamond wheel cut off saw. Each sample was then polished with progressive finer grit sandpaper using a wet sanding wheel. Care had to be taken to progress through the selected grits of sandpaper so as not to move too fast and cause scratches evident in the sample under magnification. This entire process itself added potential opportunity for error. If the different grits of sandpaper was progressed through too quickly as stated above, scratches and smearing of the copper or brass may lead to difficulties in differentiation. Also, variation in the process could also be attributed to the location of the sectioning. At different planes within the sectioned parts different results could be derived. A final area for variation in the sectioning evaluation methods was in the calculation of the percentages. The calculations for the percent reduction in diameter and percent of circumference welded assume a nominal wire diameter of 0.65mm. Any variation from this nominal value would lead to error.

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5.0 CONCLUSIONS

A microjoining design and process has been developed to join 0.65mm diameter, copper magnet wire with polyesterimide over-coated polyamideimide insulation to tin plated brass terminals without prior removal of the insulation of the wire. This work has permitted the following important advancements to be achieved:

5.1 Product/Process Design

1. Microjoining provides a suitable process, with the correct process and product design, to join 0.65mm diameter, copper magnet wire with polyesterimide over-coated polyamideimide insulation to tin plated brass terminals without prior removal of the insulation of the wire as demonstrated by the range of acceptable welds presented.
2. The fold over terminal (welding tab) design coupled with a parallel gap electrode arrangement is an effective means of displacing the insulation when welding 0.65mm diameter, copper magnet wire with polyesterimide over-coated polyamideimide insulation.
3. In order to seat the fold over terminal tab, control contact resistance and balance heat a dual pulse weld process is required when utilizing a fold over terminal design to weld 0.65mm diameter, copper magnet wire with polyesterimide over-coated polyamideimide insulation.
4. Visual inspection techniques, with specific criteria, of a welded joint between 0.65mm diameter, copper magnet wire with polyesterimide over-coated polyamideimide insulation and tin plated brass terminals provided acceptable results when analyzing the quality of the joint.
5. Tin plated brass terminals of 3.3mm width provide a larger area of acceptable welds in comparison to terminals of 2.5mm width while welding 0.65mm magnet wire without prior removal of the insulation.
6. When evaluating welded 0.65mm diameter, copper magnet wire with polyesterimide over-coated polyamideimide insulation a minimum acceptable weld is approximately 50% of the original wire tensile strength when evaluated in tension.
7. In comparing soldered versus welded joints between 0.65mm diameter, copper magnet wire with polyesterimide over-coated polyamideimide insulation and tin plated brass terminals – soldered joints

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produced higher pull strength results over non-optimized welded joints with a 2.5mm width terminal while welded joints were higher with a 3.3mm width terminal, on average.

8. When evaluating welded 0.65mm diameter, copper magnet wire with polyesterimide over-coated polyamideimide insulation a minimum acceptable weld is indicated when 30% of the original circumference of the wire is bonded to the terminal.
9. When evaluating welded 0.65mm diameter, copper magnet wire with polyesterimide over-coated polyamideimide insulation a minimum acceptable weld is indicated when there is an 8% reduction in the original diameter of the wire caused by the solid state bond.
10. Consistent acceptable welds were only produced within a specific voltage and time range at specific force values when welding magnet wire without prior removal of the insulation.

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