AN INVESTIGATION OF NUGGET FORMATION AND SIMULATION IN RESISTANCE SPOT WELDING

By

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ABSTRACT

Resistance spot welding is an important part of the automotive manufacturing industry. Today’s automobiles typically contain five-thousand or more welds. Spot welding is attractive to the industry for its speed and relative simplicity, however, it is not without its disadvantages. Current spot welding technology relies on volumes of empirical data to set the welding parameters. Often this data is not sufficient to ensure that a nugget of sufficient size is formed without a splash occurring. Complicating the matter further is the industry’s increased use of coated steel. The chemical reaction of the coatings with the electrodes cause greater variations in the nugget size.

This study seeks to characterize the nugget formation patterns of spot welding for a variety of welding materials and welding conditions. Specifically for coated steels welded over long periods with the same electrodes. The study also seeks to relate a small set of monitored parameters during welding to the accurate prediction of nugget size and splash occurrence. Welding current and voltage are identified as the key parameters of interest and are used as input to a numerical simulation to predict nugget diameter. A comparison of the simulated nugget diameters to actual diameters obtained experimentally show good agreement between the two values. The simulation, however, uses a finite difference method to obtain the nugget diameter. This method requires extensive calculations that cannot be completed in the normal welding time. Therefore, a new method of splash prediction has been investigated using the mean temperature of the workpiece. The mean temperature is obtained from a heat balance model of the workpiece. The heat balance model is advantageous to the finite difference simulation because its calculation time is short enough to be carried out during the welding process. A comparison of the maximum mean temperature and the experimental nugget diameters shows that mean temperature is capable of predicting nugget diameter. This correlation indicates that the mean temperature value can serve as a splash prediction parameter.

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Chapter 1
Introduction

Spot welding is a process in which a number of pieces of material are joined together by melting the material at the intervening, or faying surface, of the specimens. This melting forms a solid nugget that binds the specimens together. Melting is achieved by compressing the specimens between two electrodes and passing a current through the electrodes and material. The nugget size depends on the magnitude of the current, the electrode force, and the length of time that the current is applied to the specimens. If the parameters are not chosen carefully, expulsion of molten material may occur during the welding process. It has proven difficult to predict the occurrence of this expulsion phenomenon. In order to study this process more carefully, a welding apparatus has been configured to monitor critical welding parameters in real time. This apparatus has been used to obtain experimental data which was used to verify the accuracy of various welding models.

1.1 Terminology

The automotive industry has established some common terminology that can be used when describing the spot welding process. This includes references to the welding apparatus, welding parameters, and welding specimens. To start, the apparatus used for spot welding is often called a welding gun. It can be modified by the type of actuator used. In this investigation two types of welding guns were used. The first is controlled by air pressure and will be referred to as an air gun. The second uses a servo motor and will be referred to as a servo gun. The actuator, in either case, controls the position of,
and force applied by the electrode tips. These are the parts of the welding apparatus that actually make contact with the material to be welded. They are typically made of copper, because of its high electrical and thermal conductivity. When the electrodes contact the specimen there is a slight deformation of the electrode tip. This results in a larger contact area between the tips and specimens than would be found by simply measuring the electrode face diameter. This contact is referred to as the electrode diameter and is typically assumed to be circular. The force with which the electrodes are pressed together is called the electrode force. This force causes an area on the contacting surfaces of the specimens to be pressed very close together. This area is defined as the contact diameter. The entire surface between two specimens, where the weld will form, is called the faying surface.

The metal first begins to melt at this surface within the contact diameter. The metal that melts, and subsequently solidifies to bond the specimens, is known as the weld nugget. The nugget has two critical dimensions. The first is the nugget diameter which is represented by the width of the nugget at the faying surface. The second is the penetration depth which is the overall height of the nugget at its center. The area around the nugget that has had its microstructure changed due to the heat of welding is known as the heat affected zone (HAZ). A current must be passed through the electrodes to cause the heating and melting of the specimens necessary for nugget formation. This current is specified by the operator and is called the welding current, the duration that the current is applied to the specimens is called the weld time.
1.2 Welding Machines

There are various types of welding machines used in industry today. Their size and shape depend on their intended application. Many machines in the automotive industry are mounted on robotic manipulator arms to move about the body of a vehicle during assembly. Welding machines can be built for use with either DC or AC currents. The automotive industry predominantly uses AC machines. For this investigation two welding machines were used. Detailed descriptions of these machines and their operation can be found in Chapter 3.

1.3 Advantages of Spot Welding

Spot welding provides many benefits over other existing welding techniques. One of its greatest benefits is that it does not require additional material to form a weld. The nugget formed is a combination of the material from the specimens to be welded. In most other welding processes, such as arc-welding and metal-inert gas (MIG) welding, a wire or rod of material must be fed into the weld area to have enough material to form a weld. Additionally, attaching sheets of metal together is faster with spot welding because only certain areas need to be welded to establish the necessary bond strength.

1.4 Importance of Splash Prevention

Splash prevention is very important to the automotive industry. There are several negative effects of the splash phenomenon that make its elimination extremely important to the improvement of the overall welding process. The detrimental effects of expulsion
can be separated into three categories: the effect on the manufacturing process and equipment, the effect on the electrode tips, and the effect on nugget formation.

When a splash takes place, the molten metal at the faying surface is no longer contained by the surrounding solid metal. The force of the electrode tips cause this metal to spray out from between the specimens. When the spray reaches the surrounding air at room temperature it solidifies quickly into very tiny pellets. The pellets are usually on the order of 0.45 mm in diameter. Some droplets will attach to the welded material before solidifying, while others will continue to fly out from the specimen into the surrounding workspace. In either case, the effects are detrimental to the manufacturing process. In the first case, the metal that has attached to the specimen must often be removed. This involves a expensive and time consuming grinding and polishing step. If the metal is not removed it may negatively effect future welds or future steps of the assembly process. In the second case, this material can easily become lodged in the many moving parts of the equipment in the welding area. Over time these particles can build up on moving parts and cause increased wear and downtime of the equipment.

The splash condition in typical welding configurations represents an overheating condition due either to excessive welding current or welding time. This overheating extends to the outer surfaces of the weld specimens. Since the primary method of heat removal from the welded part is through the electrode tips, this additional heat is eventually carried to the tips. The combination of increased temperature at the outer surface and electrode tip contact produces increased electrode tip wear for two reasons. First, the increased heat acts to soften the electrode material. This causes increased deformation of the tip. This deformation can lead to unacceptable welds as a larger tip
will have a smaller current density and will produce a smaller weld under the same welding conditions. Second, in coated steels which are used widely in the automotive industry, there is a chemical reaction that occurs between the electrode tip and the surface coating. A zinc alloy and copper are the typical materials for the coating and the electrode tips, respectively. These two metals react with each other to form a coating of brass on the electrode. The material properties of brass are not as favorable for welding as those of copper. The conductivity, both electrical and thermal, is much lower for brass and will produce poorer welds as a result. The reaction between these two metals is related to the temperature of each of them. When they contact at a higher temperature the reaction rate is increased and performance is rapidly reduced. It is possible to reach a point where the electrode tips have become coated with enough brass that an acceptable nugget can no longer be formed. While both of these cases represent normal wear of the electrode, the increased heat generated in the splash condition accelerates this wear. This leads to more frequent changes of the electrode tips which requires the machine to be shut down.

Finally, the metal expelled during the splash comes from the pool of molten metal between the specimens. Since the weld is formed from the existing material, any metal that is lost to expulsion is no longer available to form the nugget. This generally results in a smaller nugget being formed between the specimens. If the splash is large enough, the nugget that is formed will not have sufficient dimensions in diameter and height. This leads to problems in the manufacturing line, as a significant number of extra welds must be made. This is done to ensure that enough quality welds have been produced.
1.5 Research Objectives

The goal of this investigation was to identify possible methods for controlling the process to avoid the splash condition in resistance spot welding. The results of this study will be used to identify critical parameters to be used in future quality monitoring and control routines for resistance spot welding.

1.6 Research Approach

To achieve this objective, it was first necessary to obtain welding data that would characterize the various welding conditions that might be encountered in an industrial setting. This data consisted of both the physical weld specimens produced and the current, voltage, and force data taken during the welding process. The data was first examined in an attempt to find any characteristics that could be used as an indicator of an impending splash. Since the data alone did not produce any such indicator, it was used as input to a finite element program. The results of this program were compared to the actual experimental results of the welds to verify the program's accuracy. After the program was proven to be accurate, the results were examined for feasibility of use in a control routine. It was expected that if the results of a finite element simulation proved accurate, the time required to produce these results would not be acceptable for a real-time control mechanism. Therefore, it was intended that the results of the simulation be used as further verification of future control routines that would be developed. The final focus of this investigation involves the verification of one of these welding models. The model uses the heat balance equation of a welded part to predict the mean temperature of the weld. It is believed that there is a characteristic mean temperature
during welding, beyond which splash will occur. The verification of this model is the final step of this investigation.
Chapter 2
Background

Spot welding has been used for many decades in the automotive industry as an efficient and inexpensive method of joining components of an automobile together. The average cost of a single weld is approximately $0.05. However, a typical car body contains several thousand welds. This large number of welds begins to increase the price associated with the manufacturing of the automobile. In recent years, automakers have changed the typical materials used in the frames of automobiles, preferring a coated material to the bare steel originally used. The coated material is chosen for its improved corrosion resistance. However, the typical coatings used, some form of zinc or zinc alloy, have been found to cause increased wear on the electrode tips. This doubly effects the cost of manufacturing as tips must be replaced more often and welding results become more difficult to estimate requiring more welds to be made to insure a specified number of quality welds are made [1].

Welding machines used in industry are almost entirely alternating current (AC) machines. These machines are chosen for their simple component make up compared to direct current (DC) machines. Since most supply lines today carry AC power, it is much easier to achieve the necessary currents and voltages without converting to DC. A typical welding machine is described in detail in Chapter 3. Figure 1 shows the standard parameters of interest in the welding process. Figure 2 shows the electrical fields seen in the weld specimen during welding.
Figure 1 Schematic of parameters of interest for splash prediction in spot welding and their progression during welding time.
Figure 2  Schematic illustration of spot welding parameters and electric field patterns in the workpiece during welding.
2.1 Optimization of weld nugget formation

The procedures used to obtain quality welds rely heavily on the evaluation of physical attributes of the weld. These attributes are measured over some time interval and compared to existing welding data. The existing data is used to identify what welding conditions are present and to suggest the correction needed if unsatisfactory welds are being produced. If it is found that the unsatisfactory nuggets are being produced, the data will indicate what process variables should be adjusted to get the desired nugget size [2]. To ensure accurate nugget size control throughout the welding process, continuous monitoring of the weld formation process is needed [3]. This requires that several test welds be broken to obtain experimental nugget information. This test weld must be created instead of making a structural weld. The test weld also requires special test specimens because the sample must be destroyed to obtain the data needed. This requires extra time, for the set up of the different specimen. It also increases the cost of the materials, as the specimens must be separate from the rest of the automotive structure. The difficulties associated with determining the appropriate welding parameters have been further complicated by the increased use of coated steel sheets in the automotive industry. The coating produces greater variation in the quality of the nugget produced. Often, a trial and error process is relied upon to obtain satisfactory welds.

2.2 Degradation of electrode tips

While better for corrosion resistance, it has been observed that the use of coated steel sheets causes increased wear on the electrode tips. Coated steel causes tip
degradation to occur on the order of one hundred times faster than bare steel sheets. This contributes to a significant amount of time lost, in order to change electrodes on the welding machines. Experiments were conducted by Dupuy, et al. to characterize this wear. Their results showed that the electrode is consumed by a chemical reaction with the coating more than it is deformed from the heat and stress of welding. The electrode consumption is caused by the formation and subsequent elimination of intermetallics. These intermetallics consist of some binary form of copper from the electrode and the coating material. Since zinc, or one of its alloys, is a widely used coating, brass is one of the most commonly formed intermetallics. The formation of intermetallics is not uniform across the electrode tip. Therefore, certain areas can have deeper loss of material than others. This phenomenon is known as pitting. Pitting not only changes the shape of the electrode but also causes a reduction in contact between the electrodes and the specimen. In some cases, the formation of these intermetallics can cause sticking between the electrode tips and the weld specimen. The actual effects of electrode degradation are extremely hard to predict. The entire process depends on the welding conditions, welding rate, and the coating used. Since most welding tables were originally made before coated steels were being used, poor welds are often made. These unsatisfactory welds are created because degradation effects were not accounted for in the selection of the welding conditions [1].

2.3 Nugget formation

The nugget formation process in resistance spot welding is caused by the heat generation of current passing through a resistor. The resistance is directly related to the
resistivity of the weld material. The current density, the current divided by the area through which the current flows, is also important in the nugget formation process. The electrode degradation would not be as serious an issue if not for the importance of the current density. The electrode tip degradation described above contributes to a larger electrode tip contact area. This causes the current, assumed to be a constant value, that passes through the electrode tip to be spread over a larger area. Therefore, it is the current density rather than the actual current value that cause the discrepancies in predicted and actual nugget diameters. The effects of varying current density are determined by the diameter of the current path estimated as a rod. Therefore the current density is proportional to the resistance of the rod, given as

\[ R = \frac{\rho l}{\pi d_e^2 / 4} \]  

(1)

where \( \rho \) is the resistivity of the workpiece, \( l \) is the thickness of the welded area, and \( d_e \) is the electrode contact diameter.

This is illustrated in Figure 3 which shows the actual welding setup in part a and the approximation of the current path as a rod in part b.

Several studies have also been conducted to determine what differences exist between AC and DC welding conditions. These results concluded that current fluctuation, seen in AC welding, has an effect on nugget formation and nugget temperature. This fluctuation causes a corresponding fluctuation in both diameter and temperature. However, the final resultant nugget is found to be nearly identical for AC and DC welding machines [4]. Further studies in AC and DC current sources found that the effect of current fluctuation is dependent of the thickness of the material being welded. The fluctuation was determined to be significant when using sheets thinner than

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Figure 3 Approximation of current path during welding to evaluate the resistance between electrode tips: (a) schematic of actual welding conditions, (b) modeling workpiece as homogeneous rod.
1.0 mm. In contrast, the effects of fluctuation were determined to be negligible in specimens greater than 1.5 mm thick [4].

Another cause of concern in modeling the nugget formation process is the role of contact resistance. Contact resistance is defined as the resistance between the electrode tips and the specimens. It was perceived to be a greater issue with the use of coated steels, because the coating causes an increase in the contact resistance. Models and prediction methods were created to include the effects of this resistance. A recent study was conducted in which two models were compared to experimental results. The first model included the effect of contact resistance while the second did not. Contrary to earlier beliefs, it was found that the results from both models accurately represented the experimental results. Therefore, it was concluded that the contact resistance effects could be ignored when considering the nugget formation [5].

2.4 Splash Condition

Researchers in the field of resistance spot welding have been trying for some time to determine an acceptable model for the occurrence of expulsion. One model, proposed by Browne, et al, describes a contact diameter at the faying surface. The model predicts that splash will occur when the nugget diameter exceeds this contact diameter. A second model, developed by Senkara et al., proposes that expulsion occurs when the force caused by the melting of the metal in the nugget exceeds the containment force applied by the electrodes [6]. However, there are some caveats to each of these models. Most important is the large amount of calculation and information required to accurately estimate these models. The calculations must either be more rigorous or the approximation will have a
greater error, especially in the case of irregularities in the geometry. Additionally, these models have not proven to be entirely accurate in predicting splash occurrences. Most importantly, expulsions have been observed in which the nugget had not yet exceeded the contact diameter.

Another problem facing many of the proposed models is that, in AC welding, the critical expulsion current decreases because of temperature fluctuation in the corona bond area. This area is the non-melted zone that surrounds the nugget during formation [4]. After completing a weld this area would be considered the heat-affected zone (HAZ). The corona bond area would include the non-melted region described in the Alcan model, while the nugget diameter remained less than the contact diameter. The temperature fluctuation is a direct result of the current fluctuation. A third model, then seeks to describe the splash as the result of the weld part being overheated [3]. This overheated state causes a sudden melting of the corona bond area that breaks down the containment structure surrounding the molten nugget. Without containment, the metal is free to flow out into the surroundings.

2.5 Nugget Formation Simulation Techniques

Several researchers have successfully developed simulation procedures that can predict nugget diameters. A real time monitoring system has been developed to be used in conjunction with a simulation program to simulate nugget diameters. This system has been shown to produce good results for welds with both new and old electrode tips. However, as with most simulation programs, a long calculation time is needed to obtain the results. This calculation time is often on the order of 100-1000 times the actual weld
duration [7]. As a result, this process cannot be applied to real time control or prediction of the welding process. These methods typically use the differential equation form of the welding model. This is represented in the simulation model using the finite difference method. To obtain accurate results from the finite difference, finite element, or finite boundary methods, a large number of mesh points are required. These mesh points represent the discrete approximation of the simulator to the continuous real-world problem. The smaller the mesh size and greater number of mesh points, the greater the accuracy of the simulation. Unfortunately, this accuracy comes at the cost of an increased number of calculations that contribute directly to the total simulation time [3].

2.6 Heat Balance model

A new method of splash prediction involves the use of the integral form of the heat balance equation [8]. This concept was developed from the similar work of Okuda. This type of thermal consideration has been attempted for many years but the results have never been able to accurately predict the nugget formation [3].

This new model assumes that a mean temperature of the total nugget formation area can describe the welding state. The heat contained in this area is theoretically given as [3]:

\[
Q = \int_0^t \left[ v \cdot i \cdot f(d/h) + 2 Ke \frac{\partial T}{\partial z} \pi \frac{d^2}{4} + \pi dh_i \frac{\partial T}{\partial r} \right] dt
\]  

(2)

where \( Q \) is the heat contained in the workpiece, \( t \) the time, \( v \) the voltage between plate surfaces, \( i \) the welding current, \( Ke \) the heat conductivity of electrode tips, \( K \) the thermal conductivity of weld specimens, \( d \) the contact diameter between electrode and weld piece, \( T \) the temperature, \( h_i \) the total plate thickness, \( f(d/h) \) the correction factor of current
density due to fringing, \( h \) the thickness of one plate, \( r \) the radius direction, and \( z \) the vertical direction, respectively.

The mean temperature in the weld part is then described as:

\[
T(t) = \frac{4Q}{h_C \pi d^2} 
\]

(3)

where \( Q \) is the heat contained in the workpiece from Eq. 2, \( C \) is the specific heat of the workpiece, and \( \sigma \) the density of the workpiece, respectively.

It has been shown that the effect of heat loss during the welding process is negligible when considering the temperature [3]. These two results can be combined into an integral equation for the mean temperature by substitution. It is believed that a governing parameter for proper welding conditions can be obtained from this equation.

Of further importance is the development of a temperature estimation routine that can be applied to a real time monitoring system to predict splash occurrence. This estimation routine is derived from the integral form of the equation and converted into a discrete form for use with the sampling data. It is necessary to first convert the voltage and current into volts and amperes respectively. The voltage must then be adjusted to account for the effects of mutual inductance. The temperature can then be estimated from the modified voltage.
Chapter 3
Materials and Test Methods

This section describes the various test procedures and apparatus used in this investigation. It also details the test materials used.

3.1 Welding Apparatus

A welding apparatus has been designed to conduct the experiments, of various welding conditions, needed in this investigation. The welding apparatus has been constructed to represent the typical spot welding machine that is used in industrial applications. Figure 4a is a photograph of the welding apparatus; Figure 4b shows the schematic of the welding apparatus and the measurement points. The welding apparatus applies a force to metal specimens placed between two electrodes. The welding apparatus then passes a current through the electrodes and material, causing a portion of the material to melt. This molten material is what will form the weld after it solidifies. The welding apparatus shuts off the current while still maintaining a pressure on the specimens. Finally, the applied force is removed from the specimens thus allowing them to be removed from the apparatus. Water is forced through the interior of the electrodes, thereby cooling them. The welding apparatus has been modified to enable the measurement of electrode force, current, and voltage during the welding process. These measurements were capable of being recorded on a PC using an A/D converter.

For welding the typical 30 mm by 100 mm test coupons, it was necessary to construct a support platform on which the coupons could be placed and held stationary during welding. Figure 5 shows a schematic of the support platform and its relative
Figure 4 Experimental welding apparatus: (a) photo of apparatus, (b) schematic of welding apparatus showing voltage and current monitoring devices.
Figure 5 Schematic of support structure used to hold welding specimens in place during welding.
position during welding. The support platform is a four sided rectangular box with holes centered in the top and bottom. The box can be placed such that the top hole fits over the bottom electrode of the welding gun and the bottom hole fits over an adjusting screw on the support structure. Sheets of aluminum 1 mm thick can be added as needed to make the top surface of the box level with the top surface of the electrode. The box is constructed from one-half inch thick aluminum on the sides and bottom and one-quarter inch thick Plexiglas on the top that serves as an insulator.

The welding apparatus consists of three components: a controller, a welding gun, and an electrode cooling system. Each of these components is discussed in the following sections.

The welding controller used for the experiments was a Robotron Series 400 Controller. This controller allowed the use of a direct program mode where the welding parameters could be set directly at the controller. Figure 6 shows the control panel of the Robotron Series 400. These parameters could be changed after each weld if necessary. The parameters controlled by this device were weld time and welding current. Additional parameter settings, not varied in this investigation, included squeeze time and hold time. It is during these respective interims before and after the weld, that the electrodes apply force to the specimen while no current is passed through the electrodes.

The welding gun is the portion of the device at which the welding actually takes place. The welding gun can be further divided into several components and subsystems, the majority of which are unimportant to this study. The welding gun is typically a C-shaped device with one fixed end and one movable end. The movable end is attached to some form of linear actuator. The actuator is required to move the electrode tip into
Figure 6  Robotron Series 400 welding controller input panel.
contact with the welding specimens and apply the desired welding force to the specimens. The various types of actuators used in this experiment are discussed in greater detail below. The C-shaped device is affixed to a large metal structure to provide support. The support structure is fitted with an adjusting screw. This screw can be raised or lowered with respect to the lower, immobile, electrode. If desired, the screw can be moved to contact the bottom of the welding device to provide essentially zero displacement at the lower electrode. The power source and control signal from the welding controller are attached to the top of the actuator.

Two types of actuators were used during the course of this investigation. The first is powered by air pressure and is typically found in industrial applications. The second type is operated by a servo motor and was being tested for some of its improved characteristics. The air powered actuator is controlled by adjusting a pressure regulator until the desired electrode force is obtained. When activated, the air pressure is applied to a piston attached to the upper electrode. This causes the electrodes, and any intervening material to be pressed together at the desired force. The servo motor actuator is controlled using a Dengensha Servo Spot Gun controller. The desired force must be set through a computer program and is passed to the controller through a PC card interface.

There are some important differences between the two actuators. Generally, the servo motor is a faster actuator. It responds much faster to the weld signal, as it does not have the delay introduced by the air pressure. However, this can produce negative results, especially at higher welding forces. The increased speed, in this case, translates into an increased impact force that can lead to rapid tip wear and deformation. However,
an advantage of the speed of the servo motor, in conjunction with PC control, is the ability to change the electrode force during the welding cycle.

The electrode cooling system consists of a tap water feed that is connected to a series of flow regulators. The flow is controlled by a master regulator and a secondary regulator for each welding gun. A valve controls which gun receives the flow. The water is brought to the welding gun and divided among three tubes. Two tubes flow to each of the electrode tips while the third tube is used to cool the welding coil. The actual flow of the water upon reaching the gun is built into the design of the gun and is not important to this investigation. It can be noted that the flow identical for either actuator.

### 3.2 Weld Monitoring Systems

A weld monitoring system was constructed to record three important welding parameters during the welding process. The welding parameters monitored were current, voltage, and electrode force. Each system was constructed separately and is given a separate input channel on a National Instruments Lab-1200 PCI A/D converter. The components of the three systems are described below.

The voltage monitoring system measures the voltage between electrode tips during the weld cycle. This system is installed separately on each welding gun. The input to the computer is switched between the two by a switch located on the welding console. The leads of the system are attached to the top of each electrode and held in place by hose clamps. The input to the computer is controlled by a direct gain on the A/D board and is set to have a gain of 2.5.
The current measuring device consists of two coil loops placed around the lower arm of the welding apparatus. Each loop is used as an input to a separate recording device. These devices must be moved between guns, depending on which gun is being used, because there are only two such loops. The first loop is connected to a current meter. Two current meters were used during the experiment, a Miyachies Weld Checker MM356A and a Dengensha Weldscope WS-10. Each was used to provide an instant measurement of RMS welding current and weld time. This value could be manually recorded. The second loop was used as an input to an A/D converter. The signal generated on this line was converted into a voltage before being sent to the PC. The value recorded by the A/D board could then be converted back to a current measurement by a program.

The system developed to measure the force applied at the electrode tips consists of a strain gage applied to the lower arm of the welding gun. The strain gage output is connected to a Wheatstone bridge, which in turn is connected to an amplifying circuit. As with the current monitoring system, only one bridge circuit exists and the leads to the strain gage must be switched depending on which welding gun is being used. The amplifying circuit also contains a switch, which must be set to the proper gun to account for the differences in the gages used. The Wheatstone bridge contains a dial used to calibrate the system to zero force when no load is applied. This is especially important when switching between guns as the settings for a balanced bridge vary significantly. As can be seen from the circuit diagram, the output of the amplifier is used as the input to the A/D converter.
3.3 Welding Activation

There are two primary welding activation switches that the user can choose from. The most commonly used is a single-weld switch. It consists of two momentary contact switches. The first is used to start the welding process. The second is used to reset the welding controller after the weld has completed. This switch was built with safety in mind, as additional welds can not be made until the reset switch is pressed. The second activation switch is a foot pedal switch. This switch is used to produce multiple welds at set intervals. It is attached to two relays that can be used to control the interval between welds. There is no reset button required on this switch. It can be used for single welds when pressed and released once. If the switch is pressed and held, welds will continue to be made at the set interval until the switch is released. A welding control box was developed for this experiment. It functions as a secondary power switch for the welding machine. It can turn the welding machine and welding current on or off. It is used to select which welding gun will be used and to choose which gun to measure voltage from. It has controls for the servo motor, including power, calibration, and movement. Finally, it has a secondary weld activation switch. It is a single weld switch that does not require a reset. This switch is seldom used because of its location away from the welding gun.

Data acquisition is achieved by the use of the A/D card described above and the Visual Basic program described in Appendix A. Figure 7 shows the user interface. When set to acquire data, the program waits for a signal from the welding controller before collecting data. The length of time that data is collected is set in terms of cycles through the user interface. The welding current operates on a sixty Hertz power supply; therefore, one cycle is equivalent to one sixtieth of a second. The data collected during
Figure 7 User interface of resistance spot welding monitoring program (RW Mon by Lab-PC-1200)
the welding process is stored in an array. This array is then split into the components, voltage, current, and electrode force. At the user’s discretion this data may be saved in a text file and/or plotted in the chart area of the program. This is achieved by marking the corresponding checkbox in Figure 7.

After configuring the welding control devices, the weld experiments can be conducted. From this point the welding process is simple. Current and welding duration are set using the direct editing capabilities of the Robotron controller. The time input on the controller must be adjusted by a factor of two. Therefore, to achieve a 10 cycle weld time, the program must be adjusted to 20 cycles. After the welding parameters have been set, the material to be welded is placed on the support structure. This structure holds the weld specimens in place during the weld. The specimens should be aligned, according to specifications, such that the overlap of the specimens in the area to be welded is at least 30 mm. Once in place, either of the activation switches, described above, may be used to begin the welding process. If data is to be acquired from the process, the acquisition program must be running and waiting for a weld signal prior to the start of welding. The user can select a name for the files generated and a directory in which to store the files. The user can also select the length of time that data should be recorded. This should correspond to the time set for the weld in the welding controller or be slightly longer. A standard sampling time is 11 cycles as most welds have a duration of 10 cycles or less. When all settings have been established to the user’s preference the “Do Operation” button is pressed. The program then enters a “locked” mode in which it waits for the signal from the welding controller to begin sampling. When the activation button is pressed, the welding process will begin. The electrodes press down on the material with
the specified force. The selected welding current is passed through the electrodes and material for the set amount of time. The electrodes then retract, leaving the welded material on the support structure for manual removal. The monitoring program returns to a ready mode after acquiring and processing data awaiting the next weld. One modification to this procedure is made if new electrode tips are used for the welding process. In this case, the tips must be conditioned before any experimental welds can be obtained. Tips are conditioned by making approximately fifty welds on the test material. The welds are made at a moderate current, typically 7700 A, and a mid-range electrode force of 200 daN. Conditioning is done because the electrode tips deform a significant amount under the heat and force they experience during the first fifty welds. While the electrode tip shape continues to change after this number of welds, the change is not nearly as significant. Repeatability can now be achieved over an acceptably long range of welds.

3.4 Test Procedures

Weld lobe tests were conducted to characterize the nugget diameter formed under different current and electrode force conditions. The weld lobe tests were performed on a variety of materials and were conducted using electrodes in varying degrees of degradation.

The purpose of the weld lobe test is to obtain the nugget diameter as a function of the welding current. The tests also serve to identify three critical current levels. The first is the lowest current that will produce any nugget. Any current setting below this will fail to melt the specimens and produces no weld. The second is the current that produces
a nugget diameter equal to $4\sqrt{t}$, where $t$ is the thickness of the specimen. This is the value of the minimum acceptable nugget diameter recommended by the Society of Automotive Engineers (SAE). However, each auto manufacturer is given the liberty to set its own minimum nugget diameter. For this investigation the SAE recommended diameter will be used. All current settings below this value produce welds of unacceptable quality. Current settings above this level produce nuggets of equal or greater diameter than $4\sqrt{t}$ and are therefore of satisfactory quality. The final current level represents the current level of splash occurrence. At this level molten metal is expelled from the weld area during welding. Prediction of the nugget diameter after expulsion occurs is difficult. In some instances there will be little effect on the diameter, and the quality of the weld produced is still acceptable. However, in other situations the nugget diameter is greatly reduced, resulting in an unacceptable weld. The identification of these three levels is complicated by the fact that in some cases the current level for acceptable nugget formation and expulsion are nearly identical.

The materials used for the experiment are steel test coupons 30 mm by 100 mm, with a thickness of 1 mm. All of the specimens used were low-carbon mild steel, with typical carbon percentages of 0.06%. However, essentially two different types of material were tested because of a difference in coatings applied to each sheet. The first material type was galvannealed steel. It consists of a galvanic coating applied to each of the major sides of the test coupon. The second material was an organic zinc coated steel sheet. This type of coupon had a zinc coating applied to only one side of the sheet. The other side is left as bare steel.
The experiments were conducted by first choosing a starting welding current. For all of the tests conducted a standard welding time of 10 cycles was used. The starting current was selected based on recommended welding values for the given electrode force. In this investigation, the electrode forces considered were 100, 200 and 300 daN (0.3 kN). These starting currents were typically 7000 to 8000 Amperes, with lower forces having lower starting currents. The test proceeds by making a single weld between two coupons at the starting current. The current was then increased by 300 A and the welding process was repeated using another set of test coupons. This process was repeated until a visible splash was observed during welding. After the splash was detected, the current was increased once more and the specimens were welded. The current was then set to 300 A below the starting current and decreased on each successive weld until the resulting coupons could be easily broken. Once broken apart, it was also necessary to be visually obvious that no melting of either coupon had taken place and that the only joining force between the two coupons was a surface adhesion induced by the high force of the electrodes. The completion of this entire process constitutes the examination of one weld lobe. The process remains the same for any material considered and on either welding gun.

A second study was carried out to determine the ability of the electrode tips to resist wear for a given type of material. After preparing the electrodes, the test produces on the order of several thousand repeated welds. Interspersed through the welds are electrode tip impressions, tip resistance measurements, and weld lobes. The test is completed when the standard run condition, described below, fails to produce a weld of acceptable quality.
The purpose of this test is to determine the working life of electrode tips given a specific type of material and a set welding condition. The test also seeks to determine how the shape of the electrode tips changes over the course of thousands of welds. Additionally, it can be used to describe the dependence of the weld lobe on welding duration. It is widely accepted that the weld lobe for a particular material is not constant but varies with the number of welds made by a particular set of electrode tips.

This test is carried out by first conditioning the electrode tips on the material to be tested. In this experiment, the material used was the organic-zinc coated sheet with one bare steel side described in the previous section. Figure 8 shows the orientation of the sheets for all of the welds. This resulted in one electrode always contacting the coated side and the other electrode always contacting the bare side. Multiple welds are made on large sheets, 300 mm x 250 mm, of the same material. Each weld is spaced evenly from every other weld, the center to center spacing of the welds are approximately 30 mm in both the horizontal and vertical directions. These welds are made at a set electrode force and weld time. In this investigation this was 200 daN and 10 cycles respectively. The welding current for these welds was chosen from the results of the weld lobe tests on the same material. It was selected to be in the middle of the acceptable nugget diameter range and below the splash condition. After every 100 welds, six welds were made on the smaller 100 mm x 30 mm test coupons. These welds were broken and checked for nugget diameter. The test is completed when one of these samples created at the standard welding conditions failed to produce a nugget of acceptable diameter. An impression of the electrode tips is taken, beginning with the one hundredth weld and repeated every two hundred welds. This is done by placing a single sheet of test material between the
Figure 8  Orientation of organic-zinc coated steel sheets during welding in the electrode life test.
electrodes. On one side of this sheet a piece of carbon paper is placed between two sheets of paper. The welding gun is then made to compress the electrodes together without running a current through them. The result is an imprint of the tip from the carbon paper. The process is then repeated for the other electrode. After the three hundredth weld a variation study is made. It consists of making two welds at 110% and 90% of the standard welding current. This study is made only at this point and is not repeated. Finally, weld lobe tests are conducted after every one-thousand welds. These tests are important to understand how the expulsion and nugget formation currents change over the course of a large number of welds. The weld lobes are conducted in the same manner as described in the previous section. However, they are only carried out on the material in question and there is no variation made in the electrode force. Figure 9 summarizes the timeline of the process.

The materials used for this test were the large test sheets and smaller test coupons of organic-zinc coated sheets. This test was carried out on the air activated welding gun only. The activation switch used was the pedal switch with a delay time of 3 seconds. A pressure release valve located on the air pressure regulator was used to activate the electrode tips without applying a current through the material when creating the tip impression.

Several tests were performed on thin cold-rolled steel sheets in an attempt to verify or identify modifications needed in the formulation of the non-dimensional welding parameter obtained from the heat-balance equation. These tests included a weld lobe test, hardness tests, and tensile tests.
Figure 9  Timeline of test procedures for electrode life test
As shown in the initial formulation of the heat-balance equation, the non-dimensional welding parameters were in close agreement, except in the case of very thin steel sheets. The purpose of this test was to determine if this value was correct or if it needed to be modified by some material property that would produce more similar results. The weld lobe test was performed to obtain the same data as the previous weld lobes: the critical current setting for nugget formation and splash occurrence. This data was then used to evaluate the non-dimensional parameter. Tensile and hardness tests were used to identify material property variations between the thin steel and the mild steel used in the other experiments. Specifically, the tensile test was used to obtain the ultimate tensile strength of both the thin steel and the mild steel. The values were believed to be parameters that could be added to the non-dimensional model to explain and eliminate the large discrepancy in the thin steel case.

This part of the investigation was carried out in several steps. The steel used for the testing came in rolls, essentially a long, narrow sheet. This sheet had to be cut into weld coupons for individual welds and into larger sheets for multiple welds. The coupons used were 101.6 mm x 19.05 mm (4 in. x 0.75 in.). The larger sheets were 304.8 mm x 304.8 mm (12 in. x 12 in.). All of the cutting was done on a foot stamp shearing machine. Portions of the material were not cut into test specimens and were used to conduct the hardness and tensile tests. Hardness tests were performed on sections of material 76.2 mm x 76.2 mm (3 in. x 3 in.). Tensile test pieces were specially manufactured in two steps. These pieces were initially cut on the foot stamp to 203.2 mm (8 in.) long and 19.05 mm (0.75 in.) wide. The pieces were then cut to the appropriate shape using a CNC machine programmed with the dimensions. Figure 10 shows the
Figure 10  Tensile test specimen (0.76 mm (0.03 in.) thickness).
drawing of the tensile test pieces. Bare mild steel sheets were also machined into tensile specimens in the same manner. In producing these samples, consideration was given to the rolling direction of the thin steel sheets. The majority of the samples were cut with the major axis along the rolling direction. However, to assess the variation of properties in different directions, samples were also prepared that had been cut transverse to the rolling direction as well as at a 45° angle to the rolling direction. Similarly cut samples were taken from the 1 mm bare steel sheets.

After all of the samples have been machined to the appropriate size, the individual tests can be completed. The hardness tests are performed on a standard hardness tester. The test was conducted using 100 g of mass and a Rockwell C indenter. The tests were repeated three times, for each material, to obtain an average hardness value. Then tensile tests were conducted on an Instrom tensile machine. The machine was attached to a data acquisition card that recorded force and crosshead displacement. The crosshead speed was set to 1 mm/s. The samples were clamped into the machine’s grip and loaded to failure. The data obtained could then be converted to stress-strain curves to determine the ultimate tensile strength of the material. The final test consisted of the actual weld lobe tests. These tests were carried out on the air gun in the same manner as the weld lobe tests described previously. However, due to the change in thickness of the material being welded, several welding parameters were modified for this test. While welding current was still the parameter being investigated, the starting value of that current was much lower. The welding time was also reduced from 10 cycles to 4 cycles. The electrode tip forces considered in this test were 42 daN (94 lb.), 48 daN (108 lb.), and 60 daN (134 lb.).
Materials that were required for this test were the bare mild steel sheets (SPCC) and the cold rolled steel. The thin steel was ordered from the selection of shim stock offered by MSC. It has a nominal thickness of 0.254 mm (0.01 in). The material comes in rolls, 304.8 mm x 3.658 m (12 in. x 12 ft). Table 1 shows the material properties.

3.5 Waveform Viewers

Throughout this investigation, it was often necessary to examine the data acquired during the welding process. This was facilitated by the use of several waveform viewers. Two different viewers were developed with similar purposes. Each showed a graphical representation of the current and voltage waveforms captured during welding. Additionally, once the data file had been loaded, each program allowed the user to perform calculations on the data to obtain other useful information.

The ShowWave program allows the user to open a welding data file and view the results in graphic form. The program plots the current and voltage waveforms versus time. The program also calculates the dynamic resistance and plots this on the same axis. In a separate field, the voltage is plotted against the current for each half cycle. A scroll bar is provided for the user to move between different cycle times in the data file. The user is given the option to view the entire waveform or look at the waveform on an expanded time scale that shows, at greater magnification, only 4 cycles of the weld at a time. In this mode, the scroll bar must be used to view the entire weld cycle. The movement of the scroll bar also causes the voltage vs. current, V-I, plot to be updated to the next half cycle. The program has a check box that allows the user to choose whether to have the program calculate the mutual inductance from the data or to apply a user
defined mutual inductance to the data. The user also has the option of applying a noise reduction routine to the input data and to show the force curve vs. time. No other input is required from the user to operate this program. Besides the output plots listed above, the program also calculates the RMS welding current, welding time, in cycles, and the electrode force. For each half cycle, the electrode tip resistance is calculated and displayed below the V-I plot. Figure 11 shows the user interface of this program and the output it provides the user.

A similar program was developed by the author. This program was initially designed to determine the scaling factor to be used for the conversion of the input current data to amperes. This program was not developed as far as the Show Wave program because of the overlaps of functionality. Instead, it was modified to fill in functionality not addressed by the other viewer. Figure 12 shows the user interface of the program. The program provides the user with a drive, folder and file selection box, seen on the left, from which to choose the input data file. The user is given the option of choosing between two basic modes of operation. The first mode is designed to identify the scaling factor. In this mode, the user is required to input the measured RMS current for the input data. The program uses this information in conjunction with the actual current data to produce a scaling factor for the current which will result in the same RMS current. The derivations of these calculations are shown in Appendix B. The second, and more commonly used mode, calculates the actual RMS current from the input data using a predetermined scaling factor. It should be noted that the first mode was used to obtain this scaling factor. This second mode only requires the user to select a data file. The program calculates, over each half cycle, the value of the resistance and mutual
Figure 11 User interface of original Show Wave program used to view captured welding data.
Figure 12 User interface of Monitoring Data Extraction program used to calculate the gain value for current inputs or the RMS current.
inductance of the welding circuit. These values are then averaged over the 20 half cycles in a normal weld and displayed to the user. Once the data is entered into the program, the user can choose one of two plots to display on screen. The first is a plot of current, dynamic resistance, and voltage vs. time and the second is a plot of voltage vs. current. The user may enter a numeric value to scroll through the cycles as only 5 cycles are displayed in the case of the time plot or 1 cycle for the V-I plot. Additionally, the user may attempt to refine the value of mutual inductance. This is done to eliminate the effect of mutual inductance on the voltage waveform. As of this writing, this functionality is best executed in the Show Wave program and has not been given further consideration in this program. The output from this program is very similar to the Show Wave program. It consists of either the current scaling factor or the RMS current, the average welding resistance, the mutual inductance, and a choice of current and voltage vs. time or voltage vs. current.

3.6 Simulation of Nugget Formation Process

A portion of this investigation was dedicated to the use of a finite element program to simulate nugget formation using data captured from actual welds. The simulation results were then compared to the actual value of nugget diameter obtained from the welded specimens. The process consisted of identifying the key input parameters of the program and conducting sensitivity studies on many of the other parameters. The goal of the process was to identify a standard set of parameter values that would accurately predict the nugget diameter over as wide a range of welding conditions as possible. For parameter values to be set as constant through all of the
simulations, it was necessary to show that the results were insensitive to changes in this value over the range that may be encountered during the welding process. Values that were determined to not be constant had to be formulated so that they could be easily determined from a given set of welding conditions.

The finite element simulation program used in the testing was developed in Fortran and is run through an MS-DOS window[9]. The actual operation of the program is very straightforward. After starting the program, the user is prompted for an input file containing a list of the data to be run. The user must enter the location of this file in a global reference format, (i.e. c:\sim\samp_list). The program then runs the simulation routine on each of the data files listed in the sample list file. During the run, the program uses the same parameters on all of the files listed. These parameters are discussed in greater detail in the next section. The program saves the simulation in an output file of the user’s choosing for future use. When all of the simulations specified in the sample list have been completed the program exits.

To run the simulation program, the user must first configure five parameter files. These files are described in detail below and are included in Appendix C for reference. The files are named BSOGBE.dat, samp_lst2, prams4sim.mit, and matconwla.dat.

The first file to be examined is the BSOGBE.dat. This file contains seven parameters of interest. Among these are the maximum welding current, plate thickness, the name of the electrode tip configuration file, the initial work piece temperature and the name of the material. These values were entered and remained constant throughout the simulation study. The name of the electrode tip file and the type of material did not change so these parameters could be left alone. Additionally, the electrode tip file was not
modified during this investigation and simply contains a geometrical representation of the electrode tips used. Plate thickness was constant for all material considered and minor variations in the initial work piece temperature amount to less than one-thousandth of the melting temperature of steel and therefore are not considered. The values of interest in this file are the settings for contact diameter, \( d_c \), and electrode tip diameter, \( d_e \). These values represent the contact diameter between the two specimens and between the specimens and the electrode tip, respectively. Variations in these parameters, or more specifically, in the difference of these parameters, has a large effect on the predicted nugget size. The second parameter of interest in this file is the electrode tip resistance. This value is used to find the actual resistance of the weld specimens by removing a fixed resistance from the circuit. This value represents the total resistance of both electrode tips. It was found that the predicted nugget diameter is insensitive to changes in this value over most welding ranges. However, over the course of 1500 to 2000 welds, the value changes enough that better accuracy is obtained when the true value of resistance is used in the simulation.

The sample list file, samp_lst2, is used to specify the input data, output file name, control files, and output location. The first non-comment line of this file is a single integer. This value tells the simulator how many simulations to run. The lines below this number represent the different input files. If more input lines are listed than the number specified, only the first lines corresponding to the number of specified items will be run by the simulator. The input line itself contains, from left to right ignoring the leading ‘-1’, the name of the monitoring data file to be run, the name of the simulation output file, the name of the program control file (BSOGBE.dat), a temporary file name that does not
need to be changed, the name of the material constant data file, the directory to which the output should be stored, and the directory which the program should look in to find the input file. In its current form, the simulator will exit before running the simulation if an output file name specified already exists in the output directory.

The material constant data file, matconwla.dat, contains information about various material properties of the weld specimens. It contains three sets of data that are temperature dependent. These represent the electrical resistivity, thermal conductivity, and specific heat of the steel. Additionally, the file specifies the melting temperature, tensile strength, yield strength, and density among other properties. The only property variation considered was the electrical resistivity. However, the weld nugget simulation was later shown to be insensitive to variations in this property.

The last input file was used to specify the scaling factors imposed on the measured data when recorded by the A/D board. This includes the gains necessary to convert the measured values of current, voltage, and force into amperes, volts, and daN, respectively. These values have been previously determined and do not need to be changed. One line of importance in this file contains the values of mutual inductance for the monitoring circuit. In simulations where the monitoring data has been treated to remove the mutual inductance, via treatment with the Fast Fourier Transform (FFT) or some other process, these values must be set very near zero. If these values are not changed, the program will essentially attempt to remove the effect of mutual inductance from the data twice, producing invalid results.

After completing a run of the simulation program, the results are stored in a text file under the specified name in the specified directory. This file is located in Appendix

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C. The output file can best be described by looking at a single output sequence and then noting that this sequence is repeated for each time step in the simulation. Since each simulation time step is 1/8 of a cycle there are approximately 80 of these data sets contained in the output file of a standard 10 cycle weld. The first few lines of the file provide the details of the files used in the simulation as well as the dimensions of the radial and vertical sizes considered and mesh number in each of these directions. The simulation program actually simulates one quarter of the nugget. It is then up to the viewing program, described later, to mirror those results about two planes to produce a full nugget. This information remains the same for each simulation run. The data of interest begins on the eighth line of text in this file. The data is arranged in tab delimited fields. The first line contains 21 different fields, 9 of which contain pertinent information to someone examining the file. These values are numbered in order, from left to right. The first value is the time, in cycles, of the data set; this value increases, as mentioned previously, in increments of 0.125 cycles. The remaining data represent values of the various parameters at this time. The next values indicate the RMS current, this is followed by the radius, the faying surface contact diameter, and the electrode tip contact diameter. The next four values represent the diameter of the nugget and HAZ, and the penetration depth of the nugget and HAZ. The remaining values are not of interest. The next lines essentially form a temperature matrix with each entry representing the temperature, $T$, at mesh point $ij$ where $i$ represents the radial mesh number and $j$ represents the vertical mesh number. The value of $T_{ij} = T_{i,j}$ represents the temperature at the center of the weld. As can be seen in the file, there are 40 mesh points in the radial
direction and 9 in the vertical direction. This indicates that each dataset will have 9 fields and 40 lines of data, after this point in the file, data for the next time step is listed.

While it is important to understand the significance of the data contained within the simulator output file, it is extremely cumbersome to extract any meaningful information by simply looking at the text. For this reason the Show Out program was developed. Show Out is a viewing program that provides the user a graphical representation of the data. Figure 13 shows the user interface of the viewer. With the program running, the user clicks on the read button to open a simulation output file. After selecting a file from the dialog box, the program proceeds to read the data from the file. The program has four main display areas in which it now presents a representation of that data. The first display consists of two text boxes. These boxes show the molten nugget diameter and the weld penetration depth at the currently selected cycle time. Below this, from top to bottom, a graph of welding current, dynamic resistance, weld center temperature, contact diameter, nugget diameter and penetration depth are shown vs. time. The top right corner of the screen contains a graphic representation of the temperature distribution in the weld part. Molten metal is represented in this display by a pink color. In black and white images, the molten portion can be identified as the solid light gray area located at the center of the weld. Below this a text box displays each of the time steps with the corresponding center temperature. The user can scroll through the text box containing the temperatures to view the center temperature at each simulation step. The user is also provided with a scroll bar beneath the temperature distribution plot. This allows the user to update the plot to any of the simulation steps. While the plot of welding parameters vs. time remains fixed for each file, the values of molten diameter
Figure 13  User interface of Simulation Results viewer used to graphically display the results of finite element simulations of welding conditions.
and penetration depth change in synchronization with the changes in the temperature distribution plot.

A modification was added to the simulation routine in the form of FFT filter in the Show Wave program. The FFT routine works inline with the Show Wave, however, upon loading the viewer the user is now required to select a parameter file that defines the FFT treatment. This file can be found in Appendix C. A check box has been added similar to the smoothing filter that must be selected before the sample data is loaded. Figure 14 shows the updated user interface of the program. The standard cutoff frequency defined in the parameter file for the FFT treatment is 50 kHz and the treatment is done using 256 data points on every half cycle. To use the FFT treatment, the user is required to modify the value of the non-dimensional mutual inductance to produce a waveform with the mutual inductance effects removed to a satisfactory degree. After the user is satisfied with the results of the treated data they have the option of saving the treated data for use in the simulation program, or for viewing at another time. It is a highly recommended practice, which was followed during the course of the study, that the FFT treated data be saved as a new file and never over the original monitoring data.

Short of repeating the weld under exactly the same conditions and obtaining new monitoring data, there is no effective way to undo the FFT treatment once it has been applied. After FFT treatment, the saved data should only be reviewed when the FFT box is unchecked. It is undesirable to apply a second FFT treatment to the already treated data. Additionally, it is necessary to set the mutual inductance value to zero since it has already been accounted for and removed from the data. A non-zero value for mutual inductance will cause an undesirable shift in the already clean waveform. A similar
Figure 14 User interface of updated Show Wave program using FFT treatment.
constraint is imposed when using the FFT treated data as input to the finite element simulation program. As mentioned in the description of the program, the program’s values of mutual inductance must be set nearly to zero to avoid modifying the cleaned waveform. The mutual inductance value can not be set exactly to zero, as this will cause a program error.

3.7 Preparation of Etched Samples

One method to determine the nugget diameter of a spot weld is to cut the welded material through the center of the weld; the piece is then mounted in epoxy and polished. The polish specimen can then be etched to reveal the microstructure of the weld. This etching will show the boundary of the nugget formed during welding as well as the boundary of the heat affected zone (HAZ). These samples can then be photographed for further study or have other tests, such as micro hardness of the nugget and HAZ, performed on them.

The samples to be etched must first be trimmed down to a size that will fit on both the cutting machines and in the mounting mold. The first trimming step is done on a foot stamp shearing press. This procedure cuts the welded specimen leaving only the overlapping section of the metal plates. The rest of the material may be discarded. Once trimmed down to this smaller length, now approximately 30 mm by 30 mm, the sample is made thinner by trimming a small section off of either side of the weld using a high speed cut-off wheel. Figure 15 shows the step by step cutting procedure.

At this point the sample is now ready to be cut to expose the central cross-section of the weld. This cutting is done on a low-speed saw. The blade used for this procedure
Figure 15 Cutting steps to observe cross section of weld nugget: (a) coarse cut to isolate nugget, (b) coarse cut to reduce specimen width, (c) fine cut to reveal center cross section of nugget.
is a high concentration diamond coated blade. The blade is aligned such that the center of the weld is lined up with the inner edge of the blade. Figure 15c shows the proper alignment of the blade. This ensures that the center of the weld is not removed during the cutting process. Since some material will also be removed from the cut surface during the polishing process the edge of the blade may be offset even further to make sure that the true center of the weld is seen at the final stage of the process. After the specimen has been cut, it is cleaned thoroughly with soap and warm water and dried. This removes the oil used in the cutting process from the part. It also removes the contaminants that can become lodged between the non-welded section of the workpiece during the cutting process. As the polishing steps progress, a contaminant can cause problems if it is larger than the polishing grit size used.

The specimen is now ready to be mounted. It is placed in a mounting clip to ensure that it remains positioned properly as the epoxy is hardening. The desired mounting position is to have the cut face of the welded part completely horizontal, parallel to the bottom of the mold. The inside of the mold should be rubbed with a thin layer of silicon grease to allow easy removal of the sample after the epoxy hardens. The sample is placed in the mounting cup so that the edge containing the weld is firmly pressed against the bottom of the cup. The epoxy mixture is made by mixing 15 parts resin with 1 part hardener. The mixture must be stirred for 3 minutes before use to ensure homogeneity. When the epoxy is ready, the mold is placed in a vacuum container. The container is used to draw the epoxy from a holding cup into the mounting cup. The vacuum also allows most of the air trapped in the epoxy during mixing to reach the surface and escape before hardening producing a higher quality mounting. Any residual
water or air trapped between the welded pieces will also tend to rise to the surface reducing the effect of the contaminants. Ideally, any gaps between the workpieces would be filled in with epoxy during the mounting. However, this does not typically happen because of the viscosity of the epoxy mixture. Therefore, the gap between the workpieces will continue to be a cause for concern if water or contaminants become trapped there. Once the mold is filled with epoxy, the epoxy must be allowed to harden for approximately twenty-four hours at room temperature.

After the epoxy has hardened, the samples may be removed from the mounting cups. It is necessary to clean the remaining silicon grease off of the samples at this time. This can wiped off with a dry paper towel. The samples are then polished using a three step process, prior to which the bottom edges of the epoxy are rounded off to prevent it from catching the paper. Each step of the process is carried out using an auto-polisher. The polisher applies a uniform load to each of the samples and allows the user to select the rotation speed of the polishing disk, the rotation direction of the samples relative to the disk and the duration of the polishing. In each step, a counter-rotating sample holder was employed with a load of 30 N on each sample. The first step uses 500 grit sandpaper at 300 rpm, this step is used to smooth out the cut surface to some degree, but its primary purpose is to remove the epoxy that may be covering the weld and to expose the metal of the sample. This step used polishing times in 10 second increments. Since the sample holder can polish six samples a once, samples that were exposed first were removed so as not to remove excess metal from the weld. Between each step the samples are rinsed in water to remove contaminants that could scratch the surface of the metal. The second step uses 1000 grit paper to further smooth out the specimen. This step is done using as
short a polishing time as possible, also in 10 second intervals, to prevent the removal of excess metal from the specimen. This step is complete when the surface appears to have a uniform scratch pattern under a microscope. The final step is a polishing step using 4000 grit paper with a rotation speed of 150 rpm. This is done for 30 seconds to ensure a smooth surface. This longer time is acceptable since this paper removes very little material and is moving at a slower speed.

After the samples have been polished they are rinsed in warm water and dried. This drying step is very important as water trapped between the welded parts has a tendency to seep out over time. When left on the polished or etched surface of the part this water aids in corrosion causing rust to form on the surface. Once the rust begins to form, the part must be re-polished. Samples are considered dry after 5 minutes in a hot air flow and are then ready to be etched. The etching solution is composed of 55 percent alcohol, 40 percent water, and 5 percent nitric acid. The etching is done in a small glass dish using between three and five milliliters of solution. For each milliliter of solution used, one drop of liquid soap is added as an activating agent. The samples are then placed weld down in the solution and moved slowly for 3 minutes after which they are removed from the solution and rinsed. The etching is carried out at 20 °C (68 °F). The samples are then dried with a paper towel and then further dried under forced hot air to remove any residual moisture. This drying is again critical to prevent rust from forming on the specimen. For storage the samples are placed in a sealed plastic bag.

The final step in this process is to take a photograph of the etched weld. Photographing the samples is done on a Leitz microscope using lenses that produce a photo with 10x magnification. The samples are mounted on the microscope and viewed
using the III and IV filters which, on this microscope, produce a light with a green hue. The instrument is adjusted so that the image on the photo screen is focused. The photo tray is then inserted into the instrument and the exposure time selected. Exposures of 1/125 s were used for the photographs. Film is inserted into the photo tray and the outer covering is pulled back out to its edge. This places the film in a position ready for exposure. The switch on the microscope activates the shutter for the set time. The casing is then pushed back in and the lever on the photo tray is activated. The entire package, film and casing, are pulled quickly to the end of the casing. This step allows the developing chemicals to mix and come in contact with the film. The lever is then returned to its original position which allows the film and casing to be completely removed from the photo tray. The film used is Polaroid 54 and is self developing. This film requires a development time of only twenty seconds. After the picture is removed from it’s casing it can be treated with a polish for preservation.
Chapter 4
Welding and Simulation Characterization

4.1 Weld Lobe Tests

One of the first requirements in conducting this investigation was to obtain experimental data identifying the critical welding current for splash and for no-weld. It was also important to obtain the characteristic form of nugget growth vs. current. This information was obtained through the weld lobe tests.

Initially, the weld lobe tests were carried out using old electrode tips. These electrode tips had been used for some time and had therefore experienced a dramatic shape change in comparison to new tips. Rather than a round contact surface at the end of the tip, the contact area was distinctly oval shaped. Tests were carried out with these tips using 1 mm thick galvannealed and organic zinc coated mild steel (SPCC). Weld lobes were obtained using electrode forces of 100, 200 and 300 daN with a welding time of 10 cycles. After completing the welding process, the specimens were sheared apart at the faying surface to reveal the nugget that had been formed. This nugget was then measured along both the length and the width of the specimen. Figure 16 shows the results of the weld lobe tests for galvannealed steel specimens using the pneumatic welding gun with old electrode tips. The figure shows the nugget diameter progression as welding current is increased. It can be seen from these results that the typical nugget formed followed the shape of the electrode tip very closely. That is, the nuggets were oblong in shape with the major axis corresponding to that of the electrode tip. While this experiment provides a general indication to the critical current conditions the results were not suitable for further use due to the preexisting deformation of the electrode tips. This
data was also used, initially, to search for a possible weld indicator within the monitoring data. The plot in Figure 17 shows a selected waveform of the monitoring data representing a splash condition. It was noticed that there are two distinct features among these waveforms when a splash has occurred. The first is a sudden drop in the measured welding voltage. This drop happens as the splash is occurring and the voltage remains at or near this level for the duration of the weld. The second indicator is a small “blip”, also in the voltage waveform. This indicator does not appear on all waveforms for which splash occurred. It was determined, however, that these indicators appear after the initiation of expulsion and are therefore not useful for splash prevention. As mentioned previously, for the splash to be controlled, detection must occur at least one half-cycle prior to the actual event.

Critical splash conditions and minimum welding current conditions obtained from this experiment are outlined in Table 1.

Table 1: Splash and No-weld current for varying welding forces on galvannealed and organic-zinc steel.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Material</th>
<th>Force (daN)</th>
<th>Current (kA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Galvannealed</td>
<td>Splash</td>
<td>100</td>
<td>6.55</td>
</tr>
<tr>
<td></td>
<td></td>
<td>200</td>
<td>9.85</td>
</tr>
<tr>
<td></td>
<td></td>
<td>300</td>
<td>10.40</td>
</tr>
<tr>
<td></td>
<td>No-Weld</td>
<td>100</td>
<td>5.09</td>
</tr>
<tr>
<td></td>
<td></td>
<td>200</td>
<td>6.51</td>
</tr>
<tr>
<td></td>
<td></td>
<td>300</td>
<td>7.66</td>
</tr>
<tr>
<td>Organic Zinc</td>
<td>Splash</td>
<td>100</td>
<td>5.51</td>
</tr>
<tr>
<td></td>
<td></td>
<td>200</td>
<td>8.25</td>
</tr>
<tr>
<td></td>
<td></td>
<td>300</td>
<td>9.48</td>
</tr>
<tr>
<td></td>
<td>No-Weld</td>
<td>100</td>
<td>4.65</td>
</tr>
<tr>
<td></td>
<td></td>
<td>200</td>
<td>5.51</td>
</tr>
<tr>
<td></td>
<td></td>
<td>300</td>
<td>6.44</td>
</tr>
</tbody>
</table>
Figure 16 Nugget diameter vs. welding current. Welding time of 10 cycles, old dome electrodes used with pneumatic welding gun on galvannealed steel.
Figure 17 Waveform of monitoring data taken during splash condition in the weld lobe tests.
Figure 18 shows the weld lobe results when organic-zinc coated steel was used as the test specimens.

These results show that the critical current levels of the organic-zinc coated sheets were generally significantly lower than those of the galvanealed sheets. However, the change in current between the splash condition and the no-weld condition are seen to be nearly the same for both types of materials. This would seem to indicate a constant shift of the welding range introduced by the difference in material rather than an expansion or contraction of the welding range.

To obtain data that would better represent the actual tip condition, the electrode tips were replaced with new ones. With the new tips in place, the weld lobe test was repeated after conditioning the tips. In this test only coupons of galvanealed steel were used as specimens. The conditions used were the same, 10 cycles at 100, 200, and 300 daN. When the samples were broken for measurement it was found that the nugget was no longer of an irregular shape. The nugget again mimicked the shape of the electrode tip, which was now nearly a true circle. The plots of nugget diameter show that nuggets measured in either direction were nearly identical. This test was conducted on both the air gun and servo gun. Figure 19 shows the weld lobe results from the pneumatic welding gun and Figure 20 shows the results from the servo gun. The critical splash conditions from each test are outlined in Table 2 below. It should be noted that due to the discrete setting of the servo force, the actual electrode force used was not exactly 100, 200, and 300 daN. The actual force is listed in Table 2.
Figure 18  Nugget diameter vs. welding current. Weld lobe test results: welding time of 10 cycles, old dome electrodes used with pneumatic welding gun on organic zinc coated steel.
Figure 19  Nugget diameter vs. welding current. Weld lobe test results: welding time of 10 cycles, new dome electrodes used with pneumatic welding gun on galvannealed steel.
Figure 20 Nugget diameter vs. welding current. Weld lobe test results: welding time of 10 cycles, new dome electrodes used with servo welding gun on galvannealed steel.
Table 2: Splash and No Weld currents for varying welding forces on air and servo welding guns.

<table>
<thead>
<tr>
<th>Welding Machine</th>
<th>Condition</th>
<th>Force (daN)</th>
<th>Current (kA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Gun</td>
<td>Splash</td>
<td>100</td>
<td>6.78</td>
</tr>
<tr>
<td></td>
<td></td>
<td>200</td>
<td>8.12</td>
</tr>
<tr>
<td></td>
<td></td>
<td>300</td>
<td>11.31</td>
</tr>
<tr>
<td></td>
<td>No-Weld</td>
<td>100</td>
<td>4.97</td>
</tr>
<tr>
<td></td>
<td></td>
<td>200</td>
<td>5.40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>300</td>
<td>6.38</td>
</tr>
<tr>
<td>Servo Gun</td>
<td>Splash</td>
<td>95</td>
<td>7.08</td>
</tr>
<tr>
<td></td>
<td></td>
<td>205</td>
<td>9.08</td>
</tr>
<tr>
<td></td>
<td></td>
<td>308</td>
<td>10.31</td>
</tr>
<tr>
<td></td>
<td>No-Weld</td>
<td>95</td>
<td>4.70</td>
</tr>
<tr>
<td></td>
<td></td>
<td>205</td>
<td>6.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td>308</td>
<td>5.98</td>
</tr>
</tbody>
</table>

There are minor differences between the results from each machine; however, neither machine seems to produce consistently higher or lower current values. It is believed that the difference in actual welding forces between the machines is responsible for the observed differences. It is also believed that the difference in impact speeds of the electrode tips may contribute to the variation. The servo gun has a higher impact speed when the specimens are clamped between the tips. This is also thought to cause greater wear and deformation of the electrode tip.

It was also necessary to conduct experimental welds using a constant current and varying the welding time used. In this test, the objective was to capture the nugget formation at a particular current every two cycles. In conducting this test it was assumed that the variations seen in the actual welding current were not significant enough to effect the nugget diameter. Likewise, the electrode force was assumed to be constant for each weld.

This test was performed in conjunction with the weld lobe tests. It was performed after the completion of the weld lobe for a given electrode force. The weld lobe data was
used to select a welding current that fell within the range of acceptable nugget sizes and below the splash condition for a 10-cycle weld. This test was performed on galvanealed steel sheets with both the air and servo guns. This data was saved and used for further verification of the simulation program. The results will therefore held and reported in Chapter 5 to improve understanding of their meaning.

4.2 Electrode Life Tests

As described in the methods section, the electrode life test sought to characterize the nugget progression under a fixed welding condition over a large number of welds. The test was completed when a nugget was produced that fell below the minimum acceptable nugget diameter. After completing the test, a representative sample was taken from each group of one hundred welds and broken on a tensile machine. This was done not only to identify the ultimate tensile strength of the weld formed, but also to expose the weld center so that its diameter could be measured.

It was found that as the number of welds produced increased, the nugget diameter decreased. As is expected, a decrease in nugget diameter also leads to a structurally weaker weld. The weld lobes conducted each one-thousand welds are shown in Figure 21. The nugget diameter and tensile forces of the specimens are shown vs. weld number in Figure 22. The relationship between weld diameter and tensile strength was found to be nearly constant, this is shown in Figure 23. This is as expected since the strength of the nugget is dependent on the surface area of the nugget cylinder that is a linear function of nugget diameter. The data obtained from the electrode life test would be used later in the investigation to verify the results obtained from the finite element simulator. Once
Figure 21  Nugget diameter vs. welding current from weld lobes taken during the electrode life test.
Figure 22  Tensile force vs. welding current for weld lobes taken during the electrode life test.
Figure 23  Weld diameter vs. tensile force for weld lobes conducted during the electrode life test.
the nugget pattern of the electrode life test was observed to coincide with what had been expected, the data would prove useful for this purpose.

The weld lobes conducted throughout the electrode life test would be used for two purposes. The first was to identify how the weld lobe changes over time. This is important because it represents the variation in the critical splash condition with weld number. One would be wrong to assume that the critical splash current remains constant. Instead, it is widely recognized that the splash condition decreases, while at the same time the current needed to form a minimally acceptable nugget increases. Figure 24 shows the variation in these values as weld number increases. As the electrode tips wear this pattern brings the two current levels close to each other. It is in the time when these current levels are nearly the same, that the control process is most important. Additionally, Figure 25 depicts the current level difference between acceptable nugget formation and the splash condition. It can be easily seen from this figure that the two currents tend to merge to a common value making selecting a good welding current increasingly difficult, if no control procedures are implemented. A second function of the weld lobe test was to provide experimental data with which to verify the simulation program. These weld lobes provide the opportunity to check the sensitivity of such program parameters as tip resistance and tip shape. Since both change over the course of the test, a simulation program that could accurately predict nugget diameter, without modifications needed in these values, would be considered insensitive to these values and would be an extremely attractive model.

During the course of the test, an impression of each of the electrode tips was taken every two hundred welds. These impressions show that the upper tip experienced a much
Figure 24 Current levels of minimum nugget formation, acceptable nugget formation, and splash condition for each weld lobe test conducted during the electrode life test.
Figure 25 Difference between critical nugget formation current and splash condition current over the course of the electrode life test.
greater change than the lower tip. This can be seen in the progression shown in Figure 26. The lower tip is seen to remain nearly constant in size and shape; however, the upper tip contact area clearly becomes larger over the course of the test. These results are believed to be a result of the material in contact with each of the tips. The lower tip is always in contact with bare steel; this is because there is no coating placed on the bottom of the welded specimens. The upper tip, however, is always in contact with the organic zinc coating placed on the opposing surface of the specimens. It can therefore, be concluded, using the bare steel as a baseline, that the zinc coating contributes to the increased deformation of the electrode tip. The cause of this is the chemical reaction between the copper of the electrode tip and the zinc coating described in the introduction. A plot of tip diameter vs. weld number is shown in Figure 26. The plot clearly shows that the upper tip diameter grows much more rapidly than the lower tip.

To generate further data for use in verifying the simulator program, two of the weld lobes of the electrodes were cut, polished, and etched. The samples were then photographed at a magnification power of 10. The photographs could then be used to detect the nugget diameter as well as the boundary of the heat affected zone, and the penetration depth of the nugget. These last two values can only be obtained by this method and not by using the tensile test method. The standard microstructure of mild steel as seen at this magnification is a very fine-grained structure. At such a low magnification it appears as a fine, uniform texture on the surface of the material. The heat affected zone and nugget, in contrast, have much coarser microstructures. They appear to have a dendrite form with sharp contrast between the grain boundaries. The nugget boundary actually appears as a thin line through the microstructure. Figure 27
Figure 26  Tip diameter vs. weld number for electrode life test.
shows the growth of the nugget and heat affected zone for increasing weld time for the same welding conditions. All welds were conducted using a welding force of 200 daN and a welding current of 7.40 kA on the pneumatic welding gun. The figures show nugget size starting from Figure 27a at 8 cycles and increasing to 27c after 12 cycles, where 1 cycle is equal to 1/60 seconds.
Figure 27 Photographs of etched cross-section of weld nugget showing nugget boundary and heat affected zone changing over welding time. Welding current of 7.40 kA and a welding force of 200 daN were used for all samples: (a) welding time 8 cycles, (b) welding time 10 cycles, and (c) welding time 12 cycles.
Chapter 5  
Simulation and Temperature Estimation

5.1 Finite Element Simulations

One of the major steps of this investigation was the verification of the finite element simulation program. This process involved two major tasks. The first was to identify those simulation parameters that the simulation results were insensitive to changes. This was carried out by considering a small number of welds and making similar variations to welding parameters in each. The results were then compared to each other and to the experimental data from the weld. Once the insensitive parameters were identified, the second step could proceed. This consisted of making simulations of a large number of welds. In this process, the insensitive parameters were left as constants while the sensitive parameters were modified. This served to further verify that the parameters chosen in the first part were indeed insensitive as well as to determine which values of the sensitive parameters are best suited to the simulation under different conditions. The final step of the simulator verification process came with the comparison of the use of FFT treated data as input as compared to using the original monitoring data.

As described above, the initial verification of the simulator involved the identification of sensitive and insensitive parameters. Several parameters were immediately identified as requiring verification. These included the value of the resistance of the electrode tip (\( R_{\text{tip}} \)), the resistivity (\( \rho \)) of the specimen, the difference in contact diameter (\( d_c \)) and electrode tip diameter (\( d_e \)), and in later tests, the value chosen for the mutual inductance.
The first values considered were those pertaining to resistance, \( R_{\text{tip}} \) and \( \rho \). These values were varied independently. Variations of ten percent were imposed on each value and the results were compared. The results show that for a large variation in either of these parameters the predicted weld nugget variation was much smaller. The effects of change in the resistivity were found to be negligible; therefore, future tests were conducted using a constant value for resistivity. Changes in the value of \( R_{\text{tip}} \), however, were seen to have a greater impact on the valued of the predicted nugget size. Since changes in tip resistance itself can be considered negligible, except in the case of large weld numbers, the tip resistance was only modified when conducting experiments on the electrode life test data. For this data a linear approximation of tip resistance was made as a function of weld number. This approximation was made from actual tip resistance data taken during the test. During the simulation run the tip resistance value was recalculated for changes in weld number of 1000 or more and was assumed to be constant for all welds over that range.

Next, consideration was given to the value of the contact diameter and electrode tip diameter. It was found that the critical value to consider in this case is not either of the individual values, but rather the difference between the two values, \( d_c - d_e \). The initial formulation of this parameter is given as:

\[
d_c - d_e = \alpha h
\]  

(4)

where \( d_c \) is the workpiece contact diameter, \( d_e \) is the contact area of the electrode-workpiece interface, \( h \) is the workpiece thickness, and \( \alpha \) is a material dependent constant.
That is, the difference is proportional to a constant times the thickness of the material being welded, measured in mm. The constant, $\alpha$, varies depending on the coating of the material being used. The initial values of this constant are shown for each material considered in Table 3.

**Table 3: Values of $\alpha$ for common steels.**

<table>
<thead>
<tr>
<th>Material</th>
<th>Values of $\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Galvanealed</td>
<td>0.7-0.8</td>
</tr>
<tr>
<td>Bare Steel</td>
<td>0.5-0.6</td>
</tr>
<tr>
<td>Organic Zinc Coated</td>
<td>0.6-0.7</td>
</tr>
</tbody>
</table>

When tests were run using modified values of this parameter it was found that the predicted values of the nugget diameter varied dramatically. The parameter $d_c - d_e$ was immediately identified as a sensitive parameter and could not be considered constant for each weld. This parameter of interest will be known as the contact diameter difference, $\Delta_c$. Once this was determined it remained to be seen if a value could be found that would accurately predict the nugget diameter. This would mean that rather than varying with each weld, the value of $\Delta_c$ would depend only on the material being welded. Due to the sensitivity of the simulation on $\Delta_c$ choosing the appropriate value would be the most difficult part.

The final parameter of concern was the value of the mutual inductance that the simulator applied to the monitoring data. In later experiments the monitoring data had been treated with a FFT routine that smoothed the data. In processing the data on the modified Show Wave, it was also possible to remove the mutual inductance during the
treatment. This data was saved and used as input to the simulation program. The mutual inductance of the simulator had to be modified to insure the effect of the mutual inductance was not removed from the data twice. However, the calculations involving the mutual inductance in the simulator required that it have a non-zero value. As a first attempt the mutual inductance values were simply set to very low values. Initial results showed that the results matched up well with those obtained before the treatment. It now remained to be seen how variations in the values would effect the output.

It can be clearly seen from this data that, large changes in mutual inductance do not have any meaningful impact on the predicted nugget diameter. This value was found to be insensitive and could be considered to alternate between two constants, one for untreated data and the second for treated data. The actual results of the simulations using FFT treated data can be seen in the following sections.

The results from the simulations on untreated monitoring data immediately showed a very good accuracy for predicting nugget diameter. These simulations were run on the weld lobes of both the air gun and the servo gun as well as the weld lobes conducted throughout the electrode life test using organic zinc coated sheets. In the simulations of the standard weld lobes, the value of tip resistance was fixed by the average value obtained from tests of a thin copper sheet placed between the electrode tips. The value for these tests was set at 25 \( \mu \Omega \). For the electrode life test, the tip resistance was determined by measuring the tip resistance every 1000 welds throughout the test. An equation was fit to the data obtained to give the resistance at a given point in the test. The resistance as a function of weld number is described as:

\[
R_{\text{tip}} = 0.002127N + 20
\]  

(5)
where $R_{\text{tip}}$ is the tip resistance and $N$ is the weld number.

The tip resistance was found to vary between 20 $\mu\Omega$ and 30 $\mu\Omega$. The resistivity of the material was fixed as a linear equation in the matconwla.dat file. The resistivity was given as a function of temperature that the simulation would calculate for each mesh point of the sample. The equation is:

$$\rho = AT^2 + BT + C$$

(6)

where $T$ is the mesh point temperature in $^\circ$C.

In this simulation values chosen were $A=10.56 \times 10^{-5}$ $\mu\Omega\text{-cm}/^\circ$C$^2$, $B=3.575 \times 10^{-2}$ $\mu\Omega\text{-cm}/^\circ$C, and $C=16.0$ $\mu\Omega\text{-cm}$. The value of the mutual inductance, $AMIND1$ and $AMIND2$ in the simulation input, was not considered until the FFT treatment was applied to the data. For this simulation process the values used were $AMIND1=0.2$ and $AMIND2=0.05$. The final value was $\Delta e$, which had been determined to be the sensitive parameter. It was this value that was varied over successive simulations to determine the best value to use for accurate nugget diameter prediction. Since the crucial factor is the difference, $\Delta e$, rather than the absolute value of either $d_e$ or $d_e$, the value of $d_e$ was set to a fixed 3.5 mm. The value of $d_e$ was varied to produce the resulting change in $\Delta e$.

The first simulations conducted were carried out on data from the electrode life test. These tests sought to verify the use of equation 5 for electrode tip resistance described above. As the data from the results shows, the resistance produced results that accurately reflected the measured nugget diameter. All of these tests were conducted using a constant resistivity and a $\Delta e$ value of 0.7 mm. When variations were made to the tip resistance and the samples rerun, the resulting change in predicted nugget diameter was very small compared to the change imposed on the tip resistance. This not only
substantiated the consideration of the tip resistance as an insensitive parameter, but also showed that the proposed tip resistance equation would be sufficient to obtain accurate simulation results.

Initial variations in $\Delta_c$ were carried out in very small increments. The original changes were found to produce nearly identical results. The changes in these values had to be increased until significant changes in nugget diameter were observed. This occurred with changes in the $\Delta_c$ value of 0.1 mm or greater. The range first considered was from $\Delta_c = 0.9$ mm to $\Delta_c = 0.5$ mm with the initial value chosen at 0.7 mm. Data from these initial calculations are shown in graphical form in Figure 28. It was possible to make two conclusions from this initial run. First, the behavior of the nugget diameter in relation to the $\Delta_c$ value was that nugget diameter increased as $\Delta_c$ decreased and a corresponding increase in $\Delta_c$ would trigger a decrease in predicted nugget diameter. Second, $\Delta_c$ values of 0.7 mm and above produced predicted nugget diameters that were too small. The errors of these simulations typically exceeded 20-30% and were well above the $\pm 0.05$ mm range that was targeted for the simulations. The results from a set of simulations using variations in $\Delta_c$ from 0.5 to 0.9 mm is in Table 4:

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Exp. Result</th>
<th>$\Delta_c$ values (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>1004</td>
<td>6.17</td>
<td>6.20</td>
</tr>
<tr>
<td>1007</td>
<td>6.32</td>
<td>6.55</td>
</tr>
<tr>
<td>1008</td>
<td>6.54</td>
<td>6.55</td>
</tr>
<tr>
<td>1011</td>
<td>5.75</td>
<td>5.80</td>
</tr>
</tbody>
</table>

From the simulation results it was possible to narrow down the range of $\Delta_c$ values for which to conduct simulations. From Figure 28 it is clear that the two best choices for
Figure 28 Predicted nugget diameters as a function of $\Delta_c$ in the simulation program.
$\Delta_c$ are 0.6 and 0.5 mm. Once the parameter ranges had been narrowed down, additional simulations were run on a wide variety of monitoring data. This data included the original weld lobe tests and weld lobes conducted throughout the electrode life test. The optimal value of $\Delta_c$ was found to be different for each of the materials considered. While a $\Delta_c$ value of 0.5 mm produces the best results for the galvanealed sheets, the organic zinc coated sheets are better simulated using a $\Delta_c$ value of 0.6 mm. The results show that for the optimal setting of $\Delta_c$ the error between the predicted nugget diameter and the experimental nugget diameter are less than 10% and more importantly, less than $\pm0.1$ mm absolute difference.

5.2 FFT Treated Simulations

When an FFT treatment was applied to the same monitoring data it was first necessary to determine a suitable value of the mutual inductance, $M$, to be removed from the data during treatment. This was done manually by choosing a value for the non-dimensional mutual inductance in the Show Wave program and observing the effect it had on the voltage vs. current (V-I) curve. The ideal value of $M$ would produce a V-I curve that was entirely linear. A poor value of $M$ would produce a very rounded V-I curve. Examples of each of these are shown in Figure 29 a and b. The fact that this value of $M$ had to be applied over each cycle also made the process more difficult as the value varied slightly between cycles and a truly linear curve was nearly impossible to obtain with a single value of $M$. The final choice of $M$ also varied by material type. For the galvanealed coated steel an $M$ value of 16 was chosen which corresponded to an actual inductance of 0.14 $\mu$H. For the organic zinc coated steel, a value of 12 was chosen for
Figure 29 Monitoring waveform comparison of data using (a) properly chosen value of mutual inductance and (b) poorly chosen value of mutual inductance.
M, corresponding to 0.10 μH. A second method of verifying a good value of the mutual inductance was to look at the voltage and current waveforms vs. time. In this plot, a satisfactory M value would make the peaks of the voltage and current curves line up. An unsatisfactory value would impose a large phase shift between the two curves. This phase shift can be seen in the waveform portion of Figure 29 b. The plots in Figure 29 a and b show the results of treating data with the values chosen above. After an acceptable mutual inductance value had been chosen, the FFT treatment could be applied. The FFT treatment serves to smooth the voltage and current waveforms by eliminating noise greater than a certain frequency. As mentioned in the methods section, the cutoff frequency for this FFT treatment was 50 kHz. Figure 30a shows the results of the FFT treated data. Figure 30b shows the untreated form of the same data file for comparison. I need to wrap this

After treatment of the data, the simulator could be used to obtain a predicted nugget diameter. The simulator was run in the same manner with the FFT treated data as it was for the original monitoring data. The major parameter change came in the values of mutual inductance for the simulator. These values, AMIND1 and AMIND2, were set at 0.001 and 0.0001, respectively. The parameters AMIND1 and AMIND2 serve as the simulation program mutual inductance values. The parameters are used to eliminate the effect of mutual inductance on the voltage waveform during the simulation. However, during the treatment by the Show Wave program, the mutual inductance effect is removed. It is then necessary to set the simulator values very near zero to prevent a double treatment of the data. A zero value would result in a program error so values were chosen that were two orders of magnitude lower than the original values. The
Waveform checker for monitoring data by Lab PCI1200

- Noise reduction
- Auto-set inductance
- Non-dimensional inductance

(a)

(b)

Figure 30 Monitoring waveform comparison with (a) FFT treated data and (b) non-FFT treated data.
simulations were again run for values of $\Delta_c$ ranging from 0.5 to 0.7 mm in 0.1 mm increments. The first comparisons were made with the results from the simulation using $\Delta_c = 0.7$ mm. These results showed that the predicted nugget diameter obtained from the treated data was generally lower than that obtained from the untreated data. Based on the prior conclusion that 0.7 mm was the maximum acceptable value of $\Delta_c$, it was determined that larger values would not have to be simulated for the treated data either. After comparing the results obtained from the simulations on both electrode life test data and weld lobe data, it was clear that the optimal value for $\Delta_c$ for treated data was 0.6 mm for data from organic zinc sheets and 0.5 mm for data from galvanealed sheets. These values correspond to the optimal values obtained for the untreated data. Figure 31 shows a comparison of simulations with FFT and non-FFT treated data for three different values of $\Delta_c$. The figure shows that in each case, the simulation results for the using FFT treatment are less accurate than the untreated data. One benefit of applying the FFT treatment is that the treatment will often produce usable data from data that was previously incapable of running to completion on the simulator. In the case of extremely noisy data, often a simulation using the untreated data would cause the simulator to generate an error and exit after only a few cycles of simulation. However, with the noise removed by the FFT treatment, the new data file becomes a valid input to the simulation program and runs successfully to completion. This provides the user an incentive to apply the FFT treatment before simulation.

Further simulations were carried out for the weld lobes of galvanealed steel for varying welding forces. A constant $\Delta_c$ value of 0.5 mm was used for all of the simulations with no FFT treatment. Figure 32 shows the comparison of the simulated
Figure 31 Simulation results comparing FFT treatment to untreated data using three different values of $\Delta_c$. 

Nugget Diameter (mm) vs. Welding Current (kA)
Figure 32 Simulation results of weld lobe tests on pneumatic welding gun with new electrodes using welding forces of 100, 200, and 300 daN and a weld time of 10 cycles. $\Delta_c = 0.5$ mm.
results and the experimental data for weld lobes of 100, 200, and 300 daN welding forces. The figure shows that the simulator is effective in predicting the actual nugget diameter. However, it was also found that the simulation produces the best results for the 200 daN weld lobe. The results are somewhat less accurate for the 100 and 300 daN simulations.

Simulations for the weld lobes in the electrode life test produced similar results. Figure 33 shows a comparison of simulation results using both 0.6 and 0.7 mm for $\Delta_c$. The figure shows that 0.6 mm is the better choice for $\Delta_c$ which agrees with the results obtained previously for organic-zinc coated steel. The results for $\Delta_c = 0.6$ mm are very close to the experimental values. Figure 34 shows the simulated results for the weld lobe after 2000 welds. The simulation was carried out for a $\Delta_c$ value of 0.6 mm only. Again the results are found to be within the desired range from the experimental data.

5.3 Temperature Field Estimation

After examining results from the finite element simulation program and verifying their accuracy a new welding model was considered. This model consisted of the heat balance model of the weld specimen and is described in the background section. The heat balance results were compared against experimental results and simulation results to test its validity.

Heat balance results were obtained from a modified version of the Show Wave program. Modifications were made to the viewer which provide a mean nugget temperature estimation for each half cycle of the weld. When this process is carried out for welding data from an entire weld lobe, the maximum mean temperature calculated can be seen to have a very close correlation to the measured welding diameter.
Figure 33 Simulation results of electrode life test after 1000 welds showing two options for $\Delta_c$. $\Delta_c = 0.6$ and 0.7 mm using original monitoring data.
Figure 34 Simulation results showing selected $\Delta_c$ value after 2000 welds of electrode life test. $\Delta_c = 0.6$ mm.
Figure 35 shows the plot of nugget diameter vs. maximum mean nugget temperature. Using the results from the simulation program, two additional features of the heat balance model can be checked. First, the model can be compared to the temperature distribution predicted by the simulation. However, the simulation predicts a range of temperature distributed over a mesh, while the heat balance model only predicts a mean temperature. Therefore, a direct comparison is possible only for temperatures before the melting condition occurs. It is being investigated whether a mean temperature reading could be applied to the simulation, allowing further comparison after melting. Second, since the simulation results have already been verified against experimental data, the simulator can be used to check additional weld lobes without the need to actually obtain experimental nugget diameters.

From this comparison to experimental data, it is easy to see that there is a very close relation between nugget diameter and mean temperature as estimated by this model. Further, it can be seen that a critical temperature value presents itself where, above this temperature, a splash will occur. This is seen in comparison to several weld lobe conditions. The benefit of this model is the relatively short calculation time needed to obtain the temperature, especially when compared to the simulation program considered previously. This improvement in calculation time is enough to make it a viable candidate for use in a real time control system. An added benefit of this system is the reduction in input values. As shown in the equation above and the derivation in the background section, this system only requires that the welding current and voltage be measured. The calculation is independent of tip resistance, material resistivity, and $\Delta e$. 

105
Figure 35  Nugget diameter vs. maximum mean temperature as method of characterizing nugget formation.
6.1 Weld Lobe test results

After examining the results of the weld lobe tests, it became clear that there were certain underlying relationships between the controlled variables, electrode force, welding current, and welding time, and the occurrence of a splash. Since the welding process is controlled by adjusting the welding current, the observations are related by the change seen in the current level required to produce a splash condition.

It was found that as the electrode force is increased, the current at which expulsion occurs is increased. This is due to two factors. First the increased deformation of the electrode tips caused by the increased force causes the contact area of the tips and the test coupon to also increase. This is transmitted through the test coupon to the faying surface where the contact area between coupons is greater. Since this contact area acts as a containment zone for the molten metal during welding, the increased area allows the weld nugget to grow to a larger size without expulsion occurring. Second, the larger contact area causes a corresponding drop in current density resulting in less heat generation.

In contrast, as the electrodes wear, the critical splash current begins to decrease. At the same time, the minimum current required to produce a satisfactory weld increases. Over a prolonged usage time, the two currents will begin to converge. This convergence must be effectively handled in the welding controller design to ensure effective control over the entire electrode life.
6.2 Splash Indications

By examining the output from the welding monitoring program and the weld simulator, it was possible to identify specific portions of various waveforms that were indicative of a splash occurrence. These indicators were identified by examining differences between data of known splash conditions and those of acceptable welds.

The indication of a splash occurrence can best be seen in the graphical representation of the monitoring data taken during the welding cycle. When the voltage and current waveforms are plotted versus time the change caused by the splash condition becomes apparent. The current waveform is seen to remain nearly constant, except for a half-cycle start-up and shut-down. This is expected since the welding controller is set and controlled by specifying a constant current output. However, the voltage waveform varies as the resistance of the weld specimen changes. It is the voltage waveform in which the splash condition can most readily be observed. The splash is typically characterized by a sudden drop in the voltage waveform. The underlying cause of this is the reduced resistance that is introduced into the welding loop when the molten metal is expelled from the weld. An alternate method of describing this indicator would be to consider the dynamic resistance of the weld part. That is, the time-varying resistance, calculated from the measured current and voltage. This value is valid while the current is above thirty percent of its peak value, and therefore only calculated during these intervals of the welding cycle. For typical welding conditions, the dynamic resistance is seen to remain essentially constant over any single half cycle for which it is calculated. Over the course of the entire weld cycle, the dynamic resistance would be expected to increase slightly as the resistivity of the material will increase as the material temperature is
increased. When a splash condition is examined, the dynamic resistance will be seen to drop off sharply over the course of one or two half cycles. This drop-off is the demarcation of the splash occurrence.

There are several important points to consider regarding this particular splash indication method. First, the indicator, in both resistance and voltage waveforms can only be seen after the actual splash has occurred. Therefore, these indications can only be used to identify the presence of a splash. The indicators can not be used to predict or control the splash as there is no precursory warning of the impending expulsion. Additionally, while these particular indicators are appreciable in most cases, there are several observed splash conditions for which the resistance or voltage drop is nearly non-existent. This low signal to noise ratio for some samples calls into question the validity of this method even as an indicator of expulsion. Finally, supposing these indicators could be effectively detected, the welding controller would require an additional half-cycle to carry out any changes in the welding conditions. This added time would result in any control routine applied to only have an effect after the expulsion had already occurred.

In conducting weld nugget formation simulations using the finite difference software other splash indicators became apparent. The simulator, in addition to calculating the nugget diameter, also computes the dynamic resistance within the weld specimen and the contact diameter at the faying surface. It was these two curves, in particular, that provide the best indication of a splash occurrence. It is expected that the simulated dynamic resistance would provide an indication of the splash occurrence. The dynamic resistance computed by the simulator is theoretically identical to the dynamic
resistance calculated from the monitoring data, discussed previously. The appearance of this indicator in the monitoring data then provides some validation of the simulator effectiveness. The second indicator is found in the contact diameter curve. This curve is seen to increase sharply at the splash point. This increase can be seen to occur at the same time as the corresponding decrease in dynamic resistance.

As with previously discussed indicators, this indicator also proves to be ineffective. While the identification of the indicators is easier than others considered, there remain two fatal flaws. Again, these indicators prove to occur simultaneously with the actual splash and with no distinguishable preliminary signal. This alone is enough to make these only useful to identify a past splash condition. However, compounding this is the fact that the simulator calculations take between twenty and thirty seconds to run to completion. This calculation time is approximately one-hundred and fifty times longer than the actual weld cycle, meaning that even if a precursor could be identified, the present simulation technique would not be able to determine the results until well after the weld had been completed.

It should be noted that in examining both the monitoring data output and the weld simulator output no precursory indication of an impending splash could be detected. It is not clear whether this is due to the total lack of any preliminary indication or to the noise associated with the monitoring data. It seems that the former is more likely as the application of FFT treatment to the monitoring data still failed to reveal an additional indicator. However, if the desired signal does exist, and is of the same magnitude and frequency as the noise introduced into the system, then it would not only be indistinguishable from the noise prior to treatment, but it would also be eliminated with
the rest of the noise after the treatment. If this is indeed the case, then a sampling method insensitive to this noise would be required. Such a system would require a great deal of effort to construct as the sources of the noise would have to first be identified and then eliminated, both of which could potentially be extremely difficult.

6.3 Heat Balance Welding Model

The results derived from comparison of the heat balance model predictions to experimental data and simulator results show that the heat balance model accurately predicts the mean temperature of the weld during the welding cycle.

Comparison of the thermal model to experimental results show that the model has a direct correlation to the resulting size of the nugget produced for the samples considered.

6.4 Effectiveness of Weld Simulation Program

While the use of the weld simulation program has been shown to be ineffective for prediction of the splash condition, the program has proven to be quite capable of predicting nugget size and temperature distribution. For several sets of simulated results, the program was able to predicted the weld nugget diameter to within approximately five percent of the actual value. More importantly, the predictions can be shown to fall within a range of ±0.1 mm of the measured value of the nugget diameter. These results validate the use of the simulation program to predict nugget sizes from monitoring data and can also be used to identify splash conditions in a post welding setup.
The simulator was capable of accurately predicting nugget formation over a range of welding conditions. These conditions included variations in electrode force and welding current as well as changes encountered over the course of several thousand welds representing the welding life of the electrodes. Furthermore, the simulation parameters needed only slight adjustment over these variations to maintain accuracy. These adjustments have been identified by equations that, in most cases, prove to be a linear function of total weld number which further simplifies the setup and operation of the simulator. Ideally, the next version of the simulation program could be designed to allow the weld number as an input and compute the dependent parameters from this value rather than setting them manually as is the current method.

While conducting the simulations, an analysis was conducted to determine the sensitivity of the simulation results to various input parameters. Of greatest concern were parameters that may be either time dependent, temperature dependent or both. These parameters included the difference of the electrode contact diameter and the faying surface contact diameter, \( d_e \), \( d_c \). Also of concern was the resistivity of the test specimens and its variation between various materials, the value used for mutual inductance, and the electrode tip resistance. Through the simulations it was discovered that the simulation results are relatively insensitive to three out of four of the above mentioned parameters. The only sensitive parameter being the \( \Delta_e \) value which will be discussed later in this section.

The other parameters considered, mutual inductance, tip resistance, and resistivity were all found to produce a relatively small change in predicted nugget diameter when compared with a large change in each of the parameters. Changes of ten percent in each
of the parameters produced corresponding changes in predicted nugget diameter of less than one percent. This percent change corresponds, on average, to an absolute change in predicted nugget diameter of ±0.008 mm.

The sensitive parameter determined from this investigation, \( \Delta_c \), was found to have the greatest influence on the simulated nugget diameter. However, the simulation results show that a value of \( \Delta_c \) could be chosen that would accurately predict nugget diameters for a wide range of welding conditions. The optimal values of \( \Delta_c \) were 0.5 and 0.6 mm for galvannealed steel and organic-zinc coated steel, respectively.
Chapter 7
Conclusion

7.1 Summary of Work Completed

After viewing the results of tests conducted with the weld monitoring system it was found that the monitoring data, by itself, provides very little in the way of advanced warning of an impending splash condition. The signal to noise ratio found in this data is very low which indicates that extensive, and time consuming manipulation of the data would be required to produce accurate splash predictions. This severely reduces the likelihood that control procedures could be enacted in sufficient time to suppress the splash. Additionally, most indications of splash seen in this data occur after the actual splash event eliminating the possibility of using these for control purposes.

The results obtained from nugget formation simulations using the finite element simulation prove to produce accurate indications of the splash event. The results also provide the basis for the development of a real time controller for the welding process. The simulator has been shown to accurately predict nugget diameters using the monitoring data as input. More importantly, this system may be used to verify the initial results obtained from the thermal monitoring system, having already been shown to closely duplicate experimental results in the simulations.

Finally, the results seen from the high speed temperature monitoring system seem to be most useful in the forecasting of the splash event. The basis for this system is the integral form of the heat equation that indicates the instantaneous center temperature of the weld part. These results, which have been validated by the simulation results, can be used in a real time situation to predict an upcoming splash. This system is successful...
because it eliminates the need for extensive and time consuming finite element calculations.

7.2 Future Work

The field of resistance spot welding still has several areas in which improvements may be made in the welding process. This portion of the paper attempts to detail these in relation to the work presented previously. The future work described here is intended to be a continuation of the work carried out thus far and to point to possible avenues which may be been untested previously.

7.2.1 Search for Critical Splash Signature

It is the author’s belief, that any future work on the subject of splash control in resistance spot welding must always be on the lookout for a definitive signature of the splash condition. Though this investigation was unable to identify such a signature one may still exist. It is important for the investigator to be mindful of this fact. In continuing the work begun here a future combination of the existing monitoring parameters that accurately signifies a splash occurrence. This signal can then be watched for as a part of the control method. The ideal results, however, would be the identification of a splash precursor. This, rather than identifying the occurrence of a splash would signify an impending splash condition. This parameter, more than the previous one could be used to control the welding parameters, such as current and electrode force, in real-time.
7.2.2 Application of simulation results to real-time monitoring and control

Additionally, this investigation paves the way for development of two varying techniques of control. The first comes from the verification of the finite element welding simulation program. The results of this study show that the simulator is effective in predicting weld nugget sizes. Further expansion of the program could potentially lead to its use in a control procedure. For this to happen the program would have to be modified to run in a much shorter time than it currently needs. This would require another study to verify that the accuracy was not compromised when the speed of the program is increased. In its current form, the program may be used to make modifications to future welds. As an example, for a run batch of 20 welds, if two welds are monitored and simulated, the results of the simulations could be used to adjust the welding parameters of the proceeding batch.

7.3.3 Application of Heat Balance Model to Control System

The second control method comes directly from the application of the heat balance equation. Using the mean temperature of the weld as method of predicting both nugget diameter and splash occurrence may prove to be an effective control parameter. Since the calculations for the mean temperature are much less bulky than those used in the finite element simulation, it may be possible to evaluate the mean temperature continuously in real time during welding. This method, if proven to remain accurate in a future investigation could easily lead to a real time control procedure.
References


Appendix A
Description of Monitoring Program

The program used to capture welding data was developed for a Windows™ based PC using Visual Basic. The user interface of the program is shown in Figure 7. This appendix will serve to further describe the operation of the program.

The program requires the user to choose the drive and directory in which to store files input and then input the name of the file to be recorded. The program automatically begins the file numbers at 0 and increases the number after each sampling, keeping the chosen file name constant. Before sampling the user must also choose whether to have the program plot the results on screen. By default, the option to save the data and plot it after capturing are selected.

Once the program has been configured the "Do Operation" button is pressed. At this point the program enters into a synchronous sampling mode. Sampling ends when the user presses the "End Sampling" button. Figure A1 shows a flowchart describing the complete operation of the program.
Figure A1 Flowchart of monitoring program. (RW Mon by Lab-PC-1200).
Appendix B
Approximation of Welding Circuit
and Derivation of RMS Current

The welding monitoring system is shown in Figure 4. It consists of a welding circuit, a voltage measuring circuit and a current measuring circuit. The input to the system comes from the weld controller. This controls the current passed through the welding circuit and the duration of the welding process. The voltage measuring circuit consists of two leads connected to the electrode tips as shown in the. A current sensing loop is used to measure the current in the welding circuit.

A corresponding circuit diagram is shown for the welding circuit and voltage detection circuit in Figure B1. The welding circuit consists of a current source, a resistance from the electrode tip, between the contact point of the wire and the end of the tip, and a resistance of the specimen itself.

Due to the very high current used in the welding process a significant magnetic field is created around the welding loop. Using the right hand rule, with current flowing from upper to lower tip, the direction of the magnetic field is found to be counter-
clockwise about the page's vertical axis. Alternately, the field is coming out of the page on the right side of the welding circuit and going into the page on the left side. Since the current is oscillating, the direction of the field changes each half cycle. The effect of this magnetic field must be taken into account in two ways. First, the steel specimens will experience a self-inductance, denoted as L. Second, because the voltage measuring circuit is essentially a current carrying wire in a changing magnetic field it will experience a mutual inductance from the welding circuit.

The circuit of primary importance is the voltage measuring circuit. From the circuit diagram, using Kirchoff's Loop Rule it is possible to find the voltage measured by the A/D board. This is given in the following equation:

\[
V_t - iR - L \frac{di}{dt} - iR_t - M \frac{di}{dt} = 0
\]  
(B1)

where \( R_t \) is the resistance of the electrode tip, \( R \) is the resistance of the specimen, \( L \) is the self inductance of the specimen, and \( M \) is the mutual inductance of the measuring circuit.

Grouping terms and solving for \( V_t \) gives the following equation:

\[
V_t = i_r + M \frac{di}{dt}
\] 
(B2)

where \( r \) is now the total resistance of the circuit. Additionally, \( L \) can be considered negligible in comparison to \( M \).

In this equation, \( V_t \) represents the value measured by the A/D board for voltage at time \( t \), while \( I_r \) represents the value of the current at time \( t \). The total resistance \( r \), and mutual inductance \( M \) are still unknown. However, it is possible to manipulate the equation above to obtain two simultaneous equations that can then be solved for \( r \) and \( M \). By the loop rule it is know that the correct values of \( r \) and \( M \) will cause the following equation to be true. To account for variations in measuring conditions and errors in measurement, the result is summed over several cycles.

\[
\sum \left[ V_t - \left( i_r + M \frac{di}{dt} \right) \right]^2 \Rightarrow MIN
\]  
(B3)

To find the minimum for this equation derivatives with respect to \( r \) and \( M \) can be taken. This then yields the following set of equations:
\[
\frac{df}{dr} = 2 \sum \left[ V_i - \left( i_r + M \frac{di}{dt} \right) \left( \frac{dV}{dr} - \left( i_r + \frac{d}{dr} M \frac{di}{dt} \right) \right) \right] \tag{B4}
\]

\[
\frac{df}{dM} = 2 \sum \left[ V_i - \left( i_r + M \frac{di}{dt} \right) \left( \frac{dV}{dM} - \left( \frac{i_r}{dM} + \frac{di}{dt} \right) \right) \right] \tag{B5}
\]

\[
\frac{df}{dM} = \sum \left[ V_i \frac{di}{dt} + \left( i_r \frac{di}{dt} + M \left( \frac{di}{dt} \right)^2 \right) \right] = 0 \tag{B6}
\]

\[
\frac{df}{dr} = \sum \left[ -V_i i_r + \left( i_r^2 r + i_r M \frac{di}{dt} \right) \right] = 0 \tag{B7}
\]

Before calculations can be made to determine values for \( r \) and \( M \) using these equations, the value of \( V_i \) and \( I_i \) must be converted into volts and amps respectively. Calculating the true voltage is relatively simple as the A/D board uses only a simple gain factor when measuring voltage. The gain of the board is set via the monitoring program to a value of 2. This means that the 12-bit A/D board will use a full range scale of \( \pm 2.5 \) volts. To calculate \( V_i \), the measured value from the board, \( V_{\text{meas}} \), is multiplied by 2.5 V and divided by 2048, the number of discrete steps for half of a 12-bit converter.

\[
V_i = V_{\text{meas}} \frac{2.5}{2048} \tag{B8}
\]

The actual time of each sampling is obtained by dividing the sample number by the sampling frequency, 2400 Hz:

\[
t = \frac{\text{samp}\#}{2400} \tag{B9}
\]

Since the A/D board can only sample one value at a time, the sampling order for a given time period is as follows: C1 -> V -> C2. To estimate the current at the time V is taken, the measured values are averaged to give:

\[
c = \frac{c_1 + c_2}{2} \tag{B10}
\]

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Calculating the true current is a bit more complex than voltage. Using the value obtained from the current meter, $I_{\text{RMS}}$, on the welding circuit, a calculated value of $I_{\text{RMS}}$ was then calculated over 9 cycles (360 data points). To calculate $I_{\text{RMS}}$ one takes the square root of the sum of the squares of current divided by the number of points.

$$I_{\text{RMS-meas}} = \sqrt{\frac{\sum I_i^2}{360}}$$

(B11)

Using the value of $I_{\text{RMS}}$ obtained from the current meter for the same sample, a scaling factor could then be obtained that is used to convert $I_{\text{meas}}$ to $I_t$.

At this point, the simultaneous equations determined previously could be calculated and solved for $r$ and $M$. This process was done over each half cycle so that 20 values of $r$ and $M$ were obtained for each sample. The procedure used is as follows: find the cells in each half cycle such that $i > 0.3i_{\text{max}}$. Sum values of $V*I$, $i^2$, $i*di/dt$, $V*di/dt$, and $(di/dt)^2$ and solve the system of equations given previously. Collect the values obtained for $r$ and $M$ and average over the 20 half cycles.

Once these calculations were completed, the dynamic resistance and voltage drop across the specimens was calculated. The dynamic resistance was calculated and plotted over each sample period for $I>500$ A as is given by the following equation:

$$r = \frac{V_t - M \frac{di}{dt}}{i_t}$$

(B12)

The voltage drop over the electrode tips and specimen was also calculated by removing the voltage due to inductance from the measured voltage. This results in:

$$V = V_t - M \frac{di}{dt}$$

(B13)

Plots were then made of $r$ vs. $t$ and $dr/dt$ vs. $t$ and plotted on the same graph.
Current and voltage waveforms were also plotted against $t$ on the same graph. The voltage plotted in this case was that obtained in the equation above. This voltage was also plotted vs. current. These plots can then be used to determine if the correct value for $M$ has been obtained. Two distinct features can be noted if the proper value of $M$ has been used. First, on the waveforms vs. time plot, the peaks of each waveform should occur at the same time if the inductance effect has been successfully removed from the measured voltage. Second, in the plot of $V$ vs. $I$, hysteresis effects from the inductance will show up. When the inductance is removed, the voltage will be seen to vary linearly with the current.
Appendix C
Parameter Files for Simulator and Show Out Programs

The following files are required for the proper operation of the simulation program. These files are explained in detail in Chapter 3 and are list here for reference.

C.1 BSOGBE.dat

"*** Control data for 0.97mm bare steel sheets ***"
-1     /* place keeping parameter
0.41,0.32 /* dc-de (cm)
0.005
0.0
160
1.25
0.0
20000.0 /* Maximum current value (A)
0.65
40.0
22.128 /* Electrode tip resistance (µΩ)
0.0
0.3
0.097 /* Workpiece thickness (cm)
160
2
0
0
0
0
0
2
419.5
906.0
0
"Rtype200" /* Electrode tip configuration file
1
0.25
4.5
20.0 /* Initial workpiece temperature ºC
" SPCC " /* Material type

Bsogbe.dat is the control file for the simulation program. The parameters that are identified above are those that need to be configured correctly for proper operation of the simulation program. From this investigation, the most important values were \( d_e \) and \( d_c \) which, combined as \( \Delta_e \) had the greatest effect on the accuracy of the simulation results.
C.2 Samp_lst2

"*** File lists to work for test ****"  
4  
-1,
"ogbe1004.spdt","ogbe1004.out","BS4ogbe.dat","ogbe1030.ot2","Matconwla.dat","C:\simspt","C:\simspt"
-1,
"ogbe1007.spdt","ogbe1007.out","BS4ogbe.dat","ogbe1030.ot2","Matconwla.dat","C:\simspt","C:\simspt"
-1,
"ogbe1008.spdt","ogbe1008.out","BS4ogbe.dat","ogbe1030.ot2","Matconwla.dat","C:\simspt","C:\simspt"
-1,
"ogbe1011.spdt","ogbe1011.out","BS4ogbe.dat","ogbe1030.ot2","Matconwla.dat","C:\simspt","C:\simspt"

The samp_lst2 files contain the names of the files the simulator uses for input and specifies the file names of the output file. The first line of the file specifies the number of separate simulations that should be run, in this example 4. The simulator will perform these simulations on the next n consecutive lines listed in the file. Each line consists of a leading -1, the name of the input file, the desired name of the output file, the name of the control data file to be used for the simulation, the name of a temporary output file that does not need to be changed for each simulation, the name of the material constants file, the directory in which to find the input file, and the directory in which to create the output. It is important to note that the simulator does not have an overwrite capability. If an output file of the same name exists the simulation will terminate.

C.3 Prams4sim.mit

" Start parameters for direct monitoring using US version"
"IDIV1",4
"NFSTSKIP",6
"AMIND,AMIND1",0.2,0.05
"GAINV1",0.0012213 /* Gain constant for voltage A/D
"GAIN1",12.0 /* Gain constant for current A/D
"GAINX1",0.26866 /* Gain constant for force A/D
"ForceBS",20.0
"NRDFLG",3
"CURMIN4V,CURMIN4R (A)",300,1000
"End data list"

The Prams4sim.mit file contains one parameter of interest. This is the mutual inductance value defined in AMIND and AMIND1. These values are only modified when using input that has had an FFT treatment applied to it. In this case, the treatment removes the effect of mutual inductance and it therefore does not have to be removed by the simulation program.
### C.4 matconwla.dat

"MATCONSET.DAT for Zinc coated steel sheets"
"<Resistivity; micro-Ohm*cm T,A,B,C; A*T^T+B*T+C>"
-200.0, 10.56E-5, 3.575E-2, 15.0
800.0, 0.0, 2.875E-2, 90.4
1200.0, 0.0, 0.0, 124.0
1530.0, 0.0, 2.0, -2940.0
1590.0, 0.0, 0.0, 360.0
3000.0, 0.0, 0.0, 360.0
"<Thermal conductivity; J/cm/s/K>"
-200.0, -3.48E-7, -1.04E-4, 0.522
400.0, -3.13E-7, -4.18E-5, 0.492
800.0, 0.0, 0.0, 0.273
1530.0, 0.0, 1.56E-2, -23.595
1600.0, 0.0, 0.0, 0.891
3000.0, 0.0, 0.0, 0.891
"<Specific heat; J/g/K>"
-200.0, 1.28E-7, 3.2E-4, 0.449
400.0, 7.73E-7, 0.0, 0.449
600.0, 0.0, 3.07E-3, -1.09
750.0, 0.0, -5.43E-3, 5.29
850.0, 0.0, 0.0, 0.669
1530.0, 0.0, 0.0, 0.669
"<Other setting constants>"
1. "RMTEMP", 20.0 /* Ambient room temperature °C */
2. "MCOD", 550.0
3. "TMELT", 1530.0 /* Melting temperature °C */
4. "THAZ", 723.0 /* Boundary temperature of HAZ °C */
5. "HL", 415.625
8. "DENSITY", 7.7
11. "ALPHA", 14.5E-6
12. "C1", 4580.0
13. "C2", 230.0
14. "AM1", 6.2
15. "QE", 309000.0
16. "GASR", 8.314
17. "A", 5.0
18. "AM2", 5.8
21. "TS", 550.0 /* Tensile stress of material (MPa) */
22. "YS", 234.0 /* Yield stress of material (MPa) */
23. "ALPHSIG", 0.010
24. "SIGNIN", 1.0
25. "TEMP1", 890.0
26. "TEMP2", 1420.0
31. "TSOFT", 538.0 /* Temperature at which metal softens */
32. "RFHI", 0.002
33. "CON4SFR", 200.0
34. "RO", 0.0
35. "POW", 0.3
36. "E1", 2100000.0
37. "E2", 1200000.0
38. "THMIN", 0.38
39. "CON4ELS", 0.81
41. "FSP1", 1.5
42. "FSP2", 0.08

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The matconwla.dat file specifies the various material constants used by the simulation program. Three of these properties are considered to be temperature dependent and are given different parameter values based on the mesh point temperature. Interpolation is used to obtain parameter values for temperatures not explicitly listed in the table. The remaining parameters are independent of temperature. The more important parameters are highlighted above.
C.5 Simulation results file

The lines below show a sample of the output generated by the simulation program. The data is generated for every 1/8 cycle from time zero to the end of the weld. Examples are shown below at \( t = 0 \), \( t = 1 \) cycle, and \( t = 10 \) cycles. The values on the output below, beginning with the line below 91 indicate the cycle time which the data represents, the RMS current, \( I_{\text{RMS}} \), the contact diameter at the faying surface, \( d_c \), the contact diameter at the electrode, \( d_e \), the nugget diameter, \( d_n \), the HAZ diameter, \( d_{HAZ} \), the penetration depth of the nugget, \( p_n \), and the penetration depth of the HAZ, \( p_{HAZ} \). The values following represent the temperatures at the mesh points within the workpiece. Across the page represents the thickness of the workpiece and down the page represents the radial direction of the weld. In the results from cycles 1 and 10 it can be seen that the temperature is greatest near the center of the weld and decreases in the vertical and radial direction. The results from later cycles also show how the nugget diameter, penetration depth, and HAZ change with time.

\(<\text{Window Ver 1.2}>\) Electrode tip SHAPE; C:\simspt\Rtype200
Input data; C:\simspt\ogbel004.spdt
Material; SPCC
CALC. range;
.78000 Radius of pre-weld;
.25000 Weld pitch; 4.50000
.02000 .00970 40 11
11 57 11 57 20 29
91

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901.03 698.38 378.11
833.02 842.13 866.25 918.75 974.31 1022.00 1042.73
901.03 698.38 378.11
828.88 836.90 865.01 913.29 970.41 1026.14 1059.06
944.49 726.81 463.89
821.50 827.93 847.49 883.88 941.99 1002.66 1051.44
965.10 745.78 512.27
818.49 819.45 826.08 846.90 886.92 954.84 1025.64
1004.54 814.55 621.35
818.77 813.55 805.81 810.61 843.16 911.74 1028.09
1191.10 1004.14 629.79
811.12 800.21 778.88 770.39 794.90 887.41 1080.99
1512.90 1134.08 434.66
836.28 812.74 755.78 706.14 696.23 736.38 864.80
1378.51 1417.27 493.44
740.93 738.27 662.55 580.94 545.12 554.00 616.67
961.44 1182.19 829.83
554.61 525.08 462.01 406.02 372.41 369.16 401.70
600.72 768.49 1029.48
489.15 419.03 326.99 261.75 224.08 209.06 213.13
270.49 315.72 345.73
199.57 172.90 143.99 122.08 108.03 101.10 100.34
112.44 120.88 125.05
70.92 67.57 61.71 56.21 52.19 49.93 49.32 50.03
53.05 53.72
34.61 34.10 32.96 31.71 30.70 30.07 29.84 29.94
30.51 30.63
24.20 24.10 23.87 23.60 23.36 23.20 23.13 23.14
23.25 23.28
20.98 20.99
20.34 20.33 20.31 20.30 20.29 20.29 20.29 20.29
20.29 20.29
20.10 20.09 20.09 20.09 20.08 20.08 20.08 20.08
20.09 20.09
20.03 20.03 20.03 20.02 20.02 20.02 20.02 20.02
20.02 20.02
20.01 20.01 20.01 20.01 20.01 20.01 20.01 20.01
20.01 20.01
20.00 20.00 20.00 20.00 20.00 20.00 20.00 20.00
| 10.000 | 0.00000 | 87.04 | 0.6750 | 0.6150 | 0.6200 | 0.7283 |
| 1.261  | 0.1940  | 1774.57| 637.73 | 0.41300| 1414.02| 1146.39| 435.17 |
| 885.91 | 89.246  | 44.623 | 180.95770| 1.00010|
| 1774.57| 1768.86 | 1751.54| 1721.82 | 1677.97 | 1617.94 | 1561.35 | 1401.68 |
| 1149.98| 891.61  | 637.73 | 1722.25 | 1678.37 | 1617.72 | 1559.96 | 1397.91 |
| 1774.78| 1769.11 | 1751.89| 1722.82 | 1677.97 | 1617.94 | 1561.35 | 1401.68 |
| 1146.11| 888.23  | 635.27 | 1723.04 | 1679.30 | 1618.30 | 1557.03 | 1390.93 |
| 1775.20| 1769.60 | 1752.53| 1723.04 | 1679.30 | 1618.30 | 1557.03 | 1390.93 |
| 1139.03| 881.98  | 630.76 | 1724.91 | 1682.02 | 1618.90 | 1552.69 | 1378.50 |
| 1775.75| 1770.30 | 1753.66| 1724.91 | 1682.02 | 1618.90 | 1552.69 | 1378.50 |
| 1127.89| 872.86  | 624.37 | 1726.70 | 1685.65 | 1624.26 | 1544.27 | 1357.30 |
| 1776.07| 1770.81 | 1754.73| 1727.00 | 1685.65 | 1624.26 | 1544.27 | 1357.30 |
| 1111.99| 860.56  | 616.02 | 1728.21 | 1690.83 | 1641.45 | 1530.00 | 1321.14 |
| 1775.03| 1769.93 | 1754.46| 1728.21 | 1690.83 | 1641.45 | 1530.00 | 1321.14 |
| 1093.87| 846.66  | 606.20 | 1730.26 | 1750.90 | 1724.88 | 1688.47 | 1642.84 |
| 1771.31| 1766.26 | 1750.90| 1724.88 | 1688.47 | 1642.84 | 1529.94 | 1312.45 |
| 1082.96| 833.59  | 595.15 | 1774.57 | 1751.54 | 1722.25 | 1678.37 | 1617.72 |
| 1763.90| 1758.90 | 1743.73| 1717.91 | 1681.52 | 1637.07 | 1529.76 | 1305.70 |
| 1071.32| 820.58  | 582.60 | 1775.03 | 1769.93 | 1728.21 | 1690.83 | 1641.45 |
| 1752.14| 1747.04 | 1731.58| 1705.61 | 1668.99 | 1620.76 | 1500.48 | 1289.80 |
| 1057.42| 806.41  | 568.27 |
| 1736.41 | 1731.03 | 1714.97 | 1688.13 | 1605.01 | 1482.90 | 1273.19 |
| 1041.20 | 791.39  | 553.92  | 436.90  | 273.19  | 171.03  | 114.39  |
| 1717.35 | 1711.85 | 1695.07 | 1666.13 | 1603.29 | 1594.38 | 1381.10 |
| 1688.13 | 1648.67 | 1622.56 | 1589.30 | 1444.38 | 1333.96 | 1190.63 |
| 1654.35 | 1628.75 | 1592.65 | 1553.16 | 1418.16 | 1283.96 | 1140.63 |
| 1625.35 | 1599.35 | 1563.35 | 1528.35 | 1393.35 | 1258.35 | 1113.35 |
| 1596.35 | 1570.35 | 1535.35 | 1493.35 | 1363.35 | 1228.35 | 1088.35 |
| 1567.35 | 1541.35 | 1506.35 | 1465.35 | 1336.35 | 1201.35 | 1061.35 |
| 1538.35 | 1513.35 | 1478.35 | 1438.35 | 1310.35 | 1175.35 | 1036.35 |
| 1509.35 | 1484.35 | 1449.35 | 1410.35 | 1283.35 | 1148.35 | 1009.35 |
| 1480.35 | 1455.35 | 1420.35 | 1381.35 | 1255.35 | 1120.35 | 0980.35 |
| 1451.35 | 1426.35 | 1391.35 | 1352.35 | 1226.35 | 1091.35 | 0851.35 |
| 1422.35 | 1397.35 | 1362.35 | 1323.35 | 1197.35 | 1062.35 | 0822.35 |
| 1393.35 | 1368.35 | 1333.35 | 1294.35 | 1168.35 | 1033.35 | 0793.35 |
| 1364.35 | 1339.35 | 1304.35 | 1264.35 | 1138.35 | 1003.35 | 0764.35 |
| 1335.35 | 1310.35 | 1275.35 | 1235.35 | 1109.35 | 0974.35 | 0735.35 |
| 1306.35 | 1281.35 | 1246.35 | 1206.35 | 1080.35 | 0944.35 | 0705.35 |
| 1277.35 | 1252.35 | 1217.35 | 1177.35 | 1051.35 | 0921.35 | 0681.35 |
| 1248.35 | 1223.35 | 1188.35 | 1148.35 | 1022.35 | 0891.35 | 0541.35 |
| 1219.35 | 1194.35 | 1159.35 | 1119.35 | 0995.35 | 0865.35 | 0515.35 |
| 1190.35 | 1165.35 | 1130.35 | 1090.35 | 0969.35 | 0843.35 | 0493.35 |
| 1161.35 | 1136.35 | 1101.35 | 1061.35 | 0934.35 | 0808.35 | 0453.35 |
| 1132.35 | 1107.35 | 1072.35 | 1032.35 | 0906.35 | 0780.35 | 0403.35 |
| 1103.35 | 1078.35 | 1043.35 | 1003.35 | 0879.35 | 0753.35 | 0353.35 |
| 1074.35 | 1049.35 | 1014.35 | 0974.35 | 0848.35 | 0722.35 | 0303.35 |
| 1045.35 | 1020.35 | 0985.35 | 0945.35 | 0819.35 | 0693.35 | 0253.35 |
| 1016.35 | 0991.35 | 0956.35 | 0916.35 | 0839.35 | 0219.35 | 0703.35 |
| 1112.35 | 1111.35 | 1110.35 | 1109.35 | 1108.35 | 1107.35 | 1106.35 |
| 1327.35 | 1278.35 | 1119.35 | 1019.35 | 918.35 | 817.35 | 716.35 |

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C.6 ParamSet4ADC_1.dat

"Test Parameter data"
10,60        /* Weld time(cycles), Line Frequency
30000,2400,60 /* Sampling Rate, Scanning Rate
0.0012213,11.99,0.26866 /* Gain of Voltage, Current, and Force
6, 6
20
30
50.0,500.0   /* FFT cutoff frequency

The above file is used in the FFT treatment of the welding monitoring data. The
values in the file are used to convert the monitoring data to values of current, voltage, and
force in SI units. The FFT treatment is then applied based on the cutoff frequency. The
sampling rate is the frequency of A/D conversions performed during data capturing in
hertz and the scanning rate is the frequency with which the entire bank of A/D inputs is
sampled, also in hertz.