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Analysis and development of a real-time control methodology in resistance spot welding

Dai, Wen-Long, Ph.D.
The Ohio State University, 1991
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ANALYSIS AND DEVELOPMENT OF A REAL-TIME CONTROL METHODOLOGY IN RESISTANCE SPOT WELDING

DISSERTATION

Presented in Partial Fulfillment of the Requirements for the Degree Doctor of Philosophy in the Graduate School of the Ohio State University

By

Wen Long Dai, B.S., M.S.

*****

The Ohio State University

1991

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CHAPTER I

INTRODUCTION

1.1 INTRODUCTION

Resistance spot welding, one of the electrical resistance welding processes, has been widely used in the mass production industries, in which resistance welds are produced at localized points in workpieces held under applied pressure and current between copper electrodes. With an increase in materials available to industry, there is a corresponding increase in the demand for resistance spot welding techniques to join these materials. In particular, the automotive industry is the major demander of these techniques, followed by the appliance industry. They are also utilized by many industries manufacturing a variety of products made of thinner gauge metals.

The single-parameter in-process monitor and feedback control systems for the resistance spot welding process have been continuously developed over the last three decades. In such systems, a critical parameter is monitored during the welding cycles and is used either to indicate weld quality (in-process quality monitoring) or to control weld quality by automatic adjustment of one or more of the machine-controlled weld
parameters (in-process quality control). Obviously, the critical parameter used for these purposes has to be well-correlated to weld quality.

The distributions of the temperature in the weldment is determined and controlled by the heat input and result in the nugget formation and thermal expansion of the weldment in resistance spot welding. Therefore, the nature of temperature response to voltage and current changes, and resistance variation during resistance spot welding has an important bearing upon the techniques used for monitoring and controlling nugget formation. For correlation between nugget formation and welding parameters, a systematic analysis must be conducted. However, the processes of resistance spot welding are difficult to analyze due to the fact that the flow paths for heat and current, interface interactions and the material properties variation with temperature and phase changes are very complex.

This study is devoted to investigation of the dynamic weldment expansion under various specified welding conditions and development of an expansion-based control algorithm for resistance spot welding, using the finite element method because the nugget growth responses directly to the thermal expansion of the weldment during resistance spot welding. In the meantime, the analytical results are compared and analyzed with experimental test data through the use of a data acquisition system.

Commercial finite element code "ANSYS" was used to model and simulate the resistance spot welding process and to determine the expansion and weld quality correlation. By systematic computer
simulations, the electrical, mechanical and thermal behaviors of the resistance spot welding process were studied. The weldability characteristic curve in relation to the electrode displacements during welding was developed. In addition, the welding conditions which cause current shunting and poor fitup were determined through the weldability curves. The results from these studies lead to the development of an expansion curve which could be used as a basis for in-process monitoring and control of resistance spot welding.

1.2 Research Issues

Several variables have been used in monitoring and controlling weld quality. These include:

a) nugget temperature,
b) ultrasonic signals (reflection, attenuation, velocity),
c) acoustic emissions,
d) electric parameters (voltage, current, resistance, energy), and
e) weld expansion/contraction.

The surface temperature of the spot weld can be related to the maximum temperature at the nugget center during resistance spot welding [1]. Therefore, a thermocouple mounted on workpiece or electrode [2,3] and the infrared emission [4] from the metal surface near the nugget have been employed to determine the nugget temperature of the spot weld. However, it is difficult to attach thermocouple onto the joining and also its lead wires will interrupt the weld operation, temperature gradient variations in the electrodes because of periodic change in current level and
weld time which make the control difficult. The dirt and fumes will cause spurious feedback signals, and the surfaces oxides will cause variation in surfaces infrared emissivity. Therefore, the temperature-based monitoring and control systems have not been readily accepted in a production environment.

From the responses of ultrasonic signals through the weldment, the weld size can be detected during resistance spot welding [5]. However, the cost, the complexity and the fragility of the sensors employed in those systems make them unsuitable for all except the most specialized, high-quality applications.

The acoustic emission technique is being evaluated in several automotive applications [6]. It has been reported that these systems worked well on conventional and galvanized steels. Such systems have the same disadvantage as these based on the use of ultrasonics in that the sensors used are expensive and fragile and it would be necessary to redesign the electrode assemblies to permit their incorporation.

Electric parameter monitoring and control systems have been the most commercially successful of all in-process quality-control systems because they are the easiest to attach to the welding machine and do not require sophisticated sensing devices [7]. However, they have the following limitations:

a) their use has generally been confined to uncoated mild steel sheet, because the resistance (or voltage) characteristics with weld size relationship of this material is most suitable,
b) electrode wear can cause misleading results,
c) voltage clips generally have to be placed close to the weld zone and are vulnerable in production environment.

The thermal expansion and contraction of weldment which can be considered as electrode separation closure, is not commonly utilized for quality monitoring and process control in the resistance spot welding. The reason is probably that the functions, capability and limitations of the aforementioned monitoring and control methods, except the expansion-based control method, are fairly well understood by industrial personnel. The expansion-based control method is thought to be more complex and subjected to more limitations. However, the electrode displacements due to joint expansion and contraction directly reflects the thermal responses of the joint material to the welding condition [8-10]. The characteristics of nugget formation process in resistance spot welding have been determined through a continuous monitoring of the electrode displacements during welding. The displacement measurement techniques are simple and can be easily incorporated with the existing welding machines.

In order to make effective use of the expansion-based monitoring and control logic, understanding the interrelationships between the electrode displacements and the weld thermal behaviors is a necessity. The method of approach to such understanding has been mostly through trial-and-error experimental tests [8-23]. This approach is in general expensive and time consuming. This is particularly true when the goal of the study is to determine the effects of individual parametric changes. Alternative
approaches, other than experimental tests for characterizing the temperature distributions in the weld and their resulting thermal expansion and contraction are needed.

1.2.1 Electrical-Thermal Coupling Issue

The parameters including material properties, contact resistance of electrode-workpiece interface and workpiece-workpiece faying surface, weld time, and weld current play an important role in determining the joint quality in resistance spot welding. In order to obtain quality weld, it is necessary to put these parameters into consideration and to understand their effects on the formation of weld nugget during spot welding. Consequently, the electrical-thermal response is the first issue to study for obtaining more information about the behavior of the nugget growth.

Meanwhile, application of the finite element method (FEM) have been on the increase in virtually every field of engineering and science. Various forms of schemes and associated solution algorithm have been proposed to analyze the relationship between the aforementioned parameters and the nugget growth. In this respect, a commercialized computer program, ANSYS, was used to model and simulate the electrical-thermal coupling problem through some assumptions and modifications.

Due to the powerful post processing ability of the ANSYS computer program, the dynamic nugget growth at any localized point has been easily obtained and observed and its growing states can be related to various welding parameters during resistance spot welding.
1.2.2 Thermal-Mechanical Coupling Issue

As mentioned above, during the occurrence of nugget growth thermal loading will bear upon the weldment and cause the weldment expansion resulting in the electrodes separation. Therefore, the thermal-mechanical coupling will be the second research issue in order to obtain the relationship between the nugget growth and the weldment expansion which was used as the base of real-time monitor and control system during resistance spot welding in this study.

The calculated time-dependent temperatures from the thermal-electrical coupling analysis were employed as the thermal load of the mechanical analysis for obtaining the dynamic weldment expansion. Consequently, the electrode displacement history related to the weld quality was obtained. The electrode displacement were also monitored in the experimental studies through the use of a data acquisition system.

1.2.3 Data Acquisition System and Experimental Test Issues

In order to implement the performances of weld quality monitoring and control in real-time, the data collection, data processing, data storage and retrieval, and data printing and plotting are necessary. A data acquisition system was designed and connected to the resistance spot welder. Consequently, the electrode displacement and velocity history of various welding conditions were obtained through the use of the data acquisition system during resistance spot welding. In the meanwhile, the aforementioned information was used to develop the real-time monitor and control logic for weld quality.
I.2.4 Development of a Real-Time Expansion-Based Control Logic Issue

The characteristic displacement parameters, such as expansion displacement history, maximum displacement, expansion rate changes, and maximum and minimum expansion rate, are potential parameters for real-time control of resistance spot welding process. Obviously, the last research issue is the development of a real-time expansion-based monitor and control logic during spot welding. Through the simulation of using finite element method, all of aforementioned information was obtained and compared with the experimental results. Finally, a real-time expansion-based control logic was developed from the results of finite element analysis and experimental studies.
CHAPTER II

LITERATURE REVIEW

II.1. INTRODUCTION

Resistance spot welding, a rapid and clean joining process, was invented in 1877 by Elihu Thomson, and ever since, many investigators have tried to contribute new information on this process in spite of its complexity as mentioned above. The electrode materials, electrode geometry, welding force, welding current, squeeze time, welding time and hold time are the requirements for resistance spot welding process. All of these parameters will directly or indirectly affect the weldability in spot welding. A very popular and useful weldability Lobe curve, which represents the range of acceptable welding current as a function of time and defines the robustance of the process, had already been developed and utilized in industry.

The electrodes are activated by the electrical and the mechanical systems of the resistance welding machine to constrain the workpieces, to conduct current through the workpieces and conduct heat away from the workpieces. Therefore, the electrode materials must be have good heat and electric conductivity and sustain high loads at elevated temperature.
Meanwhile, the geometry must be suitable to generate an acceptable nugget size according to the design requirement and heat-balance consideration under the specified force and current. It is known that too small an area will lead to subsize weld and insufficient strength, and too large an area will lead to unstable and inconsistent weld growth characteristics.

The welding force must be suitable enough to produce a local deformation at the common interfaces to seat the sheets properly for constraining weld nugget growth until an adequate weld size can be achieved and to develop a good contact area for providing good interface electric and thermal conductance. The greater the welding force is, the larger the contact area to be induced as a result of the fact that the high current level is needed and the excessive indentation may occur. Too little a welding force will lead to smaller contact area and the current flow is constrained such that only a low current level is used, but preweld splash may be induced. Thus, the weldability will degrade due to either too high or too low welding force.

The optimum electrode force is related to the mechanical strength of the workpieces. Since the true area at the localized contact points is proportional to the ratio of the electrode force and the mean yield strength of material, it appears that a minimum true contact area is necessary to produce the widest range of welding conditions. Generally, if the electrode force for all material conditions is increased, the Lobe curve will shift to the higher current level. It is also noted that the increased force will extend most Lobe curves to shorter weld time and broaden the possible range of
welding current.

The Squeeze time is the welding force duration before the weld current switches on. If the squeeze time is too short, a good contact area cannot be achieved in time; this equivalent to a too low welding force. Generally, a recommended minimum squeeze allows the electrode force system achieve to 90 percent of the set value.

The welding current is the strongest of the process variables affecting nugget growth, because the heat generation is proportional to the square of the welding current. The occurrences of weld expulsion and subsize nugget are, in general, due to the excessive current and insufficient current respectively. The electric current, voltage and resistance are correlated according to the Ohm's law. If any one of these changes, the others will vary during resistance spot welding.

The welding time is the current duration. Generally, when the spot welding process achieves thermal steady state, the nugget size growth reaches its limit. That is, the nugget thickness and diameter are all stable and no growth is occurring. Thus, a recommended welding is that which allows the nugget to grow in a stable fashion throughout the available time.

The hold time is the last period of welding time, which is used to allow the weld nugget to solidify and the metallurgical quality to be established under the influence of the welding force. During the hold time, mechanical load is essential to provide the necessary forging pressure to obtain a good metallurgical structure and to prevent the formation of shrinkage voids.
II.2. EXPERIMENTAL INVESTIGATION

Early work in the 1950's in the U.K., U.S.S.R. and U.S. observed that the electrodes moved apart during welding and closed together upon cooling, and showed that the electrode displacements during the formation of a spot weld due to thermal expansion were closely correlated to weld size. A number of monitor and control systems were developed for commercial use, based on either load adjustment, thermal expansion rate, maximum expansion or peak saturation.

In 1964, Waller [11] reported that for short weld times, the heat loss and the electrode embedding were small. The electrode movement at an early stage in the heating cycle reflected the heat input in such a way that the electrode movement was approximately proportional to the square of the weld current. As the weld pulse progressed, heat conducted into the electrodes and the electrode embedding increased. This gave the round off effect of electrode movement with time and hence, the maximum electrode displacement is directly proportional to the weld current.

There are several control systems based on the thermal expansion which occurs in the weld in a direction parallel to the electrodes during resistance spot welding. Waller [11] developed a expansion rate-based monitoring and control system in 1964. In his system he measured the time required to achieve a pre-determined expansion (i.e. generally about 30 percent of maximum expansion obtainable) as a control parameter.

Janota [8] used a more sophisticated concept in his control system. When the predetermined optimum initial expansion rate, approximately 1
mm/sec, was measured, the weld current ceased to increase. When the expansion rate approached zero (corresponding to the maximum expansion), the current was switched off by the system.

Needham et. al. [16] presented another control concept in which the current was shut off when expansion reached approximately 80 percent of the predetermined maximum value for a given joint material and electrode type. In order to minimize the reduction in expansion rate as the weld grew to full size 'roll over' and to increase the tolerance of the system, a predetermined current increase was also employed in which the slope-up was used to extend over much longer time periods than normal.

Johnson and Needham [17] developed a new control concept for resistance spot welding in 1972. They reported that the electrode force affected the nugget development and a threshold load, along with weld current and duration, determined the weld quality. An automatic load adjustment system which would restrict weld expansion during welding was developed. With this system the electrode force increased through the weld cycle as a result of attempted expansion. By this means, the growth of the nugget was regulated automatically, for, if the nugget was growing too fast, the electrode force increased automatically. This suppressed weld growth by the following mechanisms. At the early stage of the weld duration, a load increase caused the interfacial resistance to decrease so that the initial heating at the workpiece-workpiece interface is reduced. In addition, the electrode contact with workpiece was improved under higher loads. The current density at interface between electrode tip and the
workpiece was also lowered which reduced effective heating between the electrode-workpiece interface. Finally, particularly with thin gauge sheet, the increased electrode load also improved the heat conduction from the workpiece to the water-cooled electrode. These three factors acted in the same direction and hence the nugget development was reasonably dependent on the electrode load. Therefore, the electrode load was considered as a critical control parameter. It was reported that, for the given set of welding conditions, the nugget diameter varied with electrode load approximately in linear relationship between the subsize nugget and the splash limit [17].

All of these aforementioned in-process monitoring and control system used the characteristics of thermal expansion trace to adjust weld current, weld time or electrode force. Their control logic were based on the thermal expansion rate and/or the maximum expansion displacement.

However, due to the flexure of arms or cranked electrode, the excessive friction in the welding head, too shorter a weld time (less than 5 cycles) and inadequate sheet thickness (less than 0.5 mm), the electrode displacement was insensitive or even lacking response to the expansion signal in the initial expansion (i.e. with 30 percent of expansion duration) rate-based control system. For expansion correction-based systems, automatic control of weld time and automatic adjustment of electrode load, seem to be more suitable quality-control systems than expansion rate-based control systems. This is because a greater portion of the expansion duration signal was used in these systems (about 80%, as compared with about 30%
for monitoring). It would, however, still give misleading results for the cases with small weld-to-edge distances and under excessive weld-splash welding conditions.

In 1987, Taylor and Xie [13] presented a new approach to the monitoring of electrode displacements in the resistance spot welding of mild steel sheet. In this investigation, combining the expansion rate, maximum expansion displacement and peak saturation factors, they found that the problems of current shunting, electrode wear, poor fit-up, and edge effect could be solved. For instance, if the expansion failed to achieve the preset value due to smaller welding heat, a good weld was still obtained by using a peak saturation principle. However, no detail about the peak saturation time used in this investigation was reported.

During the past several years, many attempts to perform nondestructive inspection and characterization of the size and quality of a spot weld have been made. Some of the earliest and simplest techniques are monitoring the voltage between the electrode tips or the secondary current. Unfortunately, several authors [9,14,15,20-23] have reported continuous variation in the electric parameters. The current or voltage varies frequently during welding duration due to resistance change in weld area. Therefore, monitoring welding power input from current or voltage measurement may not be appropriate and does not reflect the true energy state in the spot welds. Measurement of the dynamic resistance of the spot welds is important to determine accurate energy generation during welding. Unfortunately, monitoring the dynamic resistance change at the
workpiece faying surfaces is difficult. The dynamic properties of the resistance spot weld have been studied by many investigators [14, 15, 20, 23]. They measured the dynamic electrical and mechanical properties of resistance spot welds and related them to weld quality. They found that trace electrode displacements and dynamic resistance of spot welds provided more consistent information about the weld quality than dynamic voltage or current could provide.

It is obvious that the history of thermal expansion or electrode displacements during resistance spot welding is related to welding current, electrode force and weld time. However, almost all the information available to date are experimental observations. Very little information on the relationships between the expansion displacements and the actual nugget formation process has been published.

II.3. MATHEMATICAL MODELING AND SIMULATION

Since experiments alone cannot easily study and separate the effects of the many factors involved in the resistance welding process, nor can they accurately predict the complex behavior of the coupled electrical, mechanical and thermal processes. Moreover, they are often limited in scope because of the restricted operational capabilities with regard to the available hardware, or due to excessive time and cost associated with the experimental procedures which involve many influential parameters.

The modeling and simulation of the resistance spot welding processes have attracted the attention of many researchers due to its analytical capability. However, a comprehensive analysis of the welding
process could not be established in the early mathematical modeling efforts because of its complexity, which involves the interaction between physical phenomena such as electrical, thermal, mechanical, metallurgical and surface behaviors of the process. Most of the early efforts were mainly conducted to study the heat transfer problems or surface phenomena by mathematical analysis, while neglecting the possibility or reliability of using the thermomechanical responses directly to the in-process monitoring and control systems.

The electrical, thermal and mechanical behaviors of the interface between two contacting solids was studied theoretically by Bowden and Williamson in 1958 [24]. Their study showed that surface asperities condense current density and restrict contact resistance within the contact region, which causes a temperature rise at the interface. In the meantime, the contact asperities were softened and indented into the interfacial surfaces which increased the net contact area.

Greenwood and Williamson [25] theoretically and experimentally investigated the electric current distribution over a small area between two semi-infinite solids in contact. They showed that current density singularity appears at the outer rim of the contact. The bulk of the material near the contact region was not heated appreciably by the flow of current through it, but it is heated directly by conduction from the peripheral region of the contact area.

Archer [26] mathematically studied the temperature response in spot welds from a process control viewpoint in 1960. Although he made several
assumptions which simplified the problem, the results provided good insights to the dynamic response of the material to heat conduction.

In 1961, Greenwood [11] introduced the first heat conduction model, using the finite difference method to simulate the resistance spot welding process which was considered a significant contribution to the theoretical modeling efforts; It included all the major features of the spot welding process. Greenwood's analysis assumed an axisymmetric heat conduction model with temperature dependent material properties and an internal heat generation. However, the effects of contact resistance and the latent heat of fusion on internal energy generation were not considered in his model.

Greenwood's analysis showed spatial temperature distribution over the time ranges of weld duration, and indicated a temperature concentration at the periphery of the electrode/workpiece interface in the early welding cycle. An isothermal elliptical-shaped nugget along the workpiece/workpiece interface was predicted at longer weld time.

Bentley and Greenwood [27] theoretically and experimentally investigated the effect of contact resistance on the temperature distributions in the weld cycles during the formation of spot weld in mild steel specimens. They concluded that the contact resistance played a major role only in the very early stages of heat generation and became less influential in the later stages of the weld nugget formation. The dynamic characteristics of the material resistance stabilized very quickly once the joint material heated up. The early Greenwood model, which did not
consider contact resistance effects, predicted contradictory results to the experimental data during the early weld cycles, but showed good agreement in temperature distributions at the later time.

In 1966, Dix [28] investigated the behavior of the contact interface for resistance spot welding of similar and dissimilar materials with a series of simple experiments. He found that the initial melting occurred in the center of the total thickness because the contact asperities melt explosively as soon as the electric current passing through them, and caused the intimate contact of the workpieces. The workpieces eventually acted like a single piece.

In 1967, Rice and Funk [29] analytically studied the temperature distributions during resistance spot welding of composite materials, and related the effect of contact resistance to the temperature distributions throughout the welding duration. They formulated a one-dimensional multilayer heat transfer model using the finite difference method. This model considered temperature-dependent electrical and thermal properties, bulk heating and contact resistance at the interfaces but the latent heat of fusion due to phase change was ignored. Their results showed that contact resistance had little effect on thermal behaviors of the resistance spot weld. During weld cycles, the very narrow region containing the interface was quickly heated to such temperature that the contact resistance of the interface reached a constant value.

Houchens, et. al. [30] developed two analytical models using the finite difference numerical technique to simulate the resistance spot welding
process to predict the thermal response and weld nugget penetration for steel sheets, respectively. The first was a one-dimensional heat transfer model which accounted for temperature-dependent material properties, latent heat of fusion and Joule heating for both electrode and workpiece. The second was an axisymmetric model which included the geometric effects of a flat end electrode. The results from the two models indicated that the first model provided insights into the dynamics of weld penetration and the second mode gave more information on current density and temperature distribution in both electrode and workpiece.

Gould [31] studied weld nugget development using both experimental and analytical techniques with three gauges of an AISI 1008 steel in 1987. A one-dimensional heat transfer model similar to the one used by the previous authors [29,30] was used in this study. The electrode geometry, internal heat generation, phase change, temperature-dependent material properties and contact resistance were considered, and a finite difference scheme was employed to solve the nonlinear differential equations. In the meanwhile the analytical results and the metallographic examination of the heavy gauge specimens were compared and showed that the predicted nugget sizes were much larger than those observed in the experiment. He concluded that this discrepancy was evidently due to neglecting the radial heat loss to the surrounding sheet.

In 1989, Cho et. al. [32] and Han et. al. [33] respectively developed a different theoretical model, both considering the similar physical properties and using the finite difference schemes, for predicting the temperature
distributions and weld nugget formation in resistance spot welding. Although both models could handle the physical properties not considered by the previous authors, the thermal and mechanical effects were not coupled. The uncoupled numerical models have their limitations in the practical applications of their analysis when the in-process monitoring and control for resistance spot welding needs to be addressed.

As shown in the summary of the aforementioned publications, the thermomechanical coupling in the numerical models for the resistance spot welding process was seldom addressed. All the mathematical models reported by the cited authors have been devoted to analyzing the thermal behaviors of the resistance spot welding process under different sets of parameters. The interactions between the mechanical stresses and the temperature-caused thermal stresses were overlooked.

In 1984, Nied [34], using the existing finite element code "ANSYS" introduced a coupled, axisymmetric model which considered the geometry of electrode and workpiece, temperature-dependent thermal properties, melting and Joule heating. Predictions of electrode and workpiece deformations were illustrated. Stress distributions along the interfaces were also obtained. The thermal analysis predicted temperature distributions which showed the characteristic isotherms of an elliptic-shape weld nugget. The model accounted for both mechanical and thermal response of the welding process, the effects of contact resistance variations, electrode wear, poor fitup and current shunting were not considered in the analysis.
Recently, Dickinson et. al. [35] modeled and simulated the resistance spot welding process using the "ANSYS" finite element code. The mechanical behavior of the welding process was coupled with the transient thermal responses during the entire welding cycles. The weld nugget formation of stainless steel 347 of equal and unequal thickness workpieces and joining stainless steel 347 to AISI 1045 carbon steel workpieces were studied. The analysis showed that the initial weld nugget formed as a toroid and spread rapidly toward the center. For unequal thickness sheet welding, the nugget formed mostly in the thicker workpiece due to longer current flow path. For dissimilar material welding, the nugget formed in the low conductivity workpiece more than in the workpiece with higher thermal conductivity. This study provided very comprehensive information about a coupled numerical model for analyzing the interactions of various physical phenomena in resistance spot welding. This has provided a useful tool for the current study on expansion/contraction displacement analysis.
CHAPTER III

RESEARCH CONCEPT AND OBJECTIVES

III.1 INTRODUCTION

The finite difference schemes have been already used to model and analyze the thermal behaviors of weldment and nugget formation and the ambiguous relationship between the thermal response and the nugget growth. They considered material properties as temperature-dependent. Some of them considered phase change effects or contact resistance. Some of them did not put these properties into their study. Even some others only treated the simulation model as an one-dimension problem. For whatever reason, all of these did not put the thermo-mechanical coupling into their studies, except for the studies of Nied [34], and Dickinson et. al [35]. Although, they used the finite element method to model and simulate the thermo-mechanical coupling problems in resistance spot welding, the contact resistance, which causes a contrary result of nugget growth in the early stage, was not involved in their studies. No electrode displacement history or expansion rate trace was investigated before this study. Practically, the weld growth is directly dependent upon the weldment expansion which can characterize weld quality with the use of both of the
maximum electrode displacement and/or the expansion rate range or its history tracing.

Here too, testifying various weld qualities is very critical, especially for unexpected conditions occurring, for example, current shunting, poor fitup, edge effect or the material properties changes during spot welding. Therefore, the main problems occurring frequently in the resistance spot welding, the current shunting and the poor fitup, need to be studied. Their results will also be used to justify the weld quality to determine if the nugget quality is acceptable or not.

III.2. OBJECTIVES

In this research program, the study concentrated on the interrelationships between the electrode displacements, expansion rate range or expansion rate trace and the weld quality. Consequently, a weldability curve, as a basis for in-process monitor and control systems, was developed by using the finite element method along with the commercialized finite element computer program "ANSYS". The objectives of this study are summarized as follows:

(1) to calculate the temperature distributions, thermal expansion and thermal expansion rate with time to understand the behavior of nugget growth in resistance spot welding using an existing finite element code "ANSYS". From the results, the nugget sizes, based on the calculation, will be compared with the experimental data;

(2) to develop a data acquisition system for collecting and processing
the experimental data, that is, current, voltage, time-dependent electrode displacement and time-dependent expansion rate;

(3) to measure the time behavior of the thermal expansion of the weldment for various heat input and weld duration under a specified electrode force, for comparison with the results of computer simulation,

(4) with the aforementioned results, to develop correlated weldability curves for resistance spot welding processes according to the thermal expansion rate, maximum thermal expansion and weld time duration, and

(5) with the comparison between the simulation and the experimental test results, recommended real-time monitor and control methodology will be discussed.
CHAPTER IV

COMPUTER SIMULATION AND ANALYSIS

IV.1 MODELING AND SIMULATION

The finite element method, ANSYS computer program, was used to model and simulate the electrical-thermal coupling response and the thermo-mechanical coupling problem in resistance spot welding. In which thermal-electric solid elements and convection link elements were employed to the electrical-thermal modeling and simulation to analyze the Joule heating and heat transfer problems. From the modeling and simulation, time-temperature distributions were obtained and related to the nugget growth. Isoparametric solid elements and interface elements were used to model and simulate the structure deformation and the contact problem under the time-dependent thermal loading obtained from the electrical-thermal modeling and simulation. The time-dependent displacement of the electrode and stress distribution were obtained. In the meanwhile, the weldment expansion history related to the nugget formation was obtained through the analysis of the results.
IV.1.1 Geometric Modeling

Considering a typical arrangement for spot welding two pieces of metal sheet, the development of a geometric representation of two identical electrodes and equal thickness workpieces simplifies the geometry to a two-dimensional, axisymmetric model. Because of this agreement, only one quadrant of the model, as shown in Figure 4.1, has to be constructed. Due to this simplification of geometric model, elements generated are reduced to quarter folds of the original model, and hence the reduction of time cost will be the same order. Figure 4.2 shows the two-dimensional finite element mesh structure used for the analysis. Four different types of element are employed, thermal-electrical solid elements and convection link elements for thermal analysis, isoparametric solid elements for stress and strain analysis, and two-dimensional interface elements for coupling the effects of the thermomechanical phenomena.

The thermal-electrical solid element has biaxial thermal and electric conduction capability. In the meantime, Joule heat generated by the current flow is also included in the heat balance. The convection link element is uniaxial element which has the ability of convection heat transfer between its nodal points. Therefore, these two types of element are linked together at the interfaces and used to account for the resistance heating and heat transfer in the workpieces and electrodes. Consequently, they can be used to calculate the temperature distribution and history during weld cycles in resistance spot welding. The calculated time-dependent temperatures are employed as the thermal load of the
Figure 4.1 Set-up for Electrode and Workpiece, Quarter View
Figure 4.2 Finite Element Model Identifying Element Types
isoparametric solid elements through a computer resume routine which uses the obtained temperatures as thermal loads and calculates stresses developed from thermal strains and electrode squeezing. The interface elements, with their thickness considered equal to one tenth of the element thickness, is used to simulated the coupling effects of the thermomechanical phenomena between electrode-workpiece interfaces and workpiece-workpiece faying surfaces.

In this model, the contact resistance between electrode-workpiece interfaces and workpiece-workpiece faying surfaces are considered and simulated by assigning a temperature and pressure dependent resistance properties to one layer of elements along the contact interfaces.

**IV.1.2 Boundary Conditions**

The boundary conditions imposed on the model simulate the physical constraints experienced by the material and its surroundings. These boundary conditions may be summarized as follows:

**a) Electrical Conditions**

The electric current density is specified at the top surface of the upper electrode and the voltage potential reference level is put on the contact interfaces between the workpieces because of symmetric geometry. The current flow is assumed to be uniformly distributed across the top surface of the upper electrode because the temperature along the top surface of electrode is specified to be constant because the cooled-water flows inside the cavity of the electrode and this surfaces is far away from the weld. No current flow is permitted across the central axis. Along the workpiece-
workpiece faying surfaces, current flow is permitted only across the contact area.

b) Thermal Conditions

Convective heat transfer is allowed along the lateral surfaces of the electrodes and workpieces. The outer surface is subjected to heat loss to the ambient environment, while across the inner surface, heat is transferred into a water-cooled channel from electrode. No heat flow is allowed across the central axis due to the axisymmetry geometry of the joint.

The heat transfer across the electrode-workpiece surfaces is specified by the convection link elements. No heat flow is permitted in the y-direction of the contact area of workpiece-workpiece faying surface. The noncontact interfaces are assumed to be insulated.

c) Mechanical Conditions

The electrode load is applied in the model by assuming a pressure distribution across the annular end of the upper electrode. The contact area at the workpiece interface is simply supported. Radial displacement is restricted along the entire central axis due to axisymmetry.

IV.1.3 Contact Resistance

When metal surfaces are placed in contact, the surfaces support each other on the tips of their asperities. The asperities readily deform plastically even under the minutest loads. For a material which is fully work-hardened the yield pressure at the tip of each asperity is a constant value and the mean yield pressure \( P \) can be expressed as \( P = cY \) [40]. \( Y \) is some 'representative' measure of the elastic limit of the deformed metal at
the tip of the asperities. The factor c depends upon the shape and the size of the surface asperities. It was shown for a wide variety of shapes and types of surface irregularities that the factor c has a value of about 3. Consequently, in most cases, the real contact area A is proportional to the applied load W. It is also inversely proportional to the mean yield pressure, or effective hardness of the surface asperities. In the mean time the area of contact A bears no direct relation to the actual size of the surface. Thus the area of real contact is determined primarily by the applied load W and the yield pressure or hardness of the surfaces. It does not appreciably depend on the apparent size of the surfaces.

The spreading resistance of each bridge is inversely proportional to its diameter, and the area of contact is proportional to the square of the diameter. If we assume the surfaces are supported on n equal bridges of radius a, the contact resistance $R_c$ when the bridges are relatively apart is given by $R_c = E/(2n*a)$ [40,41], where E is the interfacial resistivity (Ohm-in.) and $A = n*\pi*a^2$. Holm [42] has shown that the contact resistance $R_c$ can be approximately by the formula

$$R_c = 0.5E[(1/(n*a))+(1/r)]$$  \hspace{1cm} (4-1)

where E is the bulk resistivity and r is the radius of a circle containing a cluster of n uniformly distributed contact points with radius a. This result is the same as was stated above if the bridges are relatively apart, that is, $n*a$ is much smaller than r. Therefore, under such conditions, the contact resistance $R_c$ is inversely proportional to the bridge radius, and hence it is
proportional to the square root of the yield strength or hardness of the surface.

Several investigators have demonstrated the effects of load pressure and weld current [14,22,43] on contact resistance in resistance spot welding. High enough contact pressure can break down the oxide films at the interface, collapse the asperities of contact surface and consequently decrease the contact resistance. Therefore, the higher the electrode pressure imposed on weldment, the higher the applied electric current needed to compensate for the decrease in total resistance. Figure 4.3 shows the variation of contact resistance with time for different loads. Surface condition has a direct effect on heat generation through contact resistance. Oxide films, dirt, grease and surface finish can cause variations in contact resistance [20,22]. Clean surfaces and good finishing conditions decrease the contact resistance. This is illustrated in Figure 4.4 for the resistance spot welding of low-carbon steel specimens at three different surface conditions, phosphate treated, as received, and pickled.

There are several ways to evaluate the contact resistance: from contact area, from yield pressure or hardness, etc. The yield strength or hardness is a decreasing function of temperature. The contact resistance $R_c$ of one-contact spot at constant temperature $R_c(T_0)$ was shown by Holm [42] to be

$$R_c(T_0) = 0.8667 \cdot E(T_0) \cdot (P(T_0)/W)^{1/2} \quad (4-2)$$

where $E(T_0)$ is electric resistivity of the zone far from the contact's spot at
Figure 4.3 Variation of Resistance with Electrode Force [14]

Figure 4.4 Static Resistance of Low Carbon Steel as a Function of Current for Three Different Surface Conditions [22]
temperature $T_0$; $P(T_0)$ is the contact hardness of the material at temperature $T_0$; $W$ is the applied force.

A rise in temperature will result in a decrease of yield strength or hardness of the material, an increase in plastic deformation, and an increase in the area of the contact spots. Therefore, a decrease of contact resistance is expected, and it will be directly proportional to the square root of the ratio of the corresponding yielding strength or hardness [40, 42, 44].

In this study, in order to simplify the behavior of the interfaces, the variation of contact resistance, based on the statement above, is expressed as a function of the temperature-dependent yield strength (or hardness) of contact material during resistance spot welding. Consequently, it is transferred into equivalent resistivity due to the necessity of calculating Joule heat for the computer routine.

$$ R_c(T) = \zeta R_c(T_0) \left[ \frac{P(T)}{P(T_0)} \right]^{1/2} \hspace{1cm} (4-3) $$

$$ E_e(T_0) = R_c(T_0) = \frac{A_c}{L} \hspace{1cm} (4-4) $$

$$ E_e(T) = \zeta R_c(T_0) = \frac{A_c}{L} \left[ \frac{P(T)}{P(T_0)} \right]^{1/2} \hspace{1cm} (4-5) $$

where $E_e(T_0)$ is the equivalent electric resistivity at temperature $T_0$; $E_e(T)$ is the electric resistivity at temperature $T$; $A_c$ is the contact area; $L$ is the assumed element thickness; $\zeta$ is a temperature function of contact constriction resistance. In this study, $\zeta$ is assumed to be one because the yielding stress is considered as temperature-dependent property, that is

$$ E_e(T) = R_c(T_0) = \frac{A_c}{L} \left[ \frac{P(T)}{P(T_0)} \right]^{1/2} \hspace{1cm} (4-6) $$
Figure 4.5 shows the temperature dependent electrical resistivity of the electrode and workpiece materials under electrode force 800 lbs (365 kgs) [36-39]. The contact resistance between electrode-workpiece (R_e) interface and workpiece-workpiece faying surface (R_f) is a dependent function of contact pressure, temperature and average yield strength of two contact materials [40,41].

Thermal properties, such as conductivity, specific heat, density, diffusivity, latent heat, and solidus and liquidus temperatures of both electrodes and workpieces, are given in Table 1 [36, 39]. All thermal properties, except latent heat, interface contact conductance and density, were considered temperature-dependent properties in this study.

Figure 4.6 or Table 2 shows the mechanical properties of the electrode and workpiece materials [36,39]. All mechanical properties, except poison ratio, were considered temperature-dependent properties. In which, temperature-dependent Young's modulus were used to calculate the equivalent resistivities for both workpiece/workpiece faying surfaces and the electrode/workpieces interfaces. As a result that the contact resistances of electrode/workpiece interfaces and workpiece/workpiece faying surfaces are also temperature-dependent. In reality, the contact resistances were approach null when the contact area increases to some level. Therefore, the contact resistances or equivalent resistivities were assumed to be zero if the temperatures of the interfaces reach melting point. The temperature-dependent equivalent resistivities of mild steel were shown in Figure 4.5c.
Table 1. Physical(Electrical and Thermal) Properties for Mild Steel and Copper Electrode [36]

<table>
<thead>
<tr>
<th>Temp, °F</th>
<th>70</th>
<th>200</th>
<th>400</th>
<th>600</th>
<th>800</th>
<th>1000</th>
<th>1200</th>
<th>1400</th>
<th>1600</th>
<th>1800</th>
<th>2000</th>
<th>2200</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Conductivity (BTU/sec. in. °F)x10E-3</td>
<td>.866</td>
<td>.846</td>
<td>.74</td>
<td>.668</td>
<td>.60</td>
<td>.532</td>
<td>.467</td>
<td>.408</td>
<td>.38</td>
<td>.37</td>
<td>.382</td>
<td>Mild Steel</td>
</tr>
<tr>
<td></td>
<td>5.22</td>
<td>5.09</td>
<td>4.95</td>
<td>4.75</td>
<td>4.62</td>
<td>4.48</td>
<td>4.28</td>
<td>4.22</td>
<td>4.15</td>
<td>4.08</td>
<td>4.02</td>
<td>Copper Electrode</td>
</tr>
<tr>
<td>Resistivity (Micro Ohm. in.)</td>
<td>5.6</td>
<td>7.34</td>
<td>10.5</td>
<td>14.8</td>
<td>19.5</td>
<td>25.5</td>
<td>32.2</td>
<td>39.8</td>
<td>43.9</td>
<td>45.6</td>
<td>46.4</td>
<td>47.6 Mild Steel</td>
</tr>
<tr>
<td></td>
<td>1.04</td>
<td>1.18</td>
<td>1.57</td>
<td>1.99</td>
<td>2.437</td>
<td>2.75</td>
<td>3.15</td>
<td>3.535</td>
<td>3.734</td>
<td>3.93</td>
<td>Copper Electrode</td>
<td></td>
</tr>
<tr>
<td>Coefficient of Thermal Expansion (°F)x10E-6</td>
<td>6.1</td>
<td>6.4</td>
<td>6.8</td>
<td>7.2</td>
<td>7.5</td>
<td>7.8</td>
<td>8.1</td>
<td>7.8</td>
<td>7.5</td>
<td>Copper Electrode</td>
<td></td>
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<tr>
<td></td>
<td>9.2</td>
<td>9.3</td>
<td>9.5</td>
<td>9.7</td>
<td>9.9</td>
<td>10.2</td>
<td>10.3</td>
<td>10.5</td>
<td>10.7</td>
<td>Mild Steel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Equivalent Resistivity of Interface Surface (Ohm.in. X10E-3)</td>
<td>2.464</td>
<td>2.4</td>
<td>2.332</td>
<td>2.2</td>
<td>2.0</td>
<td>1.86</td>
<td>1.355</td>
<td>.588</td>
<td>.51</td>
<td>.432</td>
<td>.355</td>
<td>Mild Steel</td>
</tr>
<tr>
<td></td>
<td>1.232</td>
<td>1.2</td>
<td>1.116</td>
<td>1.1</td>
<td>1.0</td>
<td>.933</td>
<td>.6777</td>
<td>.294</td>
<td>.255</td>
<td>.216</td>
<td>.1777</td>
<td>Copper Electrode</td>
</tr>
<tr>
<td>Temp °F</td>
<td>70</td>
<td>200</td>
<td>400</td>
<td>600</td>
<td>800</td>
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<td>1350</td>
<td>1400</td>
<td>1425</td>
<td>1470</td>
<td>2200</td>
</tr>
<tr>
<td>Specific Heat BTU/lb°F</td>
<td>.106</td>
<td>.108</td>
<td>.122</td>
<td>.134</td>
<td>.146</td>
<td>.158</td>
<td>.182</td>
<td>.24</td>
<td>.24</td>
<td>.284</td>
<td>.284</td>
<td>Mild Steel</td>
</tr>
<tr>
<td></td>
<td>.095</td>
<td>.096</td>
<td>.01</td>
<td>.0103</td>
<td>.0105</td>
<td>.0108</td>
<td>.0111</td>
<td>.0114</td>
<td>.012</td>
<td>Copper Electrode</td>
<td></td>
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</tr>
</tbody>
</table>

Mild Steel, Solidus= 2700 °F; Liquidus= 2770 °F; Latent Heat= 117 BTU/lb; Density= 0.284 lb/in.³
Copper Electrode: Density= 0.316 lb/in.³.
Figure 4.5 Material Physical (Thermal) Properties [36]
C. Equivalent Resistivity for Electrode/Workpiece Contact Area

D. Equivalent Resistivity for Workpiece/Workpiece Contact Area
Figure 4.5 (continued)

E. Thermal Conductivity for Mild Steel

F. Thermal Conductivity for Copper Electrode
Figure 4.5 (continued)

G. Specific Heat for Mild Steel

H. Specific Heat for Copper Electrode
IV.1.4 Process Simulation

The resistance spot welding investigated in this study uses an existing case studied by Cho et. al. [32]. The electrodes used in this model are a RWMA Class II with a tapered flat shape and a 0.25 in. (6.35 mm) diameter contact surface. Joining of two mild steel sheets of 0.06 in. (1.52 mm) thick is simulated. Figure 4.1 shows the dimensions and configurations of both electrode and workpiece.

Three types of joint conditions, good fitup, poor fitup and current shunting, will be simulated in this study. Joint with good fitup is assumed to be one or the other have a contact area at the workpiece-workpiece faying surface the same as the electrode contact area with the workpiece. Poor fitup causes a reduction of contact area at the workpiece-workpiece faying surface. In this study, poor fitup is quantitatively defined as percent of contact area reduction from the good fitup condition. Current shunting indicates the existence of an additional current flow passage adjacent to the nugget during the weld cycles. This phenomenon is modeled in this study by an axisymmetric annular contact area surrounding the weld nugget. For a quantitative definition of current shunting, the percent of contact area increase from good fitup condition and mean radius of this annular area from the electrode center are used in this study.
### Table 2: Mechanical Properties for Mild Steel and Copper Electrode [36]

<table>
<thead>
<tr>
<th></th>
<th>Mild Steel</th>
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<tr>
<td></td>
<td>Temp. F</td>
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<tr>
<td><strong>Young's Modulus</strong> (psi) $\times 10^6$</td>
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<td></td>
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<td></td>
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<tr>
<td>30.0</td>
<td>28.5</td>
<td>28.2</td>
<td>27.0</td>
<td>24.5</td>
<td>17.0</td>
<td>8.0</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td><strong>Yield Stress</strong> (psi) $\times 10^3$</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>36.0</td>
<td>34.5</td>
<td>32.5</td>
<td>29.0</td>
<td>25.0</td>
<td>21.0</td>
<td>11.0</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td><strong>Copper Electrode</strong></td>
<td></td>
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<td><strong>Young's Modulus</strong> (psi) $\times 10^6$</td>
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<td></td>
<td></td>
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<tr>
<td>18.0</td>
<td>15.3</td>
<td>13.5</td>
<td>12.0</td>
<td>8.0</td>
<td>5.6</td>
<td>3.6</td>
<td>2.3</td>
<td>2.0</td>
</tr>
<tr>
<td><strong>Yield Stress</strong> (psi) $\times 10^3$</td>
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<td>12.0</td>
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</table>

* Poision's Ratio for Mild Steel : 0.3
* Poision's Ratio for Copper Electrode : 0.33
Figure 4.6 Material Physical (Mechanical) Properties
Figure 4.6 (continued)

Coefficient of Thermal Expansion (/ °F)

C. Coefficient of Thermal Expansion for Mild Steel

D. Coefficient of Thermal Expansion for Copper Electrode
IV.2 NUMERICAL PROCEDURE

There are many different commercialized computer programs available on the market which use the finite element method of analysis. However, ANSYS, one of the commercially available computer programs, was used to model the resistance spot welding process and conduct the analysis. The ANSYS program is a self-contained general purpose finite element program developed and maintained by Swason Analysis Systems, Inc. The program was designed to contain many routines, all inter-related, and all for the purpose of achieving solutions to structure and heat transfer engineering analysis. The solution capability of this program include: static analysis, elastic, plastic, thermal stress, stress stiffened, larger deflection; dynamic analysis, modal (nature frequencies and mode shapes), harmonic response, linear time history, nonlinear time history; heat transfer analysis, conduction, convection, radiation, coupled to electric flow, couple to fluid flow. Analyses can be made in one, two, or three dimensions, including axisymmetric and harmonic element options. The ANSYS also contains a complete graphics and extensive preprocessing and postprocessing capabilities. Further descriptions of the computer program are contained in the ANSYS version 4.4 user manual.

ANSYS is a general purpose computer program, and hence, when it is used to solve a special problem, for instance, in resistance spot welding, you have to modify the general model, reorganize the input, and make some assumptions. Otherwise, a lot of problems will arise, and subsequently, the model or the analysis will be inaccurate when compared with that of real
First of all, it is impossible for ANSYS to directly model the contact resistances of electrode/workpiece interface and workpiece-workpiece faying surface, using inter-developed computer program. The way to solve this complex problem is to modify the model which can be developed through the use of the ANSYS program. Therefore, a very thin element (0.001 in. more or less) will be assumed to simulate the dynamic contact resistance of contact area in this study. In the meanwhile, these contact resistances are transferred into equivalent material properties of resistivity in order to reach the requirement of the ANSYS data-input way. These equivalent resistivities used for Joule heating analysis are calculated according to equation (4-6), that is,

$$
\varepsilon_c(T) = \frac{(A_c/L) \times R(20^\circ C) \times \sqrt{\sigma_{y,ave}(T) / \sigma_{y,ave}(20^\circ C)}}{L}
$$

(4 - 7)

where

- $\varepsilon_c$ = equivalent contact resistivity
- $R(20^\circ C)$ = measured contact resistance at $20^\circ C$ under a given electrode force
- $\sigma_{y,ave}(T)$ = average yield strength of contact material at a specified temperature
- $L$ = characteristic thickness (one finite element thickness = 0.01in.) of the contact layer , (0.001 in.)
- $A_c$ = contact area

Second, the original input data for Joule heating is using voltage drop as the basis of heat generation due to the current flow through a material with proper resistivity. However, in the actual cases of various
resistance spot welding, the input data are electric current and welding cycles. Therefore, the input data should be reorganized and use the average electric current through the calculation of user's file as an input data.

Third, the PREP7 command is used to prepare the data for an ANSYS analysis. However, when it is needed to couple thermal analysis and static structure deformation analysis, only a specified temperature point can be used for each iteration of load. Hence, it is very inconvenient or almost impossible to obtain a continuous or smooth curve of the deformation of a structure under varying temperature loading. The PREP6 is mainly intended as a convenience for generating a file containing data for a large number of successive load steps for a transient dynamic analysis. For example, hundreds of temperature load step is necessary to define the load time history for obtaining displacement time history and expansion rate time history of electrode movement in resistance spot welding when coupling thermal analysis and mechanical analysis. Therefore, in such case, in order to obtain dynamic electrode displacement and expansion rate in resistance spot welding, data input must be conducted by using the PREP6 data-input routine instead of the PREP7 data-input routine for obtaining reasonable results, although the PREP6 data-input command is used in the analysis of dynamic systems, e.g., varying load of vibration system.

Figure 4.7 shows the sequence of modeling and analysis using the finite element method. The input parameters are classified into two categories, a mechanical phase and an electrical phase. The mechanical
FEM Modeling and Analysis for Resistance Spot Welding Analysis

Mechanical Phase

- Force system
- Geometry
  - 1. Temperature-dependent
  - a) Coefficient of thermal expansion
  - b) Elastic modulus
  - 2. Poisson ratio

Thermal-Electrical Phase

- Material
  - 1. Temperature-dependent
  - a) Electrical resistivity
  - b) Thermal conductivity
  - c) Specific heat
  - 2. Density
- Current

FEM (ANSYS)

Structure Analysis

Stress distributions

FEM (ANSYS)

Structure Analysis

Stress distributions

Thermal loading

- Voltage potential
- Range of expansion rate vs. weld current or time curve

NO

FEM vs. Experiment data

YES

Range of max. electrode disp. vs. weld current or time curve

In-process monitor and control systems for nugget formation

Figure 4.7 Finite Element Modeling and Analysis for Real-time Control Methodology
phase defines joint geometry, applied load and material properties. The electrical phase provides information about electrical current density and flow passages, as well as electrical resistivities of the electrical material, workpiece material and contact interfaces.

The finite element program calculates interface pressure, electrical field and voltage drop between electrodes, temperature history and distribution in the joint, expansion and contraction of the joint expansion or during weld cycles, and electrode displacement as a result of joint expansion or contraction. All of these electrical, mechanical and thermal analysis are coupled through the finite element calculation procedures, that is, for electrical-thermal coupling, the thermal and electrical aspects of the problem are combined into one element having two different types of working variables: temperature and voltages; for thermal-mechanical coupling, the obtained temperature distributions (thermal aspect) were used as the thermal loads of the structure analysis (mechanical aspect) to couple the thermal and the mechanical aspect s.

Table 3 summarizes the resistance welding schedules simulated in this study. An 800 lb (365 kgs) electrode force was employed for all welding schedules. The ambient air temperature was set to 70 °F (20 °C) and the cooling water temperature in the electrode cavity was specified as 50 °F (10 °C). The material properties were treated as nonlinear, temperature-dependent properties (Tables 1, 2), and the latent heat effect due to phase change was also considered in this study.
Table 3 Resistance Spot Welding Schedule in This Study

<table>
<thead>
<tr>
<th>Weld Number (Ni)</th>
<th>Electrode Force (kgs)</th>
<th>Current (ka)</th>
<th>Time (cycles)</th>
<th>Dynamic Voltage (V/sec)</th>
<th>Thermal Expansion (mm/sec)</th>
<th>Expansion Rate (mm/sec/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N 1</td>
<td>365</td>
<td>9.8</td>
<td>16</td>
<td></td>
<td>Fig.4.24.2</td>
<td>Fig. 4.23</td>
</tr>
<tr>
<td>N 2</td>
<td>365</td>
<td>10.8</td>
<td>16</td>
<td></td>
<td>Fig.4.24.2</td>
<td>Fig. 4.23</td>
</tr>
<tr>
<td>N 3</td>
<td>365</td>
<td>12.2</td>
<td>16</td>
<td></td>
<td>Fig.4.24.2</td>
<td>Fig. 4.23</td>
</tr>
<tr>
<td>N 4</td>
<td>365</td>
<td>13.8</td>
<td>16</td>
<td></td>
<td>Fig.4.24.2</td>
<td>Fig. 4.23</td>
</tr>
<tr>
<td>N 5</td>
<td>365</td>
<td>12.2</td>
<td>14</td>
<td></td>
<td>Fig. 4.22</td>
<td>Fig. 4.21</td>
</tr>
<tr>
<td>N 6</td>
<td>365</td>
<td>12.2</td>
<td>12</td>
<td></td>
<td>Fig.4.24.1</td>
<td>Fig. 4.23</td>
</tr>
<tr>
<td>N 7</td>
<td>365</td>
<td>12.2</td>
<td>10</td>
<td></td>
<td>Fig.4.24.1</td>
<td>Fig. 4.23</td>
</tr>
<tr>
<td>N 8</td>
<td>365</td>
<td>12.2</td>
<td>8</td>
<td></td>
<td>Fig.4.24.1</td>
<td>Fig. 4.23</td>
</tr>
</tbody>
</table>

* Workpieces: Mild Steel with 0.060(16 Ga) in.(1.52 mm) Thickness
* Electrodes: RWMA Class II with a Tapered Flat Shapes, 0.25 in.(6.35 mm) Diameter Contact Area
Three types of joint conditions, good fitup, poor fitup and current shunting, were simulated in this study (Fig. 4.8). Joints with a good fitup have a contact at the workpiece-workpiece faying surface the same as the electrode contact area with the workpiece. Poor fitup causes a reduction of contact area at the workpiece faying surface. In this study, poor fitup was quantitatively defined as percent of contact area reduction from good fitup condition. The real contact area was derived as follows,

From Fig. 4.8b
\[
\cos \theta = \frac{r_c - e}{r_c} \implies \theta = \cos^{-1}\left(\frac{r_c - e}{r_c}\right)
\]
(4-8)
\[
A_i = \pi \times r_c^2 \times \left(\frac{2\theta}{2\pi}\right) = r_c^2 \theta
\]
(4-9)
\[
A_2 = (r_c \sin \theta)(r_c - e) = (r_c^2 - e \times r_c) \sin \theta
\]
(4-10)

Let \( A_i \) = the intersection area between electrodes,

and from equation (4-9) and (4-10)

then \[
A_i = 2(A_2 - A_i) = 2r_c[r_c \theta - (r_c - e) \sin \theta]
\]
(4-11)

and the real contact area,
\[
A_r = 2r_c[r_c \theta - (r_c - e) \sin \theta]
\]
(4-12)

If \( e = r_c \) or \( d = 0 \), no offset occurs
\[
\cos \theta = 0, \implies \theta = \pi/2
\]
then \( A_i = \pi \times r_c^2 \) \( \Leftarrow \) Good Fitup

When \( e = 0 \) or \( d = 2r_c \),
\[
\cos \theta = 1, \implies \theta = 0
\]
\( A_i = 0 \) \( \Leftarrow \) very bad contact occurs, or even no contact area exists

Current shunting indicates the existence of an additional current flow passage adjacent to the weld nugget during the weld cycles. This phenomenon was modeled in this study by an axisymmetric annular contact area surrounding the weld nugget. For a quantitative definition of the current shunting percent of contact area increase from good fitup
condition, mean radius ($r_n$) of this annular area from the electrode center line were used to model and simulate the effect of current shunting in this study. The mean radius was derived as follow,

From Fig. 4.8c
\[ t = r_n - (r_c + g) \]  \hspace{1cm} (4-13)

Let \[ \bar{r}_n = \frac{t}{2} + (r_c + g) \]  \hspace{1cm} (4-14)
\[ \bar{A}_n = 2\pi \times \bar{r}_n \times t \]  \hspace{1cm} (4-15)
\[ A_c = \pi \times r_c^2 \]  \hspace{1cm} (4-16)

where: $g$ = gap between welding nugget and existing weld
\[ \bar{A}_n = \text{annular area with mean radius } \bar{r}_n \]
\[ A_c = \text{contact area with radius } r_c \]

Let \[ A_c = \bar{A}_n \] to be the area of FEM model,

and from equation (4-15) and (4-16)
\[ \pi \times r_c^2 = 2\pi \times \bar{r}_n \times t \]
\[ \bar{r}_n = \frac{r_c^2}{2t} \]

From equation (1)
\[ t^2 + 2(r_c + g)t - r_c^2 = 0 \]
\[ t = \sqrt{(r_c + g)^2 - (r_c + g)} \]

Let \[ r_c + g = A \quad r_c = B \]
\[ t = \sqrt{A^2 + B^2} - A \]

then, the annular radius,
\[ r_n = A + t / 2 = (A / 2) + [(A^2 + B^2)^{1/2} / 2] \]

The resistance welding schedules of both simulation and experiment in this study are summarized in Table 3. An 800 lb (365 kgs) electrode force was employed in all welding schedules. A truncated copper alloy electrode (RWMA CLASS II) was selected for spot welding the mild steel sheets with 0.06 in. (1.52 mm) thick and 1 in. (25.4 mm) long.
Current Flow

Area Reduction = \( \frac{(r_c^2 - r_{rc}^2)}{r_c^2} \)

Mean Radius, \( \bar{r}_n = \left[ A + (A^2 + B^2) \right]^{1/2} / 2 \)

where \( A = r_c + g \), \( B = r_c \)

Shunting Area, \( A_n = 4\pi \times \bar{r}_n (\bar{r}_n - r_c - g) \)

(a) Good Fitup  
(b) Poor Fitup  
(c) Shunting

A. Electrode/Workpieces Setup for FEM Modeling

Figure 4.8 Setup of the Joining for FEM Modeling during Resistance Spot Welding Process
B. Quantitative Definition of Poor Fitup

C. Quantitative Definition of Current Shunting
IV.3.1 Predicted Nugget Growth and Thermal Response

The temperature of any location in the workpiece, as a function of time from the start of the process, can be determined by using this finite element method. Consequently, it can also define the time when the weld nugget begins to form. Figure 4.9 shows the predicted temperature histories at six locations along the central axis of the joint. The welding schedules used in this analysis are welding current, 12.2 ka, weld time, 16 cycles, and electrode force, 800 lbs (365 kgs).

The temperature history at the center of the workpiece faying surface showed thermal arrests at solidus and liquidus temperature of the workpiece material (Fig. 4.9) due to latent heat effect.

Figure 4.10 shows that the maximum temperature attained near the periphery of contact area between workpieces in the early few weld cycles. Nevertheless, the initial melting occurred almost at the same time along the workpiece faying surface because of the effect of contact resistance during weld cycles (Fig. 4.11). Once the melting occurred, the nugget began to grow into the joint thickness as the weld cycles continued. A full nugget was developed right after the end of weld cycles. Contrarily, when the contact resistance was not considered during modeling and simulating, the nugget initiated at the periphery of the contact area because current density singularity appeared at the outer rim of the contact area. The molten nugget spread rapidly toward the center in a very short time during weld cycles. These phenomena were shown in Figure 4.12. In spite of the difference of temperature distributions in the early weld cycles under
different considerations, both of the aforementioned nugget formation have the same tendency to be an elliptic-shaped weld during the later weld cycles (Fig. 4.13), because the dynamic characteristics of the material resistance stabilized very quickly once the joint material heated up. This gave a good agreement in temperature distributions for both of them at later weld cycles. Therefore, it is obvious that the contact resistance plays a major role for thinner metal sheets but a much lesser role for thicker workpieces.

From Figure 4.14, it is found that the temperature at the electrode-workpiece interface is less than in the interior of the workpiece due to the heat conduction into the electrode. However, there is a maximum temperature beyond the edge of the electrode-workpiece contact area. The temperature along the workpiece faying surfaces reduced as the radius reached the outer edge of workpiece-workpiece contact area (Fig. 4.15).

The predicted nugget size variations, represented by the ratio of nugget diameter, $D_n$, to electrode tip diameter, $D_e$, and the ratio of penetration depth, $T_n$, to the joint thickness, $T_w$, for several schedules are plotted in Figure 4.16. The experimental data obtained under the same welding conditions are plotted in the same figure. Good agreement is observed for all schedules.

From Figure 4.16, it was also shown that the nugget growth rate is not equal in the thickness and radial directions. The nugget growth rate in the radial direction is less than in axial direction in the early stage of the process, but later, the diameter growth rate becomes higher than the
penetration rate, because the temperature near the electrode-workpiece interface drops deeply.

Figure 4.17 shows the predicted nugget diameter variation with increasing weld current for a 16 cycles weld time. Good agreement is observed at various current levels. Fig. 4.18 summarizes the weld time and weld current relations and, with reference to the experimental data obtained, forms a quality window of welding parameters (i.e. Lobe curves or diagram) which produce acceptable welds. Several experimental data points are also shown in the same figure for comparison purpose.

**IV.3.2 Predicted Nugget Growth and Mechanical Responses**

During weld cycles, the joint expands when its temperature rises and contracts when it cools down. This phenomenon has been related to the electrode movement monitored during welding. The expansion displacement, which are monitored through the electrode displacements, have been found to be closely related to the nugget formation process.

Figure 4.19 shows the predicted variation of the electrode displacements during weld cycles and hold cycles at various current levels. With reference to the quality window (Fig. 4.18), the upper and lower tolerance limits and the acceptable characteristic curves are summarized in the same figure. Figure 4.20 shows the typical characteristics of the dynamic electrode displacements as observed in many studies [11], and the results of simulation will be compared with the experimental testing in this study. This schematic diagram verifies the predicted electrode displacement characteristics.
Figure 4.9 Predicted Temperature through the Thickness of Workpiece in the Center of Weldment during Welding; Weld Current, 12.2 kA, Weld Time, 16 Cycles
Figure 4.10 Temperature Distribution along the Faying Surfaces, Electrode Force, 800 lbs (365 kgs), Weld time, 1 Cycle, Current, 12.2 ka (contact resistance considered)

Figure 4.11 Temperature Distribution along the Faying Surfaces, Electrode Force, 800 lbs (365 kgs), Weld time, 7 Cycles, Current, 12.2 ka (contact resistance considered)
Figure 4.12 Temperature Distribution along the Faying Surfaces, Electrode Force, 800 lbs (365 kgs) (no contact resistance considered)
Figure 4.13 Elliptic-Shaped Nugget during the Later Weld Cycles
Figure 4.14 Temperature Distribution along the Electrode/Workpiece Interfaces

Figure 4.15 Temperature Distribution along the Workpiece/workpiece Faying Surfaces
Figure 4.16 Nugget Growth for Different Welding Schedules with Constant Current, 12.2 ka and Electrode Force, 800 bs (365 kgs)
Figure 4.17 Nugget Growth for Different Welding Schedules with Constant Weld Time, 16 cycles, and Electrode Force, 800 lbs (365 kgs)
Nugget Diameter, mm

Welding Current, kva

Weld Time, cycles

Welding Current, kva

Figure 4.18 Conventional Lobe Curve, Weldability Window
Figure 4.19 Variation of Electrode Displacement with Time after Weld Cycle Starts, Electrode Force, 800 lbs (365kgs), Weld Time, 16 cycles

Figure 4.20 Typical Dynamic Electrode Displacements during Resistance Spot Welding [11]
Figure 4.21b shows a continuous trace of the expansion rate of the workpiece material, which is determined from the derivative of the predicted electrode displacements (Figure 4.21a). The expansion rate increases (to 2.4 mm/sec, point 1) and then drops (to 1.15 mm/sec, point 2) within a very short period of time during the initial weld cycles due to high initial contact resistance, followed by a quick resistivity drop because of the fast temperature rise of the workpiece faying surfaces which causes a rapid thermal expansion of the contact area and followed by its softening. The expansion rate decreases gradually (to point 4) during later weld cycles because of moderate changes in the material resistivity due to mild temperature change. The sudden drop of the expansion rate after the weld cycles shows a quick material contraction due to solidification of the molten nugget. The contraction displacement becomes steady upon the cooling of the workpiece.

Figure 4.22 shows the predicted voltage variation between the electrodes with time during weld cycles. The voltage drops very quickly at the beginning of the weld cycles due to sharp reduction of contact resistance. However, the voltage begins to rise after the workpiece heat up because of the material resistivity increase with the rising temperature. The voltage reaches a maxima and then drops due to weld nugget formation, which causes an increase of contact area between workpieces in the electrical current flow passage.

Figure 4.23 shows the variations of the expansion rate in different schedules and the effect of poor fitup and current shunting on the predicted
expansion rate. In which, second peaks (point 2) at various welding current levels may form an expansion rate-based weldability window to give a very beginning judgement of real-time thermal expansion rate-based monitor and control system in resistance spot welding process. Poor joint fitup cause higher current density due to reduction of actual contact area at the workpiece faying surface. This phenomenon is equivalent to using higher electric current for welding and results in more expansion displacement in thickness direction or even causes nugget expulsion. On the contrary, current shunting reduces the effective current density passing through the actual contact area. An undersized weld nugget was predicted. The effect of either poor fitup or current shunting may affect weld quality.

Figure 4.24a shows the maximum electrode displacement variations with weld time at a given electrode force and weld current level. Figure 4.24b illustrates the maximum electrode displacement changes with various weld current levels for a given electrode force and weld time. As shown in both figures, the maximum electrode displacements vary almost in a linear relationship with weld time or weld current.
A. Electrode Displacement

Expansion Rate (mm./second)

B. Expansion Rate

Figure 4.21 Electrode Displacement and Expansion Rate of Weldment with Time after Weld Cycle Starts:
Electrode Force, 800 lbs (365 kgs), Weld Current, 12.2 ka, Weld Time, 14 cycles
Figure 4.22 Voltage Variation between Electrodes, after Weld Cycle Starts, with Time: Electrode Force, 800 lbs (365 kgs), Weld Current, 12.2 ka, Weld Time, 14 cycles
Expansion Rate, mm/second

Maximum Expansion Rate (first peak)

Mediate Expansion Rate (second peak)

Minimum Expansion Rate

Weld Time, cycles

A. Constant Weld Current, 12.2 ka

Figure 4.23 Predicted Variation of Expansion Rate of the Weldment with Weld Time and Weld Current: Electrode Force, 800 lbs (365 kgs)
Figure 4.23 (continued)

Expansion Rate, mm/second

---

B. Constant Weld Time, 16 cycles
A. Constant Weld Current, 12.2 ka

B. Constant Weld Time, 16 cycles

Fig. 4.24 Relationship between Maximum Displacement and Weld Time or Weld Current: Electrode Force, 800 lbs (365 kgs)
CHAPTER V

DATA ACQUISITION SYSTEM AND EXPERIMENTAL TEST

V.1. DATA ACQUISITION SYSTEM

V.1.1 Introduction

The data acquisition system used in this study of resistance spot welding is currently employed with a 100 KVA, 60 HZ., 440 Volt, single-phase resistance spot welder, Taylor Winfield 100 KVA welder. The welder was equipped with three analog sensors to monitor the voltage drop between electrodes, the current flowing through the weldment, and the electrode displacement. The outputs of the sensors were preconditioned and then input to a multichannel analog-to-digital converter (A/D), i.e., the signals are obtained from the sensors, sampled by the A/D converter, then stored in a personal computer, IBM PC or any IBM compatible PC under the control of a software program. The digitized data can be processed according to any desired algorithm to study various characteristics related to the weld process. For instance, the dynamic resistance, the dynamic energy, the dynamic electrode displacement or the expansion rate, all of which are used to characterize weld quality during welding, can be obtained from the measured data and used for a real-time monitoring and control of the
V.1.2 System Description

The resistance spot welding data acquisition system used in this study can be divided into three subsystems, the analog signal conditioning and amplifying circuits to process the analog signals obtained from the various sensors, the A/D converter circuits to encode the sampled values, and an IBM personal computer to provide most of the facilities for data acquisition, data analysis and eventual real-time feedback control. The A/D converter used in the study was originally designed by P. C. Tang and assembled by T. S. Chang [47]. The analog interface circuit was designed and described by K. C. Lee [48] and D. G. Waters [46] respectively. The block diagram of the entire system is illustrated in Figure 5.1

The system was designed to implement the following:

a) data collection,

b) data processing,

c) data storage and retrieval, and

d) data printing and plotting.

Data collection can be set to sample 4000 samples for a single source or 1500 samples per second per channel for three different sources. Depending upon the system frequency of the IBM PC, users can select the sampling rate desired. In this study, the sampling rate was set at 1200 samples per second per channel.

Data processing can be implemented via averaging, filtering, and various other calculations after data collection. For example, the dynamic
resistance, the true rms value of the current and the cumulative energy over the weld time, can be calculated using the following formula:

\[ R = \frac{V_m}{I_p} \]  
\[ I_{\text{rms}}^2 = \frac{1}{T} \sum_{u} \int_{h_c}^{i(t)} dt \]  
\[ E_{hc} = R \int_{h_c}^{i(t)} dt \]  
\[ E_{ac} = \sum E_{hc} \] 

where

- \( I_p \) = the measured peak current
- \( V_m \) = the measured voltage at the time when \( I_p \) is measured
- \( R \) = the calculated dynamic resistance
- \( h_c \) = half cycle, \( wt \) = weld time
- \( i(t) \) = the instantaneous current
- \( I_{\text{rms}} \) = the rms current
- \( E_{hc} \) = the energy input during half cycle
- \( E_{ac} \) = the accumulated energy input

The collected data can be read back into the IBM PC memory and stored either on hard disk or on floppy diskettes with some identification information for future use. In the meantime, the stored data can be displayed, printed or analyzed. At present, only the current, voltage and electrode displacement value can be printed or displayed. Examples of the display results are shown in Figure 5.2, containing the dynamic current values, the dynamic voltage values and the electrode displacement history.
Fig. 5.1 Data Acquisition System Block Diagram
Figure 5.2 Example of the Display of Current, Voltage and Displacement
V.1.3 Hardware Description

V.1.3.1 Installation

The A/D converter system was designed for use with IBM personal computers. There are three 12-bit A/D chips, ADC1210HCD, manufactured by National Semiconductor, on the board. The A/D chip works with 200 KΩ Input impedance, 0.1% linearity, ±1/2 bit accuracy. Its conversion time is less than 100 μs. The working range of voltage is ±5 volts. The sampling is triggered by an interrupt signal generated by the PC's internal programmable clock.

Figure 5.3 shows the entire sensor installation. The voltage sensors are clamped by braids onto the electrodes with a good contact area. The welding current is sensed by a toroid coil which is installed on the lower electrode. The manufacturer of the coil specifies the output as 0.2 volts per 1000 amps at 60 Hz. into a 1000 Ohm load. The displacement sensor is a linear variable differential transformer (LVDT). The LVDT is clamped in a wooden fixture and placed in the throat of the resistance welder, in a position close to the electrodes for actual sensing of the displacement.

V.1.3.2 Calibrations

The system calibration must be checked before the data acquisition, measuring the electrode current, voltage and displacement, can be carried accurately and reliably. The data collected regarding current, voltage or displacement are calibrated by using the relation between the converted digital values and the analog signal (Fig. 5.4). The input voltage range is ±5
Figure 5.3 Sensors Installation on Resistance Spot Welder [48]
Figure 5.4 A/D Converter Characteristic Curve, 0.1 % Linearity
volts, and the corresponding digital values are 0 to 4095 in digital value. The analog zero signal corresponds to the digital value 2048.

A Tektronix-221 100 MHz digital storage oscilloscope is used to calibrate the voltage. The analog signal is sampled by both the A/D converter and the oscilloscope simultaneously and then the digital values on the oscilloscope are correlated to the collected data on the A/D converter. The current is calibrated by using a Current-Time Analyzer made by Duffers Associate, INC. in the same manner as the voltage calibration.

A set of Gauge Blocks made by Doell, is used to test the sensitivity and linearity of LVDT. Using linear regression on the test data, the overall sensitivity was found to be equal to 0.4924 V/mil. The LVDT output calibration curve plotted by using the test data is shown in Figure 5.5.

The base-frequency for various personal computers will be different, depending upon the CPU used on the computer, however, the real time clock is the same for all computer systems. For example, while 4.77 MHz is the base-frequency set for an IBM PC XT or 20 MHz for IBM PC 386, their real time clocks $F_{rs}$ are set to the same value, 1.1925 MHz. The original sampling frequency $F_{os}$ is based on the real time clock, i.e. $F_{os}=1/(65536/1192500)=18.196$ (1/sec) in which the 65536 is a programmable constant $C_p$, therefore, the sampling frequency $F_{s}$ for any system can be changed by assigned different programmable constant. For example, when an IBM PC XT is used for data acquisition and the sampling frequency is specified as $F_{s}=1200$ (1/sec), the programmable constant $C_p$ will be changed
Figure 5.5 Calibration of LVDT with Gauge Blocks
from 65536 to 994 calculated by using the following formula:

\[ C_s = 65536 \times \frac{F_o}{F_s} \]

V.1.4 Software Description

In the data acquisition system, the personal computer plays the most important role in data recording, computation, and analysis. Several programs (Appendix B) have been written for the control of the sampling rate of the A/D converter and the calculation of the expansion rate. The current, voltage, electrode displacement, and expansion rate can be displayed on the screen of the monitor as shown in Figure 5.6. From these results, the weld quality is related to the maximum electrode displacement and the expansion rate. The architecture of the entire data acquisition system is shown in Figure 5.7.

V.2 EXPERIMENTAL TEST

V.2.1 Introduction

Before a resistance spot welder can be used to weld the workpieces, the characteristics of the welder heat output must be checked in other to obtain an accurate amount of current flowing through the weldment during the weld time. For example, the preset primary voltage will affect the heat output in the same proportion as heat input. The percentage of heat, correlated to the RMS current, is shown in Appendix A. The output power can be controlled by varying the magnitude of the waveform using the parallel/series and transformer tap switches and/or varying the fraction of the waveform used using the phase control. The percentage of heat is used to control the fire angle, i.e. the phase control. The transformer
tap setting control the magnitude of the waveform. Some examples of different tap and phase control setting are shown in Figure 5.8.

The characteristics of the RMS current of the spot welder used in this testing was checked by using the current analyzer and plotted in Figure 5.9 for different tap settings.

V.2.2 Equipment Setup
1. Resistance Spot Welding Machine

A 100 KVA single-phase Taylor Winfield spot welding machine operated at 440 V, 60 cycle power, and 38 ka maximum short-circuit secondary current was used along with various sensors and the data acquisition system.

2. Current Measurement

Toroidal coils are indirectly used to measure the secondary current flowing through the weldment by measuring the voltages induced by the changing magnetic fields surrounding the weld current carrying conductors (Model CIR 1000 DC). The measured analog signals are converted to digital values through an A/D converter.

3. Voltage Measurement

A Wiggy voltage tester can be used to measure the voltage drop across workpieces. In this study, the voltage drop between the electrodes is measured by mounting a lead wire at each electrode. The obtained signals are sent to the data acquisition system.

4. Force Measurement

A Toffaly 2000 lb (909 kg) force gauge is used to measure the electrode
force to which the workpieces are subjected prior to the testing.

5. Displacement Measurement

A linear variable differential transformer (LVDT) is used, producing a voltage proportional to the electrode displacement.

6. Dynamic Expansion Rate

Accurate calculation of the dynamic expansion rate is obtained through the derivative operation of the dynamic electrode displacement curve in the difference form.

V.3 DATA ANALYSIS

In order to get more information to improve the computational results, a series of tests is carried out on an air-operated spot welding machine with a rated capacity of 100 KVA. The heat input is controlled by adjusting the tap stepper or phase shift. The electrode, the squeeze time, and the hold time are set as recommended by the Resistance Welding Manufacturing Association (RWMA)[4]. During the welding process, the variation of electrode displacement, secondary current and voltage are monitored using the welder checker as shown in the measuring device setup (Fig. 5.10). These devices display simultaneously the values of the above three variables versus time. The details of the comparison will be shown in the experimental test data. The experimental data analysis will be implemented according to the test results.
Figure 5.6 Current, Displacement and Expansion Rate Display
FIG. 5.7 DATA ACQUISITION CONTROL FLOW CHART
Figure 5.8 Schematic Illustration of Current Waveforms Control by Phase and Tap Settings [50]
Figure 5.9 Characteristics of Tap Settings
Figure 5.10 System for Experimental Test
V.3.1 Characterization of the Expansion Curve

During spot welding, first the faying surfaces will be heated and then the heat is conducted to the bulk material. The relationship between the electrode displacement and the nugget growth can be categorized into four ranges;

Range I - no weld formation and the faying surface softening;

Range II - the heat-up of bulk material;

Range III - the beginning of nugget growth and the competition between the penetration and diametric growth of the nugget; and

Range IV - the critical, saturated expansion and weld expulsion.

V.3.1.1 Maximum Displacement

From the experimental tests it is found that the maximum electrode displacements has a linear relationship with weld current (Fig. 5-11) because heat conducted into the electrodes and the electrode embedding increased as more weld pulse progressed at later stage in the heating cycle. Consequently, the relationship between the maximum electrode displacements and the weld time is also linear.
A. Relationship between Maximum Displacement and Weld Time; Weld Current, 12.2 ka

B. Relationship between Maximum Displacement and Weld Current; Weld Time, 16 cycles

Figure 5.11 Maximum Displacement with Weld Time and Weld Current, Electrode Force, 800 lbs (365 kgs)
V.3.1.2 Expansion Rate

The expansion rate is calculated through the use of user files written by using Turbo Pascal programming language. From the testing results, the expansion rate curve (Fig. 5.12) could be divided into four regions.

1) The first region, range I:
Due to the very high contact resistance, the faying surfaces are heated so fast that the expansion rate will also increase rapidly. In a very short time, the expansion rate drops sharply because of the softening of the faying surfaces and more asperities coming into contact as illustrated in Figure 5.12, experimental result, and Figure 13, the result of the finite element analysis. However, due to the mass inertia of the pneumatic mechanism, the contact friction between the cylinder and piston rod of the pneumatic actuator, and the compressible air in the pneumatic system, the sharp increase of expansion is filtered out as illustrated in Figure 5.14.

2) The second region, range II:
The bulk material is heated up by the heated faying surfaces and the Joule heat of the bulk material. Because little generated heat is conducted away, the expansion rate increases. The finite element model uses a constant contact area between the interfaces, different from that of the real case, so the expansion rate still decreases. In reality, only a fraction of the apparent contact area is actually in contact, therefore the expansion rates for the simulation and the experiment are different in this region.
Figure 5.12 Measured Expansion Rate, after Weld Cycle Starts; Weld Time, 12 cycles, Weld Current, 12.2 ka, Electrode Force, 800 lbs (365 kgs)

Figure 5.13 Predicted Expansion Rate after Weld Cycle Starts; Weld Current, 12.2 ka, Weld Time, 14 cycles, Electrode Force, 800 lbs (365 kgs)
Figure 5.14 Electrode Expansion Rate and Displacement of the Experiment: Weld Time, 12 cycles, Weld Current, 12.2 ka, Electrode Force, 800 lbs (365 kgs)
Figure 5.15 Expansion Rate and Displacement of the Experiment: Weld Current 14 ka, Weld Time, 16 cycles, Electrode Force, 800 lbs (365 kgs)
3) The third region, range III:

The temperature of bulk material increases continuously and begins to melt. In early melting stage nugget grows more rapidly in thickness than in the radial direction. eventually the penetration rate will slow and causing the expansion rate to increase and then decrease.

4) The forth region, range IV:

The growth of penetration becomes steady and the growth of the nugget diameter slows, therefore the expansion rate slows continuously and finally approaches null. However, if more heat is input, over-indentation or expulsion will occur, and the expansion rate will drop sharply (Fig. 5.15).

V.3.2 Experimental Results

From the experimental testing, some important results will be discussed as the following.

1. The characteristic curves of the RMS current for both the bared steel and the galvanized steel are almost the same according to the results of the RMS current calibration. This indicates that the net secondary current flow seems to be not affected by the galvanized material.

2. The alignment of the electrodes is crucial to avoid the premature expulsion or over-indentation of the weldment. For instance, in the normal case of a good fitup welding, 12.2 ka current and 800 lbs (365 kgs) electrode force, if the weld time is set 10 cycles, it is found that the weld quality is good. However, if the alignment of electrodes is bad or a poor fitup occurs, expulsion or over-indentation will occur before 10 weld cycles due to the increase of the current density. The electrodes, therefore, must be well
aligned during welding.

3. The calibration of the LVDT plays a very important role in measuring the electrode displacement because the working range of LVDT is limited to ±5 volts. That is, the testing voltage must be adjusted to near zero volt as shown in the calibration of the LVDT linearity (Fig. 5.5). Shown on the voltmeter this value is 5 volts because the voltage range on voltmeter is from 0 to 10 volts, not ±5 volts. For example, if the output voltage of the LVDT before the spot welding begins is a little far below or above the reference working voltage (5 volts shown on the voltmeter), then the collecting data will be invalid or inverse to the valid data (Fig. 5.16). Therefore, the working range of the LVDT must be under control, depending upon the configuration and sensitivity of the joint. For example, when welding the thinner sheets or the materials with smaller expansion, the working range should be low so that the sensitivity of the LVDT can be raised through the adjustment of the data acquisition system.

4. The expansion rate result can be also calculated and/or shown simultaneously on an IBM PC (DOS operation system), or on an IBM 286 or IBM 386 personal computer (PS 2 operation system), that is, they can be implemented on-line or off-line depending upon the CPU speed.

5. The electrode displacement becomes slows when the weld growth nears expulsion due to the temporary heat balance between the heat transfer and the Joule heat and the softer weldment. For instance, the slopes at the maximum displacements, within several weld cycles and with weld current increase, approach zero and their maximum displacements
are almost identical, although the indentation is different. If the weld time or weld current is increased continuously, then weld expulsion will eventually occur. This phenomenon can be illustrated in Figure 5.16 (HB 5812, HB 58141, HB58161 and HB58182), where the weld time increased at constant electrode force of 800 lbs (365 kgs) and current (12.2 ka), or from Figure 5.17 (HB381, HB461, HB582, HB692, HB722) where the weld current increased, but the weld cycles and electrode force remain constant, i.e., 16 cycles and 800 lbs (365 kgs) respectively.

6. The weld expansion will not immediately drop when the current shuts off due to the hysteresis of current (exponentially decayed).

7. At the beginning of the weld time, the expansion rate increases in a very short time and drops a little because of the very high contact resistance and the following softening of the contact area. At later the expansion rate increases again because the generated heat of the interfaces conducted into the bulk material and associated with the increase of the resistivity of the joint material. Finally, the expansion rate decreases gradually due to the gentle increase of the temperature in the joint and the contact area increase at the workpiece/workpiece faying surface and the electrode/workpiece interface. If more heat is input, the expansion rate will approach zero because the displacement reaches a maximum level.
Figure 5.16 Electrode Displacement at Various Weld Times with Current, 12.2 ka, Electrode Force, 800 lbs (365 kgs)
Figure 5.17 Electrode Displacement at Various Current Levels with Weld Time, 16 cycles, Electrode Force, 800 lbs (365 kgs)
VI.1. INTRODUCTION

Three types of joint conditions, good fitup, poor fitup and current shunting, were simulated in this study (Fig. 4.8). Joints with good fitup have contact at the workpiece-workpiece faying surfaces the same as the electrode contact area for the workpieces. Poor fitup causes a reduction of the contact area at the workpiece faying surfaces. In this study, poor fitup was quantitatively defined as a percentage of contact area reduction from the good fitup condition. Current shunting indicates the existence of an additional current flow passage adjacent to the weld nugget during the weld cycles. This phenomenon was modeled in this study by an axisymmetric annular contact area surrounding the weld nugget. For a quantitative definition of current shunting, a percentage of contact area increase from the good fitup condition and the mean radius of this annular area from the electrode center line were used in this study. The resistance welding schedules of both the simulation and experiment in this study are summarized in Table 3. A 800 lbs (365 kgs) electrode force was employed in all welding schedules. A truncated copper alloy electrode (RWMA CLASS
II) was selected for spot welding the mild steel sheets with 0.06 in. (1.52 mm) thickness and 1 in. (25.4 mm) length during modeling and simulation. 1/16 in. (Ga 16) thick, 1.5 in. wide, 4 in. long cold rolling mild steel (SAE 1008 steel) coupons were used in the experimental testing.

VI.2 DISCUSSIONS

VI.2.1 Maximum Displacement

The electrode displacement of the experiment and the simulation for various welding schedules and constant setting force (800 lbs) are shown in Figure 5.11 and Figure 4.24 respectively. When comparing the results of the simulation and the experiment, shown in Figure 6.1, the maximum electrode displacements of the simulation, in different schedules, are very close to those of the experimental testing.

For constant electrode force, 800 lbs (365 kgs) and welding current, 12.2 ka, the maximum displacement of the experiment is approximately 7% higher than that of the simulation. The reason is illustrated in Figure 4.16. In this comparison diagram, it can be seen that the nugget growth in the radial and axial directions in the simulation is less than that in the experimental testing. This difference is due to the fact that both the penetration and diametric growth of the nugget in the experimental testing are always a slight higher than that in the simulation before 16 weld cycles. Although the penetration in the experiment becomes constant when the weld time is longer than 14 cycles, the diametric growth of the nugget in the experiment remain higher than the simulation.

For constant force (800 lbs) and weld time (16 cycles), the maximum
displacements of the simulation are very close to the experiment, and the findings are as follows:

(i) the less the current used, the maximum displacement of the experiment is very close to the simulation (Fig. 6.1);

(ii) when the current level is above 10.6 ka, the maximum displacement of the experiment becomes slightly higher than the simulation;

(iii) the maximum displacement of the experiment approaches constant when the current level is higher than 12.2 ka, but the results of the simulation still increase and remain higher than the experimental results. These phenomena can be shown in Figure 4.18. When the current level is between 10.6 ka and 12.6 ka, their penetrations are almost the same, but the nugget growth of the experimental in the radial direction is still slight higher than that in the simulation giving the result in (ii). When the current level is above 12.8 ka, the nugget growth in the axial direction in the simulation is higher than in the experiment consequently yielding the result in (iii).
A. Maximum Displacement and Weld Time:
Weld Current, 12.2 ka,

B. Maximum Displacement and Weld Current:
Weld Time, 16 cycles

Figure 6.1 Relationship Between Maximum Displacement and Weld Time or Weld Current: Electrode Force, 800 lbs (365 kgs)
VI.2.2 Expansion Rate

The expansion rate of the experiment and the simulation are shown in Figure 6.2, Figure 6.3 and Figure 4.23. Figure 6.2 shows that the expansion rate reach zero closing when weld time increases gradually and finally occurs (HB 58201) due to more heat input. Figure 6.3 shows that peak 2 and peak 3 increase when current increases, and finally expulsion occurs due to more heat input. When comparing the expansion rate of the simulation and the experiment, shown in Figure 6.4, the first extreme expansion rate of the simulation is very high, but the expansion rate at this time in the experimental testing is filtered out due to the effect of the pneumatic system of the resistance spot welder. The second extreme expansion rate of the simulation, at a different welding current level, is very close to the experiment testing (Fig. 6.5).

The third extreme expansion rates are much different. Because the air in the pneumatic system of the spot welder is compressible if the force balance of the cylinder changes the actual force bearing upon on the weldment is variable. T. C. Pienkowski [49] made an experimental testing to measure the variation of the force, to which the weldment was subjected. From his findings we know that the maximum force change is approximately 10% of the preset force, depending upon the amount of heat input and the physical configuration of the welding machine.

Also of interest is the variation in force during the weld time. When comparing the variations of the force and the expansion rate, it is found that these rates change in a quite similar manner. The higher the
expansion rate of the weldment is, the larger the force change is and vice versa (Fig. 6.6); therefore, it is predictable that the expansion rate will slow down. The expansion rate may, however, jump to a very high level when the expansion of the weldment reaches a certain value due to the greater heat input to the weldment which causes a more rapid penetration of the weld. This phenomenon can be seen in the expansion rate, at the third extreme value, or in the electrode displacement trace near the inflection point of the displacement curve. This may be the reason for the difference between the third occurrence of extreme expansion rate values in the simulation and the experiment.
Figure 6.2 Measured Expansion Rate at Various Weld Time: Weld Current 12.2 ka, Electrode Force, 800 lbs (365 kgs)
Figure 6.3 Measured Expansion Rate at Various Current Levels: Weld Time, 16 cycles, Electrode Force, 800 lbs (365 kgs)
Figure 6.4 Expansion Rate in Various Welding Schedules with Electrode Force, 800 lbs (365 kgs)
Figure 6.5 Expansion Rate of the Simulation and the Experiment with Weld Time, 16 cycles, and Electrode Force, 800 lbs (365 kgs)
Figure 6.6 Variation of the Applied Force on the Weldment [49]
VII.1 INTRODUCTION

Single-parameter, in-process monitor and automatic control systems for the resistance spot welding process have been studied by many investigators. Some of these have already been commercialized and used by sheet metal fabricators. These control systems operate primarily on one of the three process parameters: maximum voltage or voltage drop, dynamic resistance, or thermal expansion between electrodes during nugget formation.

Control systems based on voltage or dynamic resistance have been successfully implemented for industrial applications. A great amount of experience on these two control methods has been accumulated through trial-and-error approaches. The expansion-based control system is not commonly utilized due to a lack of experience and understanding of the process.

Since the expansion displacement between electrodes during welding responds directly to the weld nugget formation, this control parameter provides a better means to produce more precise spot welds. However, the control algorithm of this method is more complex than the other two
methods. Fruitful development of such systems can not be obtained by trial- and error approaches.

This proposal gives a systematic approach to develop the expansion-based control algorithm for resistance spot welding. The finite element method was used to simulate the welding process and to determine the physical responses of the joint materials to the various welding conditions. Direct correlations between nugget formation and expansion displacement between electrodes was obtained.

By systematic computer simulations, a weldability characteristic curve for resistance spot welding was developed. This weldability curve shows inadequate welding conditions which would cause nugget expulsion or current shunting. A welding duration curve, which shows appropriate time for squeeze, weld, and hold cycles, was developed and used as a basis for an in-process resistance spot welding control.

The weldability curve in this study was developed according to the electrode displacements (separation). From this characteristic curve, the formation and limitation of weld nugget are discussed. For maintaining a long production runs and consistent conditions, the poor fitup and the electrical current shunting were also considered in this study. Consequently, a welding duration curve, as a basis of in-process monitoring and control, was established.

VII.2 DEVELOPMENT APPROACH

Figure 7.1 shows the architecture of a dual-variable real-time monitoring and control system. The welding system is initially set for
welding according to an appropriate Lobe diagram. Welding current and weld time are used as the dual control parameters to obtain adequate nugget expansion characteristics. A displacement transducer attached to the electrode head monitors the electrode displacement and head velocity during welding. The displacement data is compared with the expansion-based weldability curves from which a feedback control decision can be made to incrementally adjust the two welding variables for satisfactory weld result. The weldability curves can be developed from the finite element analysis and the Lobe diagram.

VII.3 WELDABILITY CURVES

The weldability Lobe diagram has been used by the resistance welder to preset the welding schedule for satisfactory welding results. The Lobe diagram is generated by experimental tests and defines a window of welding parameters, weld current and times, which produces quality welds. However, these window welding parameters cannot be directly used to a real-time control system.

From finite element modeling and analysis, the relationships between weld current, weld time, nugget formation and electrode displacement will be correlated. The finite element analysis can generate a series of current versus time curves similar to the experimental Lobes. By comparing the predicted current-time relations with the acceptable ranges of weld current and time, which are defined by the experimental Lobe diagrams, a new weldability window, based on the electrode displacement characteristics, can be generated.
VII.4 EXPANSION-BASED CONTROL LOGIC

The characteristic displacement parameters, such as expansion displacement history, maximum displacement, expansion rate changes and maximum expansion rate during welding process, may be used for real-time control of resistance welding process. For example, the dynamic electrode displacement curves (Fig.4.21) have been used for this control purpose [11]. For simple control purpose, the history dependent control method could be replaced by a dual-point control logic, which uses the maximum and minimum expansion rate simultaneously. The control logic can be more simple if the maximum displacement alone is sufficient for screening the welds.

VII.5 CONTROL ALGORITHM

VII.5.1 Introduction

The finite difference schemes have already been used to model and analyze the thermal behavior, nugget formation and their relationship. They considered material properties as temperature dependent, however, latent heat was not involved in some studies of them. Also, a one-dimension model was used by some authors and a two-dimension model analysis was considered by some other investigators as states in the literature review. Nevertheless, thermal-mechanical coupling scheme was not discussed in these aforementioned studies, which can be directly related the thermal behavior to nugget formation for a real-time monitor and control systems.

Although the finite element method which can solve the thermal-mechanical coupling problems, their studies are also limited to the
discussion of thermal behavior. In the meantime, they considered the structure deformation to be only limited at the specified temperature, but the history of weldment deformation was not discussed or studied. Also, they considered the voltage drop as a constant value which were not consistent with the way of the real welding input schedules.

All of these limitations will be solved in this study by using a special scheme. Consequently, the unexpected welding conditions will be found and solved. For example, current shunting, poor fitup can be easily monitored and controlled in a real-time control systems. These schemes will be discussed in the paragraphs which follow.

Generally speaking, the maximum electrode displacement and the weldment expansion rate or its history are powerful schemes for testing the weld quality, especially for the aforementioned unexpected welding conditions. There are several criteria to adjust the occurrence of expulsion or over indentation which will causes unacceptable weld quality.

First, the over indentation will occur during the welding process if the nugget penetration is over 80%, or the smaller and brittle nugget occurs if the penetration were less than 20%. All of these welding conditions will cause unacceptable weld quality. Second, if the fusion pressure exceeds the arrest pressure around the nugget, expulsion will occur. Third, if the nugget growth becomes unstable or the heat transfer is not balanced when the growing nugget approaches the desired size, then the over indentation occurs, or the fusion weld will splash out of faying surfaces. However, using ANSYS computer code to solve these problems can only be applied to
the first criterion.

**VII.5.2 Maximum Displacement-Based Control**

The maximum electrode displacement which can be directly related to the nugget growth, is found in this study to be linearly proportional to the welding current and the weld time respectively (Fig 4.25). Therefore, it is much easier to monitor and control the weld quality using aforementioned characteristics of the relation between the maximum displacement and time or current. It is obvious that the weld quality is acceptable if the maximum displacement is between the upper tolerance (splash weld) and the lower tolerance (small nugget). For example, if the optimum welding condition, 800 lbs (365 kgs) electrode force, 14 cycles weld time, 12.2 ka weld current, is scheduled for spot welding mild steel with 0.06 in. (1.52 mm) thickness, then the maximum electrode displacement will be 0.182 mm in 14 cycles with good weld quality. Nevertheless, if the current is out of the set value due to the variation of current during welding, the weld quality is still acceptable as long as the maximum electrode displacement is within the upper tolerance and the lower tolerance (Fig 4.20). If the maximum electrode displacement is falling below lower tolerance in scheduled weld cycles, then weld duration is increased until the acceptable weld can be obtained. If the maximum displacement exceeds the upper tolerance in the scheduled weld cycles, the weld current should be shut off as long as it reach the upper tolerance. In the meanwhile, the next schedule must be changed, decreasing current level or reducing welding cycles.
VII.3 Expansion Rate-Based Control

If the maximum displacement is not suitable to the weld quality control, the expansion rate will be used to monitor and control the weld quality accurately and reliably. In this control algorithm, partial fraction of the overall expansion rate history will be used depending on the material properties used, the welding conditions scheduled, or the joint setup.

Under normal welding conditions with sufficient current density, the electrode displacement achieves the preset or predicted maximum displacement. The weld quality is under control and acceptable. However, if the current flowing through the fusion zone is reduced due to current shunting, edge effect or electrode wear, the expansion will not reach the predicted value so that the weld quality will be unacceptable. Also, if the current density increases in the contact area due to an extremely poor fitup, the expansion rate will increase sharply in the early period of welding time so that the quality weld can not obtained.

Under abnormal welding conditions, for instance, when an extremely poor fitup causes the fusion weld to splash due to the reduction of contact area, the electrode displacement will reach the preset maximum displacement before the scheduling weld cycles. In such a case, the expansion rate, in the early period of the weld time, will be higher than the preset expansion rate. Therefore, the current must be shut off before the expulsion occurs according to the monitoring of expansion rate. In the meantime, the schedules which follow should be changed. For instance, resetting the joint setup or increasing the electrode force is necessary to
make a good contact area so that a normal current density distribution can be obtained, and consequently, the weld quality is acceptable.

VII.6. JUSTIFICATION OF THE RESEARCH

When engaging in the study of thermal-mechanical responses of the workpieces during resistance spot welding, it is difficult to arrange the temperature distributions and thermal expansion measurements. Furthermore, it is almost impossible to measure the temperature distributions as a directly controlling signal for mass production in the plant during spot welding processing.

The voltage or resistance parameter in-process monitor and control are not very reliable for the in-plant spot welding process, because any unexpected variation of electric circuit, machine conditions, material properties and even the noise of the radiation and inductance coming from the very high weld current [23] will indirectly deteriorate the variation of voltage or resistance of the weldment. The electrode displacement is a direct response from the weldment, therefore its reliability seems to be higher than that of the voltage-based or resistance-based system.

According to above statements, it is very clear that this research is very significant and practical in the study of the thermo-mechanical coupling response of the weldment as a basis of in-process monitor and control systems during resistance spot welding processes.

This research has lead to a direct one-parameter or dual-point real-time control methodology according to the electrode displacement and/or velocity in resistance spot welding.
Figure 7.1 A Dual-Variable Real-Time Monitoring and Control System for Resistance Spot Welding
CHAPTER VIII

CONCLUSIONS AND FUTURE WORK

VIII.1 CONCLUSIONS

Finite element modeling and analysis has provided detailed information regarding the formation of the nugget during resistance spot welding. Furthermore, the weldability window, based on the expansion displacement characteristics, provides a real-time control logic, by which oversized nuggets or undersized welds can be easily monitored (in-process quality monitoring) and controlled (in-process quality control). If the nugget formation is undersized, a duration curve using specified weld current and electrode force can be used to obtain an appropriate nugget size. Also, current shunting or poor electrode fit-up can be monitored through the use of these characteristic curves. From this study, it was found that the maximum electrode separation can still meet the requirements of nugget formation well within a quality weld, even though the nugget diameter is somewhat small. Therefore, the maximum displacement, based on the results of the simulation, can be used in single-parameter, in-process monitor and control systems.
Although the third occurrence of extreme expansion rate values is different due to the variation of the electrode force and the smaller predicted nugget size, the expansion rate in simulation has the same variation trend as that found in the experiment in the early stage of nugget growth and as the nugget growth approaches a quality weld. Essentially, for a lower current level or earlier weld time, the penetration of the nugget in the simulation is smaller and its growth is slower, thus the inflection point of the displacement characteristic curve does not appear resulting in the third occurrence of extreme expansion rate values.

The characteristics of the expansion rate provide a good explanation of the details of the nugget growth. From the point view of real-time monitor and control, the second peak of the expansion rate can be used to predict nugget growth in the very beginning. The characteristics of the expansion rate zero closing, based on the material properties, can be used in stead of the simulation to predict the final nugget quality, although the third peak of the expansion rate does not exist in the simulation. Therefore, the expansion rate, based on the results of the simulation and the expansion rate zero closing, can be used in single-parameter dual-point in-process monitor and control systems.

The characteristic curve of the expansion rate of the simulation might fit well with the experimental, if the variation of the electrode force were considered and the true contact area were remodified. A dynamic model can be considered as a modification of this simulation.
VIII.2 FUTURE WORK

(1) More work on this kind of modeling and simulation, according to the Lobe curves of different materials, is necessary to develop a wide variety of expansion-based weldability curves as a data base for real-time control systems in the future.

(2) In order to make the weld quality more reliable, the effect of expansion/contraction on the microstructure according to the thermal expansion, expansion rate and temperature gradient of the weldment, must be considered in future work. Furthermore, we can improve the weldability of the weldment and obtain a wider current range from the control of the electrode force and displacement through the use of finite element modeling and simulation, and correlate these to the variation of the contact resistance ratio $R_f/R_e$.

(3) In order to make the expansion rate more valid, it appears necessary to modify the contact problem and to consider the effect of force variation in future work. A dynamic model which considers the weldment, contact area and electrode as a stiffness and the pneumatic system as the combination of the stiffness and the damping, could possibly be used for post modification of the joint deformation during the weld time in resistance spot welding process.

(4) Due to the complexity of the expulsion, to solve the problem of the expulsion of the weldment, a user file must be associated with the "ANSYS" finite element code.

(5) Because the electrode setup crucially affects the nugget growth,
development of criteria for electrode setup through the study of poor fitup modeling and simulation is necessary.
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APPENDIX A
THE FINITE ELEMENT COMPUTER PROGRAMS

A.1 SQUEEZE CYCLES

/PRP7
/SHOW,FILE33
RESUME
/TITLE R.S.W. DYNAMIC DISPLACEMENTS AND STRESSES ANALYSIS
C*** STEP 1 - PRESSURE LOAD ONLY
C*** STEP 2 - PRESSURE AND TEMPERATURE LOADS
C*** STEP 3 - PRESSURE AND COOLING DOWN TEMPERATURE LOADS
KAN,0
ET,1,42,,1
,2,42,,1  * FOR SURFACE STRESSES REQUESTED
,3,42,,1
,5,12,,1,1,,1
NUXY,1,3 $,2,,3 $,3,,3 $,4,,33 $DENS
MPTEMP,1,0,200,400,600,800,1000
MPDATA,EX,1,1,30.0E6,28.5E6,28.5E6,27.0E6,24.5E6,17.0E6
MPTEMP,7,1200,1400,1600,1800,2000,2200
MPDATA,EX,1,7,8.0E6,4.0E6,4.0E6,4.0E6,4.0E6,4.0E6,4.0E6
MPTEMP,13,3600

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MPDATA,EX,1,13,2.0E6
MPTRES,EX,1
MPDATA,EX,2,1,30.0E6,28.5E6,28.5E6,27.0E6,24.5E6,17.0E6
,EX,2,7,8.0E6,4.0E6,4.0E6,4.0E6,4.0E6,4.0E6
,EX,2,13,2.0E6
MPTRES,EX,1
MPDATA,EX,3,1,30.0E6,28.5E6,28.5E6,27.0E6,24.5E6,17.0E6
,EX,3,7,8.0E6,4.0E6,4.0E6,4.0E6,4.0E6,4.0E6
,EX,3,13,2.0E6
MPTRES,EX,1
MPDATA,EX,4,1,18.0E6,15.3E6,13.5E6,12.0E6,8.0E6,5.6E6
,EX,4,7,3.6E6,2.3E6,2.0E6,1.0E6,1.0E6,1.0E6
,EX,4,13,1.0E6
MPTRES,EX,1
MPDATA,ALPX,1,1,6.1E-6,6.4E-6,6.8E-6,7.2E-6,7.5E-6,7.8E-6
,ALPX,1,7,8.1E-6,7.8E-6,7.5E-6,7.5E-6,7.5E-6,7.5E-6
,ALPX,1,13,7.5E-6
MPTRES,ALPX,1 $MPDRES,ALPX,1,ALPX,2
MPTRES,ALPX,2 $MPDRES,ALPX,2,ALPX,3
MPTRES,ALPX,3
MPDATA,ALPX,4,1,9.2E-6,9.3E-6,9.5E-6,9.7E-6,9.9E-6,9.9E-6,10.2E-6
,ALPX,4,7,10.3E-6,10.5E-6,10.7E-6,10.7E-6,10.7E-6,10.7E-6
,ALPX,4,13,10.7E-6
TREF,70
N,1
,13,15,0
FILL
N,21,.5
FILL
NGEN,2,21,1,21,",",001
,6,21,22,42,,.012
,2,21,127,147,,.001
N,173,.25,.1075
FILL,158,173,4,169,1
N,174,0,.087
N,184,.125,.087
FILL
NGEN,5,16,174,184,,.025
N,253,.25,.177
FILL,173,253,4,189,16
,248,253,4,249,1
,184,189,4,185,1,4,16
NGEN,6,16,238,253,,.051
,7,6,328,333,,.12
N,370 $,382,.15 $FILL
N,390,.5 $FILL $N,391,0,.062 $N,401,.125,.062 $FILL
MAT,3
TYPE,3
E,1,2,23,22
EGEN,20,1,-1
MAT,1
TYPE,1
E,22,23,44,43
EGEN,20,1,-1
,5,21,-20
MAT,2
TYPE,2
E,127,128,149,148
EGEN,20,1,-1
MAT,4
TYPE,1
E,148,149,175,174
EGEN,10,1,-1
E,158,169,185,184
,169,170,186,185
EGEN,4,1,-1
E,174,175,191,190
EGEN,15,1,-1
,9,16,-15
E,328,329,335,334
EGEN,5,1,-1
,6,6,-5
MAT,5
TYPE,5
REAL,1 $E,370,1 $,148,391
REAL,2 $E,371,2 $,149,392
REAL,3 $E,372,3 $,150,393
REAL,4 $E,373,4 $,151,394
REAL,5 $E,374,5 $,152,395
REAL,6 $E,375,6 $,153,396
REAL,7 $E,376,7 $,154,397
REAL,8 $E,377,8 $,155,398
REAL,9 $E,378,9 $,156,399
REAL,10 $E,379,10 $,157,400
REAL,11 $E,380,11 $,158,401
REAL,12 $E,381,12 $REAL,13 $E,382,13
REAL,14 $E,383,14 $REAL,15 $E,384,15
REAL,16 $E,385,16 $REAL,17 $E,386,17
REAL,18 $E,387,18 $REAL,19 $E,388,19
REAL,20 $E,389,20 $REAL,21 $E,390,21
R,1,5.850E5,-.001 $,2,4.6875E6,-.001
,3,93750E7,-.001 $,4,1.4063E7,-.001
$5$,1.8750E7,.001 $6$,2.3438E7,.001
$7$,2.8125E7,.001 $8$,3.2813E7,.001
$9$,3.7500E7,.001 $10$,4.219E7,.001
$11$,4.688E7,.001 $12$,5.156E7,.001
$13$,5.625E7,.001 $14$,2.543E8,.001
$15$,3.120E8,.001 $16$,3.690E8,.001
$17$,4.266E8,.001 $18$,4.840E8,.001
$19$,5.400E8,.001 $20$,6.000E8,.001
$21$,3.210E8,.001

C*** BEGIN FIRST LOAD STEP (SQUEEZE CYCLE:PRESSURE LOAD ONLY)
ITER,1,1,1
TUNIF,70
TIME,0

C*** DEFINE DISPLACEMENT CONSTRAINTS
D,1,ALL
D,2,UY,,11,1 $22$,UX,,148,21
D,174,UX,,318,16
P,364,365,5432,,368
AFWRITE
FINISH
A.2 WELD CYCLES

/PREP7
/SHOW,FILE33,1
/TITLE  R.S.W. THERMAL-ELECTRICAL ANALYSIS
KAN,-1
ET,1,67,,,1,1
,2,67,,,1,1
,3,67,,,1,1
ET,5,34
HF,5,01
DENS,1,.284 $,2,.284 $,3,.284 $,4,.316
MPTEMP,1,50,200,400,600,800,1000
MPDATA,KXX,1,1,8.663E-4,8.464E-4,7.39E-4,6.682E-4,6.0E-4,5.32E-4
MPTEMP,7,1200,1400,1600,1800,2000,2200
MPDATA,KXX,1,7,4.676E-4,4.08E-4,3.8E-4,3.7E-4,3.82E-4,3.98E-4
MPTEMP,13,3600
MPDATA,KXX,1,13,3.98E-4
MPTRES,KXX,1 $MPDRES,KXX,1,KXX,2
MPTRES,KXX,2 $MPDRES,KXX,2,KXX,3
MPTRES,KXX,3
MPDATA,KXX,4,1,5.22E-3,5.09E-3,4.95E-3,4.75E-3,4.62E-3,4.48E-3
,KXX,4,7,4.28E-3,4.22E-3,4.15E-3,4.08E-3,4.02E-3,4.02E-3
,KXX,4,13,4.02E-3
MPTRES,KXX,4
MPDATA,RSVX,1,1,5.9E-3,7.7458E-3,1.09E-2,1.56E-2,2.0E-2,2.68E-2
,RSVX,1,7,3.39E-2,4.198E-2,4.632E-2,4.8E-2,4.95E-2,5.1E-2
,RSVX,1,13,5.1E-2
MPTEMP,1,50,200,400,600,800,1000
MPDATA,RSVX,2,1,1.2945,1.2675,1.23,1.162,1.0789,.99
MPTEMP,7,1200,1400,1600,1800,2000,2800
MPDATA,RSVX,2,7,.715,.305,.265,.225,.185,.0255
MPTEMP,13,3600
MPDATA,RSVX,2,13,.003
MPTRES,RSVX,2
MPDATA,RSVX,3,1,2.589,2.535,2.46,2.324,2.1578,1.9777
,RSVX,3,7,1.43,.61,.53,.45,.37,.051
,RSVX,3,13,.0059
MPTRES,RSVX,1
MPDATA,RSVX,4,1,1.1034E-3,1.245E-3,1.6564E-3,2.0784E-3,2.49E-3,2.9E-3
,RSVX,4,7,3.3234E-3,3.735E-3,3.94586E-3,4.15686E-3,4.15686E-3,4.15686E-3
,RSVX,4,13,4.15686E-3
MPTEMP,1,50,200,400,600,800,1000
MPDATA,C,1,1,.1053,.1077,.122,.134,.146,.158
MPTEMP,7,1200,1350,1400,1425,1470,1600
MPDATA,C,1,7,.182,.2,.56,.2,.203,.284
MPTEMP,13,2400,2600,2700,2770,2770
MPDATA,C,1,13,.284,.284,.287,1.67,1.67,.287
MPTEMP,19,3600 $MPDATA,C,1,19,.287
MPTRES,C,1 $MPDRES,C,1,C,2
MPTRES,C,2 $MPDRES,C,2,C,3
MPTEMP,1,50,200,400,600,800,1000
MPDATA,C,4,1,.095,.096,.10,.103,.105,.108
MPTEMP,7,1200,1400,1600,1800,2000,2200
MPDATA,C,4,7,.111,.114,.116,.117,.118,.12
MPTEMP,13,2600,2700,3600
MPDATA,C,4,13,.123,.13,.13
N,1
,13,.15,0
FILL
N,21,.5
FILL
NGEN,2,21,1,21,,,,.001
.012
.001
1075
169,1
0.087
125,0.087
FILL
25,0.025
177
4,189,16
248,4,249,1
4,185,1,4,16
051
7,6,333,0.12
382,0.15
FILL
390,0.5 $FILL $N,0.062 $N,125,0.062 $FILL
MAT,3
TYPE,3
E,2,23,22
EGEN,20,1,-1
MAT,1
TYPE,1
E,44,43
EGEN,20,1,-1
,5,21,-20
MAT,2
TYPE,2
E,127,128,149,148
EGEN,20,1,-1
MAT,4
TYPE,1
E,148,149,175,174
EGEN,10,1,-1
E,158,169,185,184
EGEN,4,1,-1
E,174,175,191,190
EGEN,15,1,-1
E,328,329,335,334
EGEN,5,1,-1
MAT,5
TYPE,5
REAL,1 $E,370,1$148,391
REAL,2 $E,371,2$149,392
REAL,3 $E,372,3$150,393
REAL,4 $E,373,4$151,394
REAL,5 $E,374,5$152,395
REAL,6 $E,375,6$153,396
REAL,7 $E,376,7$154,397
REAL,8 $E,377,8$155,398
REAL,9 $E,378,9$156,399
REAL,10 $E,379,10$157,400
REAL,11 $E,380,11$158,401
REAL,12 $E,381,12$13 $E,382,13$
REAL,14 $E,383,14$15 $E,384,15$
REAL,16 $E,385,16$17 $E,386,17$
REAL,18 $E,387,18$19 $E,388,19$
REAL,20 $E,389,20$21 $E,390,21$
C*** DEFINE REAL CONSTANT SETS
R,1,2.0E-5 $,2,1.5625E-4 $,3,3.125E-4 $,4,4.6875E-4
C*** BEGIN FIRST LOAD STEP

ITER, 1, 1, 1
TIME, 0
KTEMP, 0
KRF, 1
KBC, 1
NT, 364, TEMP, 50, 369, 1 $, 1, VOLT, ,, 11, 1
HFLOW, 364, AMPS, 1186 $, 365, AMPS, 271 $, 366, AMPS, 3151
, 367, AMPS, 3626 $, 368, AMPS, 4067 $, 369, AMPS, 2203
HFLOW, 1, HEAT, ,, 11, 1 $, 1, HEAT, ,, 148, 21
, 174, HEAT, ,, 318, 16 $, 12, AMPS, ,, 21, 1
, 1, AMPS, ,, 148, 21 $, 174, AMPS, ,, 318, 16 $, 318, AMPS, ,, 328, 1
, 328, AMPS, ,, 364, 6
CV, 12, 13, 9E-6, 70, 20, 1 $, 21, 42, 9E-6, 70, 147, 21
, 158, 159, 9E-6, 70, 167, 1
, 158, 169, 9E-6, 70 $, 169, 170, 9E-6, 70, 172, 1
, 173, 189, 9E-6, 70, 317, 16
, 333, 339, 9E-6, 70, 363, 6 $, 318, 319, 9E-3, 50, 327, 1
, 328, 334, 9E-3, 50, 358, 6
LWRITE

C*** BEGIN SECOND LOAD STEP

ITER, 128, 128, 1
TIME, 2688
KRF, 1
KBC, 1
LWRITE
**C*** BEGIN THIRD LOAD STEP
ITER,30,30,1
TIME,.6
HFDELE,364,AMPS,369,1
LWRITE
**C*** WRITE ANALYSIS FILE-27
AFWRITE
FINISH
/EXEC
/INPUT,27
FINISH
A3 STRUCTURE DEFORMATION ANALYSIS AND THE HOLD CYCLES

/PREP7
/SHOW,FILE33
RESUME
/TITLE R.S.W. DYNAMIC DISPLACEMENTS AND STRESSES ANALYSIS
C*** STEP 1 - PRESSURE LOAD ONLY
C*** STEP 2 - PRESSURE AND TEMPERATURE LOADS
C*** STEP 3 - PRESSURE AND COOLING DOWN TEMPERATURE LOADS
KAN,0
ET,1,42,,,1
,2,42,,,1 * FOR SURFACE STRESSES REQUESTED
,3,42,,,1
,5,12,,,1,,,1
TREF,70
R,1,5.850E5,,.001 $,2,,4.6875E6,,.001
,3,,.93750E7,,.001 $,4,,1.4063E7,,.001
,5,,1.8750E7,,.001 $,6,,2.3438E7,,.001
,7,,2.8125E7,,.001 $,8,,3.2813E7,,.001
,9,,3.7500E7,,.001 $,10,,4.219E7,,.001
,11,,4.688E7,,.001 $,12,,5.156E7,,.001
,13,,5.625E7,,.001 $,14,,2.543E8,,.001
,15,,3.120E8,,.001 $,16,,3.690E8,,.001
,17,,4.266E8,,.001 $,18,,4.840E8,,.001
,19,,5.400E8,,.001 $,20,,6.000E8,,.001
,21,,3.210E8,,.001
NUXY,1,3 $,2,3 $,3,3 $,4,33 $DENS
MPTEMP,1,0,200,400,600,800,1000
MPDATA,EX,1,1,30.0E6,28.5E6,28.5E6,27.0E6,24.5E6,17.0E6
MPTEMP,7,1200,1400,1600,1800,2000,2200
MPDATA,EX,1,7,8.0E6,4.0E6,4.0E6,4.0E6,4.0E6
MPTEMP,13,3600
MPDATA,EX,1,13,2.0E6
MPTRES,EX,1
MPDATA,EX,2,1,30.0E6,28.5E6,28.5E6,27.0E6,24.5E6,17.0E6
,EX,2,7,8.0E6,4.0E6,4.0E6,4.0E6,4.0E6,4.0E6
,EX,2,13,2.0E6
MPTRES,EX,1
MPDATA,EX,3,1,30.0E6,28.5E6,28.5E6,27.0E6,24.5E6,17.0E6
,EX,3,7,8.0E6,4.0E6,4.0E6,4.0E6,4.0E6,4.0E6
,EX,3,13,2.0E6
MPTRES,EX,1
MPDATA,EX,4,1,18.0E6,15.3E6,13.5E6,12.0E6,8.0E6,5.6E6
,EX,4,7,3.6E6,2.3E6,2.0E6,1.0E6,1.0E6,1.0E6
,EX,4,13,1.0E6
MPTRES,EX,1
MPDATA,ALPX,1,1,6.1E-6,6.4E-6,6.8E-6,7.2E-6,7.5E-6,7.8E-6
,ALPX,1,7,8.1E-6,7.8E-6,7.5E-6,7.5E-6,7.5E-6,7.5E-6
,ALPX,1,13,7.5E-6
MPTRES,ALPX,1
MPDATA,ALPX,2,1,6.1E-6,6.4E-6,6.8E-6,7.2E-6,7.5E-6,7.8E-6
,ALPX,2,7,8.1E-6,7.8E-6,7.5E-6,7.5E-6,7.5E-6,7.5E-6
,ALPX,2,13,7.5E-6
MPTRES,ALPX,2
MPDATA,ALPX,3,1,6.1E-6,6.4E-6,6.8E-6,7.2E-6,7.5E-6,7.8E-6
,ALPX,3,7,8.1E-6,7.8E-6,7.5E-6,7.5E-6,7.5E-6,7.5E-6
,ALPX,3,13,7.5E-6
MPTRES,ALPX,3
MPDATA,ALPX,4,1,9.2E-6,9.3E-6,9.5E-6,9.7E-6,9.9E-6,9.9E-6,10.2E-6
,ALPX,4,7,10.3E-6,10.5E-6,10.7E-6,10.7E-6,10.7E-6,10.7E-6
,ALPX,4,13,10.7E-6
C*** BEGIN FIRST LOAD STEP (SQUEEZE CYCLE: PRESSURE LOAD ONLY)
ITER,1,1,1
TUNIF,70
TIME,0
C*** DEFINE DISPLACEMENT CONSTRAINTS

D,1,ALL
D,2,UY,,11,1
D,22,UX,,148,21
D,174,UX,,318,16
P,364,365,5432,,368

AFWRITE
FINISH

/PREP6

/TITLE  DYNAMIC DISPLACEMENT ANALYSIS

NSTEPS,159
NTABLE,5
FILL,1,1,159,1,1,1
,2,1,159,,1
,3,1,128,,0
,3,129,129,,1
,3,130,158,,0
,3,159,159,,1
,4,1,159,,1
,5,1,129,,0,.0021
,5,130,159,,28984,.02104

KTEMP,1 $NITTER,2 $NPRINT,3 $NPOST,4 $TIME,5
PRVAR,1,2,3,4,5
LFWRITE
FINISH

/EXEC

/INPUT,27
/INPUT,23
FINISH
APPENDIX B

DATA ACQUISITION COMPUTER PROGRAM

Program of Spot Welding

Uses

Crt, {Unit found in TURBO.TPL}
Dos, {Unit found in TURBO.TPL}
Turbo3, {Unit found in TURBO3.TPU}
Graph,
Graph3,
Slib3;

Type

Ctrltype = Array [0..6] of Integer;
String14 = String[14];
String80 = String[80];
Filarray = Array[1..8] of Byte;
Extarray = Array[1..3] of Byte;
Dummy = Array[1..25] of Byte;
FCB = record
  Driver: Byte;
  Filenames: Filarray;
  Extension: Extarray;
  Reversed: Dummy;
end;
Buffer = Array[1..128] of Byte;
RegPack = record
case Integer of
  0: (AX, BX, CX, DX, BP, DI, SI, DS, ES, Flags : word);
  1: (AL, AH, BL, BH, CL, CH, DL, DH : byte);
end;

Const
  clock = $40;
  kb_buffer_head = $41a;
  ad1_lb = $280;  { for the i/o card designed by P.C.Tang }
  da1_lb = $280;
  ad1_mb = $281;  { higher 4 bits }
  ad2_mb = $281;  { lower 4 bits }
  da1_mb = $281;  { higher 4 bits }
  da2_mb = $281;  { lower 4 bits }
  ad2_lb = $282;
  da2_lb = $282;
  foto1_mb = $283;  { higher 4 bits }
  foto2_mb = $283;  { lower 4 bits }
  pdo = $283;
  ad3_lb = $284;
  ad_hold = $284;
  ad3_mb = $285;  { lower 4 bits }
  pdi = $285;  { higher 4 bits }
  foto1_lb = $286;
  foto2_lb = $287;

ADCounting : integer = 0;
D_Seg : integer = 0;
LVDT_Offset : integer = 0;
Voltage_Offset : integer = 0;
Current_Offset : integer = 0;
Totnum = 1200;
LVDT_Scale = 0.00012592959;
Voltage_Scale  = 0.008113;
Current_Scale  = 23.52;
flagi        :  integer = 0;
var
Workfcb     :  FCB ;
DTA         :  Buffer ;
Regs        :  RegPack ;
D_File      :  Text ;
Choice, Ans, D_Source, Ans2  :  Char ;
Have_Check, Quit, Have_Data ,
Have_Save   :  Boolean ;
Name, Date, Filename,
Piece, Machine      :  String14 ;
I, J, K, NO, Flagr,
JUST        :  Integer ;
LX, LY, X1, X2, Y1, Y2  :  Real ;
Blink       :  Byte ;
Int_base, Int_offset :  Integer ;
LVDT      :  Array [0..1200] of Integer ;
Voltage    :  Array [0..1200] of Integer ;
Current    :  Array [0..1200] of Integer ;

Procedure Ad_Sampling(flags,cs,ip,ax,bx,cx,dx,si,di,ds,es,bp: word);
Interrupt;
Var LOffset, VOffset, COffset : Integer ;
Begin
  Port[AD_HOLD]:=$ff;
  ADCounting:=ADCounting+2;
  if ADCounting < 2401 then
  Begin
    LOffset := LVDT_Offset + ADCounting;
  End;
VOffset := Voltage_Offset + ADCounting;
COffset := Current_Offset + ADCounting;
memw[D_Seg:VOffset] := ((port[ad3_mb] and $0f) shl 8) + port[ad3_lb];
memw[D_Seg:COffset] := ((port[ad2_mb] and $0f) shl 8) + port[ad2_lb];
memw[D_Seg:LOffset] := ((port[ad1_mb] and $f0) shl 4) + port[ad1_lb];
end;
end

Procedure Discare_AdR;
Var
 regs : RegPack;
Begin
if flagi=1 then
Begin
  with regs do
  begin
    ax := $251c;
    ds := int_base;
    dx := int_offset;
    end;
    msdos(dos.registers(regs));
    port[clock] := 0;  { recover clock }
    port[clock] := 0;
    flagi := 0;
  end;
end;

Procedure Initial_AdR;
Var
 regs : RegPack;
Begin
if flagi=0 then
begin
    port[clock]:=$e8;  \{Sampling period 0.83333 ms.\}
    port[clock]:=$03;
    int_offset := memw[$00:$1c*4];
    int_base := memw[$00:$1c*4+2];
    with regs do
    begin
        ax:=$251c;
        ds:=cseg;
        dx:=ofs(AdSampling);
        end;
        msdos(dosregisters(regs));
        flagi:=1;
    end;
end;

Function TLVDT( var ILVDT : Integer ) : Real ;
Begin
    TLVDT:=ILVDT*LVDT_Scale;
End ;

Function TVoltage( var IVoltage : Integer ) : Real ;
Begin
    TVoltage:=IVoltage*Voltage_Scale;
End ;

Function TCurrent( var ICurrent : Integer ) : Real ;
Begin
    TCurrent:=ICurrent*Current_Scale;
BEGIN { main program }  

D_Seg:=DSeg;
LVDT_Offset:=Ofs(LVDT[0]);
Voltage_Offset:=Ofs(Voltage[0]);
Current_Offset:=Ofs(Current[0]);
Cursor_Offset;
Have_Data:= False ;
Have_Check:= False ;
Have_Save:= True ;
Quit:= False ;
Main_Head ;
Repeat
  Main_Menu ( Choice ) ;
  case Choice of
    '1': Begin { -- On Line Measurement -- }
      if not Have_Check then
        begin
          Main_T ( 1 ) ;
          Welcome_C ;
          repeat until Keypressed ;
          Ans := ReadKey ;
          if Ans in ['y','Y'] then
            begin
              { IO_Initial ; ***} 
              Have_Check:= True 
            end ;
    end ;
ClearWindow (10, 13, 71, 23)
end;
if Have_Check then
begin
  Check_Save (1, Have_Save);
  if Have_Save then
  begin
    Measurement;
    D_Source:='1';
  end
end;
ClearWindow (1, 10, 80, 10);
ClearWindow (1, 25, 80, 25);
end;
'2': Begin {-- Show Graph on Screen--}
If Have_Data = True then
  CrtShow
else
  begin
    ClearWindow(1, 10, 80, 25);
    Band (20, 14, 60, 18);
    WriteXY(23, 16, 'No Data! Press SPACE to Continue.');
    repeat
      Ans:=ReadKey;
      until Ans = #32;
  end;
end;
'3': Begin {-- Read Data from Disk--}
  Check_Save (3, Have_Save);
  if Have_Save then
  begin

Read_Disk ( Have_Data )
if Have_Data then
begin
{Main_Head ;}
WriteXY ( 22, 25, "******* WAIT A MOMENT *******");
gotoxy(9,25);
write('Do You want to look at','
The Orginal Graph ? <Y/N> ');
Ans:='';
repeat
Ans:=ReadKey;
until Ans in ['Y','y','N','n'];
if Ans in ['Y','y'] then
  Crtshow;
  D_Source:= '2';
  Have_Save:= True;
end
end;
end;
'4': Begin  { -- Save Data to Disk -- }
if not Have_Data then
begin
Band ( 10, 14, 71, 18 );
WriteXY ( 17, 16, 'NO DATA !!! Press any key to Continue .');
repeat until KeyPressed;
ClearWindow ( 10, 14, 71, 18 )
end
else
if not Have_Save then
  Save_Data ( Have_Save )
else
begin
Band(15,13,66,19);
WriteXY(25,15,'These Data Had Been Saved. ');
WriteXY(25,17,'Press any key to Continue! ');
repeat until KeyPressed;
ClearWindow(15,13,66,19)
end
end;
'5': Begin { -- quit to DOS -- }
    if Have_Save = False then Check_Save(5,Have_Save);
    if Have_Save then
        Leave(Quit)
    end
end; {case}
Until Quit;
TextBackGround(Black);
GotoXY(1,1);
GotoXY(1,1);
TextAttr:= White + Black*16;
Clrscr;
Cursor_On;
END. { main program }
APPENDIX C

THE CALCULATION OF PERCENT HEAT

The governing equation of current flow in a resistance spot welder can be expressed as follow

\[ R_i(\omega t) + \omega L \frac{di}{d(\omega t)} = V_d(\omega t) = V_o \sin(\omega t) \]

where \( R \) = the resistance shown in Fig. C.1

\( V_o \) = the maximum voltage of primary circuit

\( V_d \) = the line voltage drop refereed to primary circuit

\( L \) = the line inductance

\( \omega \) = the current flow frequency

\( i \) = the primary circuit current

\( t \) = time

where \( Z = \sqrt{R^2 + \omega^2 L^2} \)

\( \cos(\phi) = \frac{R}{Z} \) = the power factor, \( \phi \) = the power factor angle

The RMS value of the current for a half cycle is given by
\[ I_{rms}^2 = \frac{1}{\pi} \int_0^\phi i^2(\omega t) d(\omega t) \]

\[ I_{rms}^2 = \frac{1}{2\pi} \left( \frac{V}{Z} \right)^2 \left[ r + \cos \theta \sin \theta - \cos(\theta + r) \sin(\theta + r) - \tan \phi \sin^2 \theta \left\{ \exp\left(-\frac{2r}{\tan \phi}\right) - 1 \right\} \right. \]

\[ \left. + 4 \sin \theta \sin^2 \phi \left\{ \exp\left(-\frac{r}{\tan \phi}\right) \left( \frac{1}{\tan \phi} \sin(\theta + r) + \cos(\theta + r) - \frac{\sin \theta}{\tan \phi} - \cos \theta \right) \right\} \right] \]

Where \( \theta = \alpha - \phi \)

\( \gamma = \beta - \alpha \)

\( \alpha = \) the fire angle

\( \phi = \) the secondary power factor angle

\( \beta = \) the extinction angle

If the fire angle is equal to the power factor, then the maximum conduction occurs. For a given fire angle, the percent heat is the ratio of the resulting rms current value to the value that would result in maximum conduction angle, that is, the percent heat, \( % H \) is expressed as

\[ % H = \frac{I_{rms}}{I_{rms}(\alpha = \phi)} \times 100 \% \]

For \( \alpha = \phi \), \( \theta = 0 \), the rms current value becomes

\[ I_{rms}(\alpha = \phi) = \frac{V_o}{Z \cdot 2^{1/2}} \] and the percent heat is given as

\[ % H = \left( I_{rms} \times \frac{Z \cdot 2^{1/2}}{V_o} \right) \times 100 \% \]
Figure C.1 Typical Single Phase Welder - Heat Control [50]