CONTROL OF MATERIALS PROCESSING VARIABLES IN PRODUCTION RESISTANCE SPOT WELDING

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ABSTRACT

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How can high-volume manufacturers resistance spot weld sheet steels with maximum quality, repeatability and efficiency? What are the key variables of this process? What are the requirements for feedback control? These are a few of the technical problems relevant in today's automotive industry. Effective answers to these questions stem from the knowledge of spot welding metallurgy, and the physical and cultural environment of the shop floor.

In the spot welding process, some of the classical variables are: material weldability, zinc coatings, metal fit, sheet thickness, electrode alignment, force, time, current density, cooling, and others. This work focused on ranking the known variables according to their relative influence on process control. Consequently, a number of variables were characterized in both laboratory and plant environments.

The results show that from a process control standpoint, peak efficiency and quality occur when operating close to the expulsion limit. Surprisingly, when welding about the expulsion limit, the key variables were found to

be in the equipment maintenance area, rather than in the material properties and coatings area. Thus, through analysis, the long list of key variables was reduced to the following four important maintenance variables:

1) **Electrical resistance of the total circuit.**
2) **Cooling water efficiency.**
3) **Mechanical condition of the weld guns.**
4) **Operating current.**

A distant fifth variable was metal fit, but only when metal fit was extremely poor. Additionally, it was found that an electrode misalignment of less than 40% had little impact on quality, provided the process was operating at expulsion. And, the power factor was found to be an effective feedback signal for keeping the process centered at the expulsion limit. The results of the study, conducted in both laboratory and plant environments, are discussed at length in this dissertation. The recommendations were successfully implemented in a large automotive plant.

ACKNOWLEDGMENTS

First of all I would like to recognize my wife Lynne for her unfailing support, forbearance, prayers and encouragement throughout this project. I would like to express appreciation to my academic advisors, including Professor Kali Mukherjee and the faculty and graduate students at Michigan State University. I would also like to thank Dr. Jerry Gould of the Edison Welding Institute, and Professor Thomas Eagar of the Massachusetts Institute of Technology. I am profoundly indebted to my steadfast supporters at General Motors, including Michael Camp, James Armstrong, Richard Conley, Gary Sweeley, Dave Stevenson, Gerald Wood, Robert Angeli, John Stark, John Headley, Jerry Graul, Wayne Grandy, Robert FitzPatrick, Dave Purchase, James Gilbert, Bruce Kelly, Greg Nagel, and many, many others. Thanks to Medar, Inc. and Physical Acoustics Corp. for their willing assistance with the feedback controls. And a very special thanks to the enthusiastic members of the United Auto Workers, Locals 652 and 1618, who willingly sacrificed their time and creative energy to make this project a success. Without the help of each of the above persons, I could not have completed this work. This dissertation is therefore dedicated to all of them, toward the continuous improvement of the American manufacturing industry. Many thanks also to Dr. Parwaiz A. A. Khan, my friend and colleague, for his guidance and assistance in proofreading this manuscript.

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1. INTRODUCTION

1-1 Overview

Resistance spot welding is the most popular method of joining sheet metal. This opinion is based upon the number of welds made per year and the annual material consumption of the major users of the spot weld process. The automotive industry for example, is by far the largest tonnage user of steel. It is estimated that the auto industry alone produces 90 billion spot welds per year, based upon a conservative average of 3000 spots per vehicle and a worldwide annual production rate of 30 million vehicles. Some of the reasons for the popular success of this welding process are the following:

a) Relatively high energy density and rapid welding.
b) No filler metal or shielding gas.
c) Low heat input and low distortion.
d) Relatively low cost of equipment and operation.
e) Simplicity and maintainability of equipment.
f) Highly automatable and flexible.

Unfortunately, as with all high volume manufacturing processes, efficiency plays a major role in the cost of production. In spot welding, one of the main efficiency issues is weld quality. Weld quality is defined primarily in terms of the average bond diameter at the weld interface. Weld quality is important because it affects manufacturing costs in many ways. For example, since only acceptable parts can be used, weld quality directly affects rework, scrap, downtime, inventory costs, and the proliferation of redundant welds. However, if it should become possible to improve the control of weld quality on a broad scale, engineers would in time develop more streamlined products and processes that require less material, fewer welds, less rework, and less scrap to produce comparable vehicles. Significant cost savings could be achieved through the elimination of redundant operations, which would allow for less tooling, fewer operations, less floorspace, less manpower and less administration. Thus greater efficiency will be enjoyed by manufacturers who learn to optimize and control their weld processes.

As a general rule, process control is the key to greater efficiency in manufacturing. But process control always requires adequate knowledge of the process. Process knowledge is only adequate once the key variables and their critical interactions are known.

1-2 The Spot Welding Variables

In manufacturing, processing variables may be conveniently listed in four categories, commonly known as the four M's: Material, Machine, Method, and Maintenance. The four M's shall now be defined in brief detail.

1) **Material** - Material variables are those variables which are physically carried to the weld process with the material to be welded.

2) **Method** - Method variables are the weld parameters and the weld requirements. These variables are largely elective and may stem from product design, tool design or the floor setup engineer.

3) **Machine** - Machine variables are variables due strictly to machine design and build.

4) **Maintenance** - The maintenance variables are associated with how and when maintenance is performed.

The applicable variables from spot welding are listed in Figure 1.1. These spot welding variables were identified through input from many people, from both academic and plant backgrounds. Seeing this long list of variables, one might be tempted to conclude that the process is difficult to control, or even that it is uncontrollable. In this study, as many of these variables as possible were evaluated, in order to rank and isolate the critical variables.

1-3 Project Summary

In this work a number of variables were characterized and tested for their relative influence. Testing was done in both laboratory and plant environments. Then the process setups were refined to minimize the impact of day to day variation. Peak efficiency and weld quality occurred consistently when operating as close to the expulsion limit as possible. When production weld equipment was calibrated

1	2	3	4
MATERIAL	**METHOD**	**MACHINE**	**MAINTENANCE**
Material Properties	**Weld Specifications**	**Electrical**	**Electrical**
Electrical Resistivity	Strength	Current Balance	Actual Loop Resistance
Thermal Conductivity	Diameter	Power Factor	Actual Loop Area
Heat Capacity	Expulsion	Designed Loop Area	
Density	Indentation	Loop Magnetism	
Magnetism	Location	Dsgn. Loop Resistance	
	Flange Width	Supply Voltage	
		Turns Ratio	
Microstructural Factors	**Weld Parameters**	**Mechanical**	**Mechanical**
Cracking	Current	Gun Design	Mechanical Tool Wear
Grain Growth	Force	Force Balance	Lubrication
Hardness	Weld Time	Cooling System	Cooling Water Flow
Heat Affected Zone	Squeeze Time	Misalignment	Misalignment
Inclusions	Electrode Selection		
Phase Changes			
Liquation Cracking			
Shape Factors			**Die Practice**
Thickness			Metal Fit
Thickness Ratio			Coating Damage
Flatness			Flange Condition
Metal Fit			
Surface Factors			
Roughness			
Oil			
Oxide			
Zinc			
Paint			
Cloth, Paper			
Misc. Contaminants			

Figure 1.1 Fifty four resistance spot welding process variables, arranged according to the "Four M's" of manufacturing processes.

1	2	3	4
MATERIAL	**METHOD**	**MACHINE**	**MAINTENANCE**
Material Properties Electrical Resistivity Thermal Conductivity Heat Capacity Density Magnetism	**Weld Specifications** Strength Diameter Expulsion Indentation Location Flange Width	**Electrical** Current Balance Power Factor Designed Loop Area Loop Magnetism Dsgn. Loop Resistance Supply Voltage Turns Ratio	**Electrical** Actual Loop Resistance Actual Loop Area
Microstructural Factors Cracking Grain Growth Hardness Heat Affected Zone Inclusions Phase Changes Liquation Cracking	**Weld Parameters** Current Force Weld Time Squeeze Time Electrode Selection	**Mechanical** Gun Design Force Balance Cooling System Misalignment	**Mechanical** Mechanical Tool Wear Lubrication Cooling Water Flow Misalignment
Shape Factors Thickness Thickness Ratio Flatness Metal Fit			**Die Practice** Metal Fit Coating Damage Flange Condition
Surface Factors Roughness Oil Oxide Zinc Paint Cloth, Paper Misc. Contaminants			

Figure 1.1 Fifty four resistance spot welding process variables, arranged according to the "Four M's" of manufacturing processes.

to operate this way, the list of important variables was reduced to just four basic maintenance items:

1) Electrical resistance of the total circuit.
2) Cooling water efficiency.
3) Mechanical condition of the weld guns.
4) Operating current.

A distant fifth key variable was metal fit, but only when metal fit was extremely poor. The remarkable aspect of these conclusions is that so many of the classic variables shown in Figure 1.1 ended up being minor variables in the shop floor environment. It turned out that proper maintenance is the key process variable on the shop floor. And fortunately, of the four M's, maintenance is the preferred main variable since it is the most controllable.

This dissertation summarizes a laboratory and plant study of the variables of resistance spot welding. The recommendations of this work were successfully implemented in a large automotive plant. The tangible result was the achievement of perfect weld quality during several extended production runs of over 8 million welds each. Data and analysis are included to explain the physical and metallurgical process of production resistance spot welding.

2. LITERATURE REVIEW

This section is to acknowledge the research of others who may have had some bearing on this study. The reviews are organized topically, beginning logically with the weld microstructure, which is the most complete measure of weld quality and is therefore the best way to define process requirements. Then, in order to understand how spot weld microstructures develop, contact resistance and heat flow are reviewed. Next, weld parameters are discussed in terms of process requirements, using a measurement tool called a weld lobe. A review of mathematical models follows. These models attempt to predict weld formation. Several classical feedback control schemes are then presented. The chapter concludes with an explanation of a significant new in-situ measurement technique for gathering voltage and temperature weld data in a laboratory environment.

2-1 Weld Microstructure

The microstructure of a spot weld resembles a rapidly cooled metal casting. On the one hand, it seems strange that spot welding is not officially classified as a fusion welding process by the Resistance Welder Manufacturer's Association (1). This is probably due to the fact that surface melting ideally does not occur in resistance welding. On the other hand, metallographic analysis reveals that melting does indeed take place in the interior "nugget" of the spot weld (Figure 2.1). Rapid cooling of the sheets by the copper electrodes causes martensitic transformation of the nugget. Surrounding the martensitic nugget are successive bands of thermally altered microstructure. The entire altered region surrounding the weld nugget is called the heat affected zone (HAZ). The microstructure of a spot weld in mild steel has been classified by Kim (2).

Solidification within the nugget follows the mechanism of cellular growth. This mechanism applies to all rapidly solidifying alloys (3-5). In short, solidification occurs by epitaxial growth of favorably oriented grains at the solid-liquid boundary. The fastest growing grains are those oriented with growth direction parallel to the maximum thermal gradient. These grains quickly dominate and cut off all slower, misoriented grains. Even though solidification is rapid, there is still opportunity for the segregation of low melting eutectics such as FeS to the center of the weld, causing "hot cracking" or porosity at the centerline. Segregation is greatest when the freezing direction remains in a straight line from the nugget wall to the nugget center, since unidirectional freezing gives the largest prior austenite grain size. If the freezing direction is gradually rotated, such as occurs near the edges of a spot weld (Figure 2.2), the favored grain orientation will also

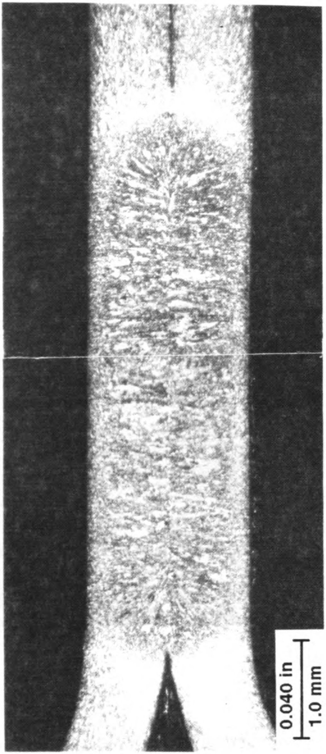

Figure 2.1 A normal spot weld in SAE 1005 DQAK cold rolled steel, 0.030 inch (0.75 mm). Microstructure shows a cast nugget formation, (Sample no 323).

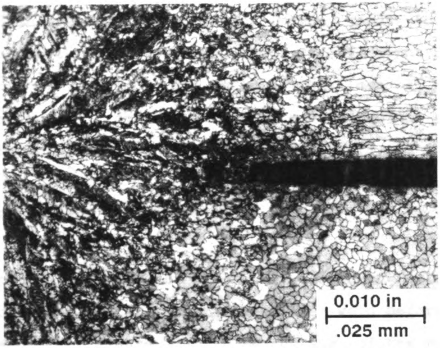

Figure 2.2 Photomicrograph of nugget edge, showing a rotating freezing direction. The upper sheet is cold rolled SAE 1005, the lower sheet is normalized SAE 1005.

rotate, trapping in segregates as new grains cut off old grains. Excessive segregation in high strength low alloy (HSLA) steels has been shown to cause a kind of hot cracking known as hold-time sensitivity (6,7).

However, core defects in spot welds generally do not pose a weld strength problem for at least two reasons. First, since structural loads are transmitted through the sheet, they are focused around the soft perimeter (HAZ) of the weld. Second, the freezing direction places the outer nugget in residual compression, which tends to inhibit fatigue growth of core cracks, since cracks do not penetrate the compressive ring. Hot welds, with loss of metal and internal voids from expulsion, have been tested and found to be structurally sound for the most part (8,9).

2-2 Contact Resistance

For the purpose of this study, contact resistance is defined as the total resistance of the weld before current is passed. In Figure 2.3, it is the sum of the resistance before welding has taken place. This resistance seems to be 5 to 30 times greater than resistance after one or two weld cycles. Contact resistance can be significant because it provides extra joulean heating early in the weld sequence. The largest part of contact resistance seems to be due to surface film and asperities touching at the interfaces R2,

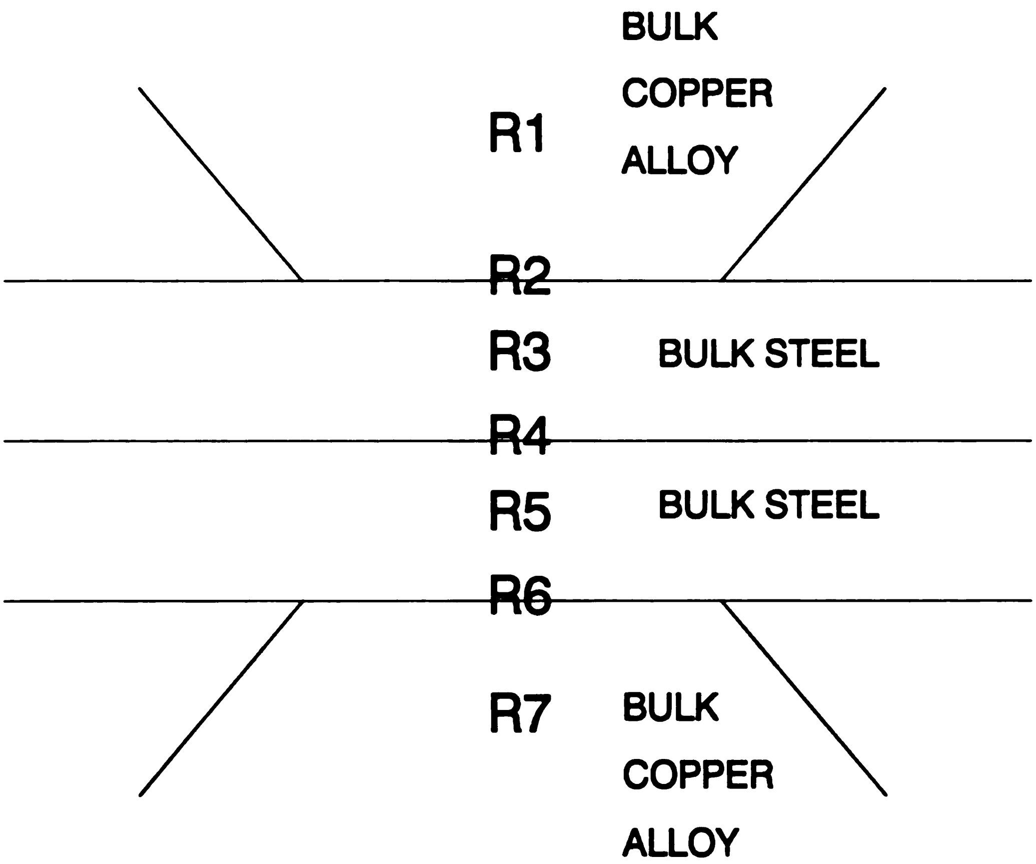

Figure 2.3 Schematic of resistances in a spot weld.

R4, and R6. This is in contrast with the bulk resistances R1, R3, R5, and R7 which are quite low in the cold preweld condition. R3 and R5 are estimated to be 6 micro-ohms per sheet for 304 stainless steel, based upon a cylindrical volume 0.030 inches (0.75 mm) thick and 0.25 inches (6.35 mm) in diameter, using a material resistivity of 25 micro ohm-cm:

$$R = \rho \cdot \frac{l}{a} \qquad [\ 2.1\ ]$$

$$R = 25 \cdot \frac{0.075}{\pi \cdot \left[\frac{0.63}{4}\right]^2} \qquad [\ 2.2\ ]$$

$$R = 6 \text{ micro ohm} \qquad [\ 2.3\ ]$$

Therefore, bulk resistance is seen to be one to two orders of magnitude smaller than the total contact resistance.

Interfacial resistance is made up of many parallel microasperity paths (10-12). These cause the data to show significant variation since surface roughness and cleanliness are generally not repeatable, especially in an industrial environment. There is however an inherent relationship of contact resistance with pressure since the current can only pass through areas of actual asperity contact. Pressure influences the amount of micro contact area by crushing the surfaces together.

Contact resistance is most influential when weld time is short, according to a study of half cycle welds made by condenser discharge. Nakata, et al (13) showed in 1975 that contact resistance has two components: surface film resistance and asperity resistance (known as spreading resistance in physics). Although surface film resistance is one or two orders of magnitude larger than asperity resistance, its heat contribution is small because the film breaks down in only 1/16 cycle (~1 ms). Therefore the main source of heat in contact resistance is due to asperities.

Nakane and Torii (14) also concluded in 1973 that contact resistance hardly affects spot welding. They dispelled the earlier "linear" theory that contact resistance generates local hot spots which in turn generate more heat and grow rapidly larger. They found that contact resistance disappeared within 1/4 cycle after heating begins, and that heat flow quickly erased local hot spots. Then they modeled the current flow path, factoring in contact area at the weld interface and the sheet separation around the contact area. Their conclusions were: the contact area limits the diameter of the current path and this diameter does not change appreciably during the course of welding before expulsion, but grows abruptly when expulsion occurs. The increase in weld area at expulsion lowers current density, which discourages further nugget growth (Figure 2.4).

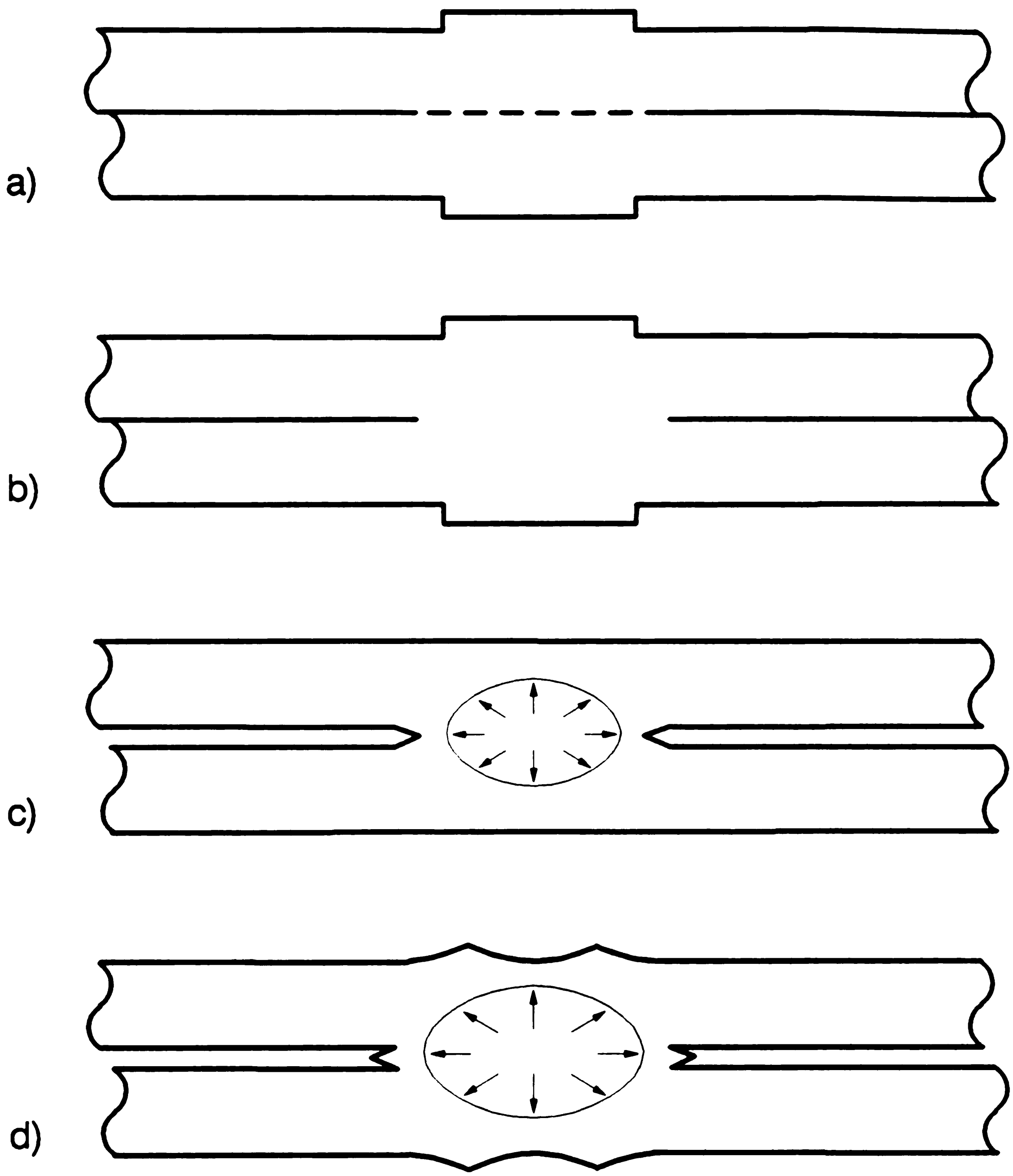

Figure 2.4 Experimental model showing the onset of sheet separation with time. Figures c) and d) represent greater weld time, (Ref 20).

An interesting experimental study of the flow of heat across metallic interfaces under pressure was done by Weills and Ryder in 1949 (15). They concluded that thermal resistance at the interface is analogous with electrical spreading resistance. As such, it decreases with increasing temperature and pressure, or by the inclusion of oil or a soft metal plating.

Using high speed cinematography of half welds, Satoh, et al concluded in 1970 (16,17):

> "the contribution of the contact surface is mainly to provide the place for sheet separation to occur, rather than the place where contact resistance prevails (since contact resistance exists for such a short time)."

In 1990, Kim and Eagar (18) concluded that,

> "the contact area at the faying interface has a greater effect on nugget growth than does the contact resistance. It is found that the ease of spot welding of bare steel is due to the small contact size, not due to high resistance. The heat generation rate at the electrode interface is about double that of the faying interface when welding galvanized steel due to the large contact area at the faying surface created by the molten zinc."

2-3 Heat Flow Fundamentals

The heat flow out of spot welds through the electrodes is a key parameter. Heat flow is expectedly high during the later stages of weld development. Some contributing factors are: nugget temperature, sheet thickness, copper electrodes, and water cooling, to name a few. For welding below expulsion, the peak amount of heat flow may be approximated by the electrical energy input. This is especially true late in the weld schedule when the weld approaches thermal balance (heat in = heat out), and nugget growth stops. Thus if the input energy density were constant for a series of welds, the final penetration of those welds should be defined and stabilized by the ability of the electrodes to draw heat away from the weld. Neglecting heat flow in the plane of the sheets, all heat leaving the weld must cross the contact boundary between the electrode and the sheet. Thus, a stable, well controlled process would have low thermal (and electrical) resistance at the electrode-sheet interface.

In 1990, Calva and Eagar published an experimental and numerical analysis of thermal contact conductance, specifically as it relates to spot welding thin, galvanized sheet (19). They cited the difficulty of producing a repeatable thermal balance due to the combined effects of coating variation and material thickness. This thermal instability was causing unstable penetration. They concluded that improved weldability would result by increasing the contact resistance at the faying interface and decreasing it at the exterior interface. The results agree with an earlier work by Eagar, et. al. regarding galvanized high strength low alloy steels (20).

An insightful comparison of short and long weld times was done by Yamamoto and Okuda in 1978 (21). They studied resistance seam welding of bare steel, but their results provide an interesting view of spot welding as well. To gain understanding from their arguments, it is helpful to consider for the moment that spot welding could be a special case of seam welding, where travel speed equals zero. They showed that similar to spot welding, low speed seam welding is controlled by heat conduction. However, high speed seam welding is controlled by contact resistance, since the weld time is too short for heat conduction to dominate. The influence of sheet thickness on transition speed between modes was both calculated and measured, (see Figure 2.5).

From a control standpoint, a process governed by heat conduction is more stable than a process governed by contact resistance. This is because the thermal properties of commercial grade steel are more repeatable than its surface properties.

2-4 Current and Time - the Weld Lobe

The weld lobe of Figure 2.6 is a research tool commonly used to study the weld variables current and time. A weld lobe is a plot of iso-diameter lines on rectangular coordinates of weld time (ordinate) and weld current (abscissa). To understand how current and time operate, we

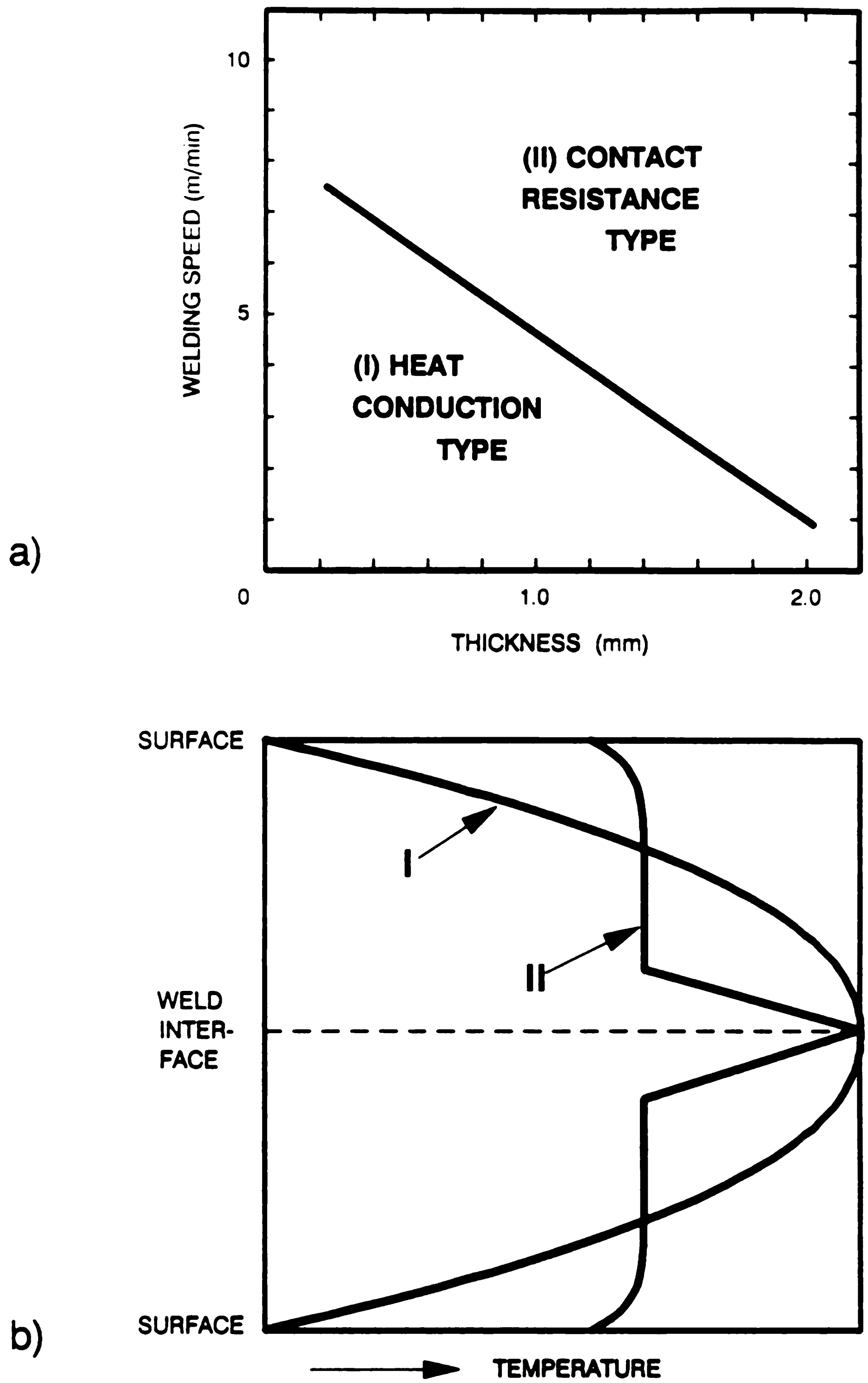

Figure 2.5 a) Seam welding transition speed from Yamamoto and Okuda's experimental model, using bare steel. b) Measured internal peak temperature profiles for the two modes, (Ref 21).

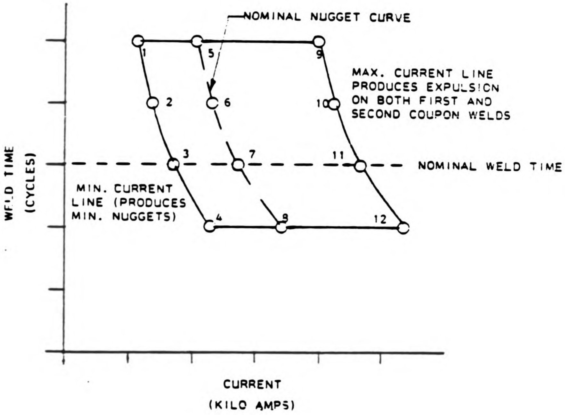

Figure 2.6 Typical weld lobe (Appendix A).

must examine their dependent variables, heat generation and heat flow. Heat generation and heat flow result from the passage of current. They produce a final temperature distribution which is of key importance in producing quality and stability in the process. The weld lobe simply records the distribution of final weld diameters. As such, the lobe indirectly tracks where the favorable temperature distributions lie, within the realm of current and time.

2-4-1 Dynamics of Heat Generation

Because of Joule's Law, current should be a parabolic contributor to the power needed to weld. Specifically:

$$H = I^2 \cdot R \qquad [\ 2.4\ ].$$

Weld time, on the other hand, linearly affects energy input as simply:

$$\text{Energy} = \text{Power} \times \text{Time} \qquad [\ 2.5\ ].$$

It is worth considering how the energy supplied to make a weld is used. First, let us remember that (approximately) 100% of the electrical energy used is released as heat. Local resistance and current density determine where the heat is released. Heat is released at all points having finite resistance and current density, according to Equation 2.4. Initially the hot spots are at the interfaces R2, R4, and R6 (Figure 2.3), since they have the highest resistance. Over time the contact resistance is quickly broken down, and the resistance "flame" for the completion of the weld shifts toward the bulk, which by this time has heated somewhat and become more resistive. As the bulk heats it becomes even more resistive and heats at an ever faster rate in a sort of "thermal runaway". But to prevent an explosive melt down and loss of control, heat flow comes into play.

2-4-2 Dynamics of Heat Flow

Provided the energy input rate is less than the maximum ability of the electrodes to dissipate this energy, the weld will continue heating until a quasi-steady state is reached. This condition is described as:

$$(Q_{rms})_{in} = (Q_{rms})_{out} \qquad [\ 2.6\ ],$$

where Q_{rms} is the root mean square of energy density with respect to time. If energy input is above this critical output rate, "thermal runaway" will occur, resulting in explosive welding and poor quality (22).

In contrast with thermal runaway, quasi-steady state is desired from a process control point of view. Here is the scenario leading up to the quasi-steady state:

1) As heat is liberated within the weld, it begins to flow conductively toward the water-cooled electrodes. Heat flow causes the surface of the weld touching the electrodes to be the coolest, most temperature-controlled part of the weld. Heat flow in the plane of the sheet is largely negligible, due to the lack of a nearby heat sink in the sheet direction. Lateral heat flow is especially small with thin sheets.

2) The region farthest from the electrodes (R4 in Figure 2.3) attains the highest temperature, since it is cooled the least. In addition, peak temperatures occur well after the interface has melted and R4 equals zero. Thus when heat flow is given time to stabilize, it is heat flow rather than resistance which determines the hottest location in the weld. This peak temperature zone becomes the center of the nugget casting. The nugget center is located halfway between the electrodes when the electrode geometry, material, and cooling are the same on both sides of the weld (Figure 2.7). It is observed that even when welding sheets of dissimilar thickness, the nugget center favors the midpoint between the electrodes, rather than the weld interface (Figure 2.8). (This midpoint principle may not be observed when dissimilar metals are welded).

3) The size of the nugget melt is restricted by the balance of heat generation and heat flow, provided there is enough weld time to achieve the quasi-steady state condition of Equation 2.6. Any additional time will not appreciably increase the weld pool size. Additional current however, will increase the pool size slightly, since the quasi-equilibrium will require this extra heat to be dissipated. The extra dissipation can only occur if the thermal gradient becomes steeper by the presence of a thicker weld pool and a thinner weld skin. The thermal gradient shown in Figure 2.7 may be approximated from the weld microstructure.

For example, if the weld penetration in two sheets of 0.030 inch (0.75 mm) mild steel were 60% as in Figure 2.7, the thermal gradient could be estimated, assuming a melting

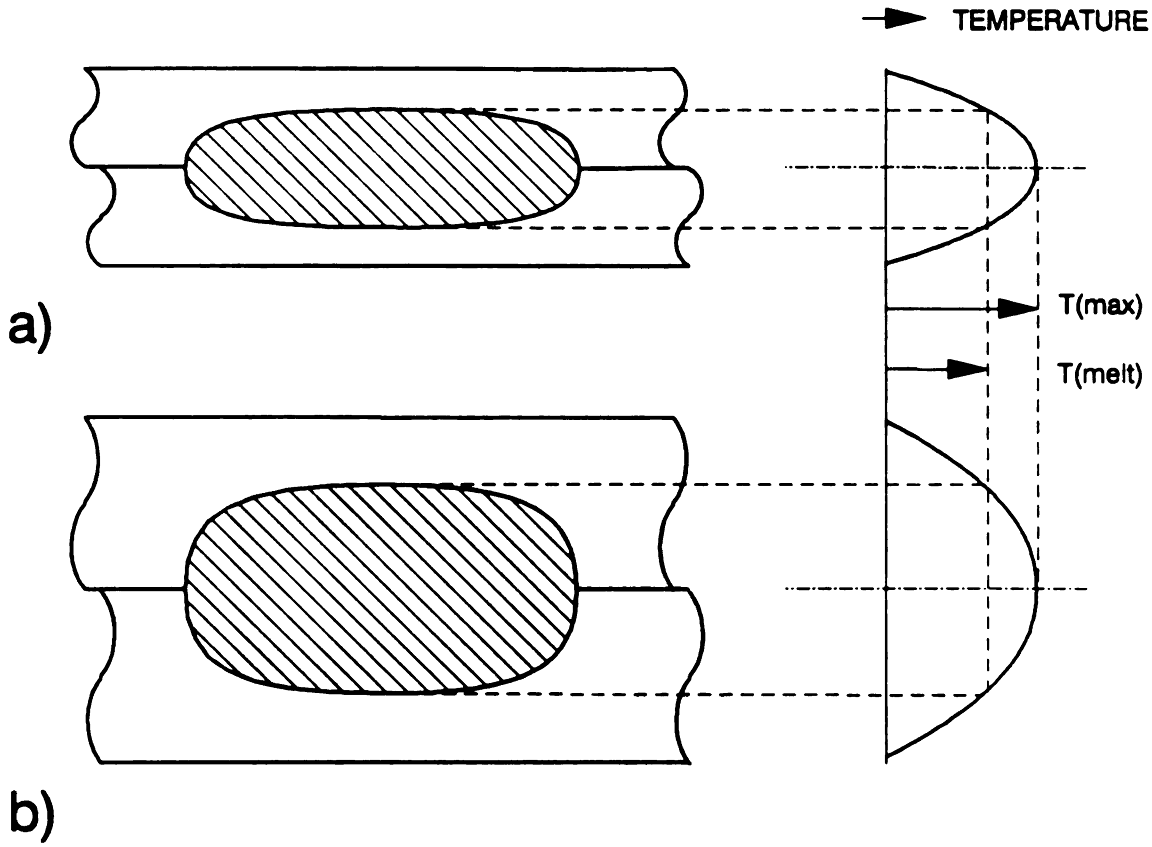

Figure 2.7 A one-dimensional temperature distribution model for spot welding, a) thin sheet model, b) thick sheet model, (Ref 24).

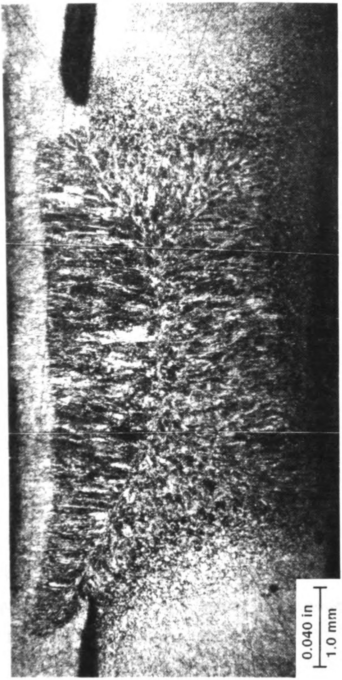

Figure 2.8 Typical nugget formation resulting from a 3:1 thickness ratio. This is a production weld of 0.040 inch (1 mm) to 0.120 inch (3 mm) drawing quality steels. Both sheets were hot-dipped galvanized. Nominal production parameters were 10 ka for 20 cycles at 600 pounds (261 kg). Notice how the nugget center lies at the mid-point of the stackup, rather than at the weld interface.

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point of 1525 C, and the outer weld surface at the transformation temperature (727 C), the thermal gradient would be:

$$\frac{dT}{dx} = \frac{T2 - T1}{t \cdot (1 - p)} \qquad [\ 2.7\ ]$$

T1 = low temperature boundary
T2 = high temperature boundary
t = sheet thickness
p = weld penetration

$$\frac{1525 - 727}{0.03 \cdot (1 - 0.6)} \frac{C}{in} = 66,500 \frac{C}{in} \qquad [\ 2.8\ ]$$

The maintenance of an aggressive yet stable thermal gradient during the final (quasi-steady state) cycles of the weld has great influence on the final temperature distribution and penetration of the weld. The goal is to produce melting at the interface, while keeping the outer surface as cool as possible. This goal dictates certain process requirements commonly seen in production welding equipment. These are at least:

1) Copper electrodes of high thermal conductivity.

2) Sufficient electrode force for good thermal coupling with the workpieces.

3) An electrode cooling system for repetitive welding applications.

2-4-3 Material Property Limitations

As seen in the previous example, the stock thickness has bearing upon the thermal gradient needed to preserve the desired temperatures at the two critical boundaries, (the outer surface and the near edge of the weld pool). This is unfortunate when welding thinner stock, because the thermal gradient eventually becomes limited by workpiece conductivity, rather than heat sink efficiency. When this happens, the heat cannot escape as fast as it is generated, and therefore the quasi-steady state cannot be attained, except when current density is reduced. Therefore quasi-steady state can only occur with current density below that required for welding. The problem with spot welding without enough current density is that sufficient melting does not occur, and diffusion bonding becomes the welding mechanism. Diffusion bonding is rather sensitive to variation in surface cleanliness, since contamination is a diffusion barrier. In this scenario, weld strength could be unpredictable.

To roughly estimate the quasi-steady state thermal gradient limitation, we shall use the Fourier Law for one dimensional steady-state conductive heat transfer.

$$Q = -k \cdot \frac{dT}{dx} \qquad [\ 2.9\ ]$$

Where,

Q = heat flow towards the electrodes [power/area],
k = thermal conductivity of the sheet material [power/length/C],
dT/dx = thermal gradient [C/length]

Rearranging for thermal gradient,

$$\frac{dT}{dx} = -\frac{Q}{k} \qquad [\ 2.10\ ]$$

For mild steel, we will use a thermal conductivity of k = 0.7544 W/[in-C], (0.0297 W / [mm-C]), and assume that it is constant in the weld skin temperature range: 727 - 1525 C. As an example, the power density of welding might be roughly:

$$Q = I \cdot \frac{V}{A} \qquad [\ 2.11\ ]$$

$$Q = 10{,}000 \cdot \frac{1}{0.098} \; \frac{amp \cdot volt}{in^2} \qquad [\ 2.12\ ]$$

$$Q = 102{,}000 \; \frac{watts}{in^2} \qquad [\ 2.13\ ]$$

Solving Equation 2.10,

$$\frac{dT}{dx} = -\frac{102{,}000}{0.7544} \qquad [\ 2.14\ ]$$

$$\frac{dT}{dx} = -135{,}000 \; \frac{C}{in} \qquad [\ 2.15\ ]$$

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which is the peak thermal gradient to be found in this material at this power level. The minimum "skin" of solid material between the nugget and electrode may be readily predicted by assuming a linear thermal gradient:

$$\frac{T_2 - T_1}{x_2 - x_1} = - \frac{Q}{k} \qquad [\ 2.16\ ]$$

At our power level and temperature range (727 - 1525 C), the theoretical minimum skin thickness to be found in the sample would be:

$$x_2 - x_1 = \frac{1525 - 727}{135000} \quad C \cdot \frac{in}{C} \qquad [\ 2.17\ ]$$

$$x_2 - x_1 = 0.0059 \quad in \qquad [\ 2.18\ ]$$

In practice, it is seen that when sheet thickness is less than about 5 times the theoretical minimum skin thickness, some tendency toward diffusion bonding begins. Thus, in terms of process control and weld quality, it is preferable to weld thicker sheet. It is proposed that thermal instability occurs when welding thin sheets because of the presence of a thermal barrier at the electrode-sheet interface, which restricts heat flow below the input rate. This means $Q_{in} > Q_{out}$ and thermal runaway is predicted. However in practice, a setup operator will compensate and reduce current to a visually acceptable level. It is this lower current which shows the tendency toward diffusion bonding.

To conclude this discussion of the thermal aspect of spot welding, the goal of the process is to produce a particular thermal profile within the sheets which will permit melting and bonding at the sheet interface, while keeping the external surfaces as cool as possible. The actual thermal profile depends upon two dynamic phenomena:

1) Heat generation, produced by electrical resistance to current flow.

2) Heat flow, dictated by the characteristics of the material (provided the time of welding is sufficiently long).

Thus, current and time are expected to be main variables affecting the thermal profile of the weld.

2-5 Weld Force and Weld Pressure Fundamentals

Consider the scenario of the shop floor tradesman who reduces force in order to increase weld diameter and penetration. Although not a sanctioned method of process control, reducing weld force does often increase the apparent heat of resistance welds. The warming effect of lower force has been explained as follows:

1) Contact resistance increases due to less asperity-crushing, which in turn generates more heat.

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2) Weld area decreases at all interfaces due to less elastic/plastic yielding of the bulk, especially when using ball-faced electrodes. The reduced area increases heat due to higher current density. Remember that local heat is proportional to local current squared (Equation 2.4).

3) As contact electrical resistance increases per item 1 above, contact heat flow resistance will also increase (15). Resistance to heat flow at the interfaces R2 and R6 (Figure 2.3) will cause more heat to be retained inside the weld.

Weld pressure in this study is defined as the weld force (delivered by the two opposing electrodes) divided by the electrode contact area.

$$P = \frac{F}{A} \qquad [\ 2.19\ ]$$

P = weld pressure
F = electrode force
A = electrode contact area

As defined, P is really an average pressure, since the true pressure varies across the face of the electrode due to the applied mechanics considerations of clamping two sheets together between flat or ball-faced tips (14). Nonetheless, P is of value in process study because of ease of measurement, and because of the implied correlation between average and true pressure.

Experimentally, weld pressure was varied rather than weld force, by changing the contact area. The above correlation with contact resistance is documented in Section 4-4.

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2-6 Mathematical Modeling

Ando and Nakamura contributed to the one dimensional mathematical understanding of spot welding in 1957 (23). They developed the heat time constant approach, which led to the law of thermal similarity introduced by Okuda in 1973 (24):

> "For the case when the plate thickness and the diameter of the electrodes are magnified by n times, if we also change the current density by 1/n times (which is current by n times), and heating time by n^2, the new temperature distribution becomes similar to the original one."

Okuda's law of thermal similarity is based purely upon a one dimensional consideration of bulk properties and does not even consider the influence of the interfaces. Consequently, actual welding begins to deviate from this rule when welding thin sheets, because there is less bulk to mask the interfacial effects, and because steeper thermal gradients are required for thin sheets (23,25). Practical welding of thick plates also deviates from this law since there is fanning of the current path and heat loss into the plane of the plate (26).

An important early numerical model was done by Greenwood in 1961 (26). Using a heat conduction model, he explained the classical understanding of heat flow and joulean heating within the weld. He showed that local thermal spikes are soon leveled out by conduction and that "the temperature (distribution) tends to an equilibrium for

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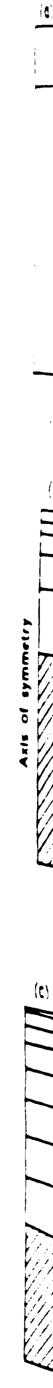
form" which "bears no resemblance to the heat production pattern" (Figure 2.9). Although he neglected surface resistance, the latent heat of fusion, and the variation of material properties with temperature, his results still correlate with the actual temperature distribution in completed spot welds. The fact that such a simple model still does a good job predicting final temperatures, even with its sweeping assumptions, indicates that perhaps contact resistance is not unduly influential in the later stages of welding, once a quasi steady-state of heat generation and heat flow is established.

Newer numerical models have included more exact data on material properties and interface resistance, but Greenwood's predictions about the thermal distribution for completed welds still stand (27-32).

2-7 Process Monitoring and Feedback Techniques

There have been longstanding efforts to develop adaptive welding systems by various means. An ideal system would detect process variation and automatically compensate as shown schematically in Figure 2.10. In practice, these systems are usually designed to terminate the weld when the desired nugget size has been reached or expulsion has been detected. Ideally, one would hope to "guarantee" quality as the welds are made. Unfortunately, many of these techniques



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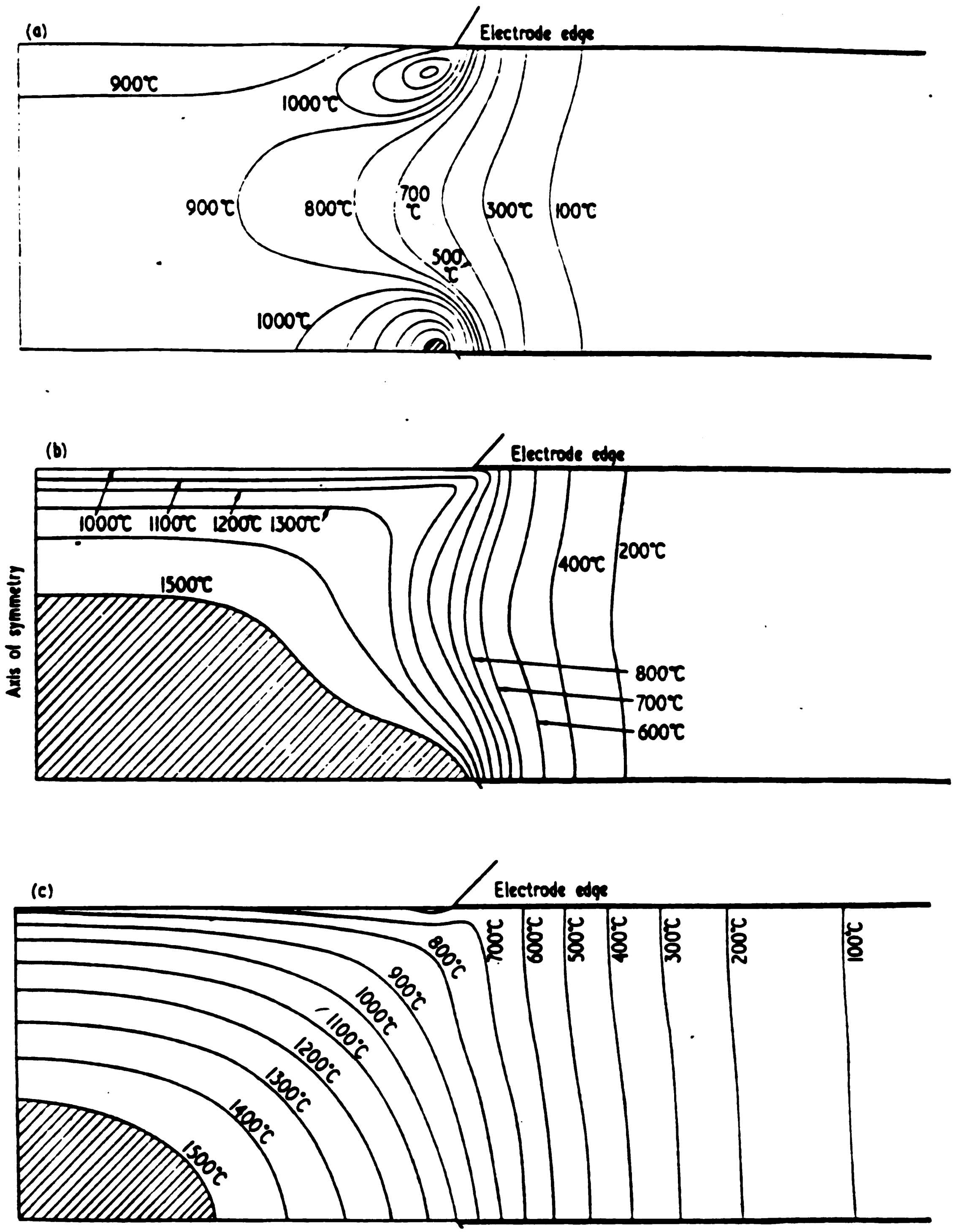

Figure 2.9 Greenwood's calculated temperature distributions after various weld times. a) 0.025 sec, b) 0.1 sec, c) 0.6 sec, (Ref 26).

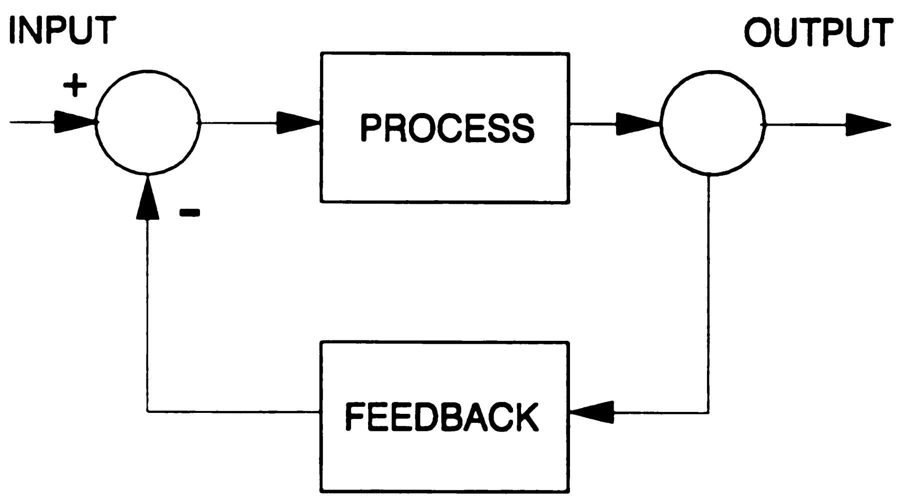

Figure 2.10 Schematic representation of dynamic feedback monitoring.

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work under laboratory conditions, but are not broadly accepted by manufacturing plants. One reason they are rejected is that they often require sensors on the weld gun. To a plant person, sensors are seen as unreliable in the dirty and often destructive environment of the secondary loop.

Of the feedback controls which have been developed to date, Stiebel, et al (33) have used a mechanical expansion sensor on the gun to detect nugget expansion. The sensor and the signal obtained are shown in Figures 2.11 and 2.12. Havens (34) tried acoustic emission detection using piezo-electric sensors on the electrode holder. Acoustic sensors and resulting signals are shown in Figures 2.13 and 2.14. Dickinson, et al. (35) tried dynamic resistance monitoring using voltage and current leads on the electrode holders (Figure 2.15). Nagel and Lee (36) terminated the weld at the resistance change which occurs at expulsion, as per Figure 2.15. Burbank and Taylor (37) developed ultrasonic through-transmission feedback using piezo-electric crystals inside the electrode cooling cavity, according to Figure 2.16. Although each method is ingenious and technically very different from the others, they all share the handicap of requiring sensors on the gun. All have shown some success in laboratory testing, yet none have achieved any significant market penetration, due to cost, practicality, or robustness in the plant environment.

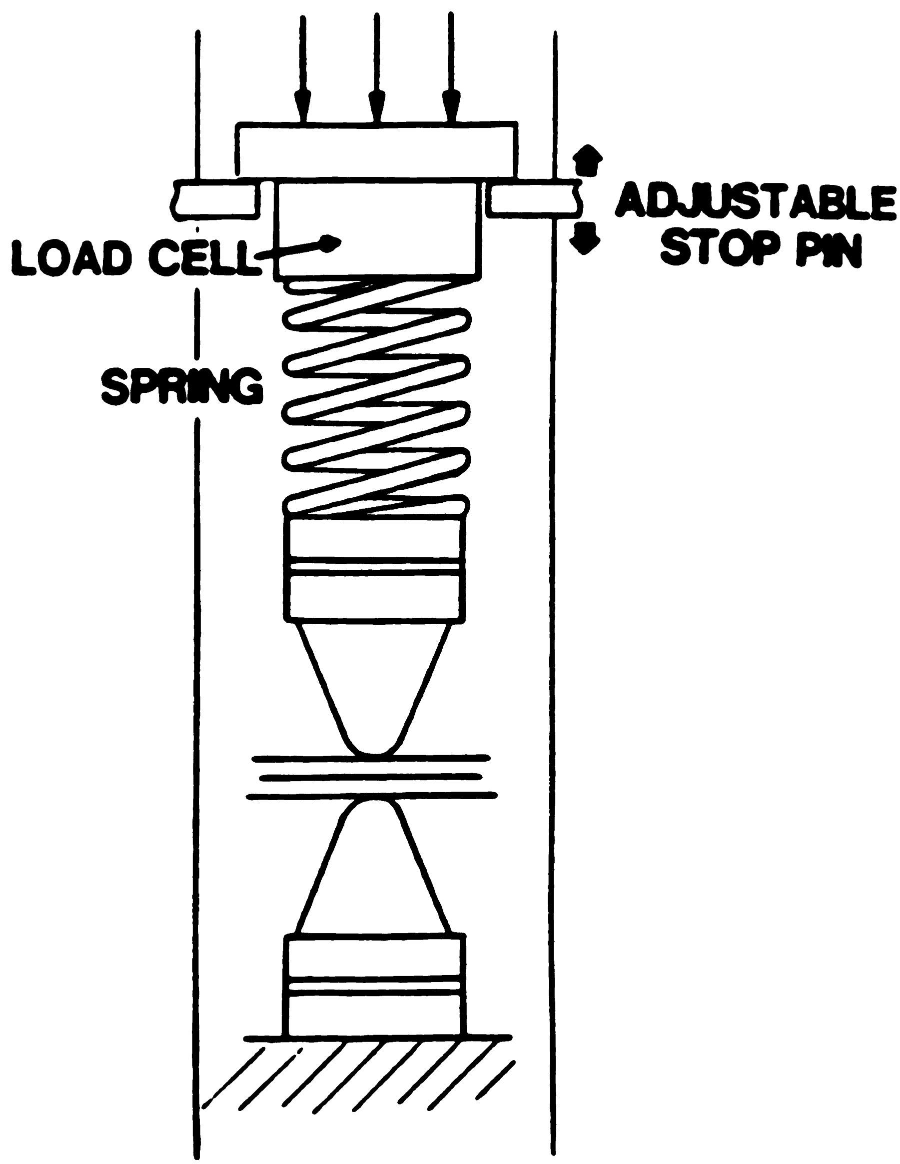

Figure 2.11 Load cell displacement sensor to detect nugget expansion during the weld, (Ref 33).

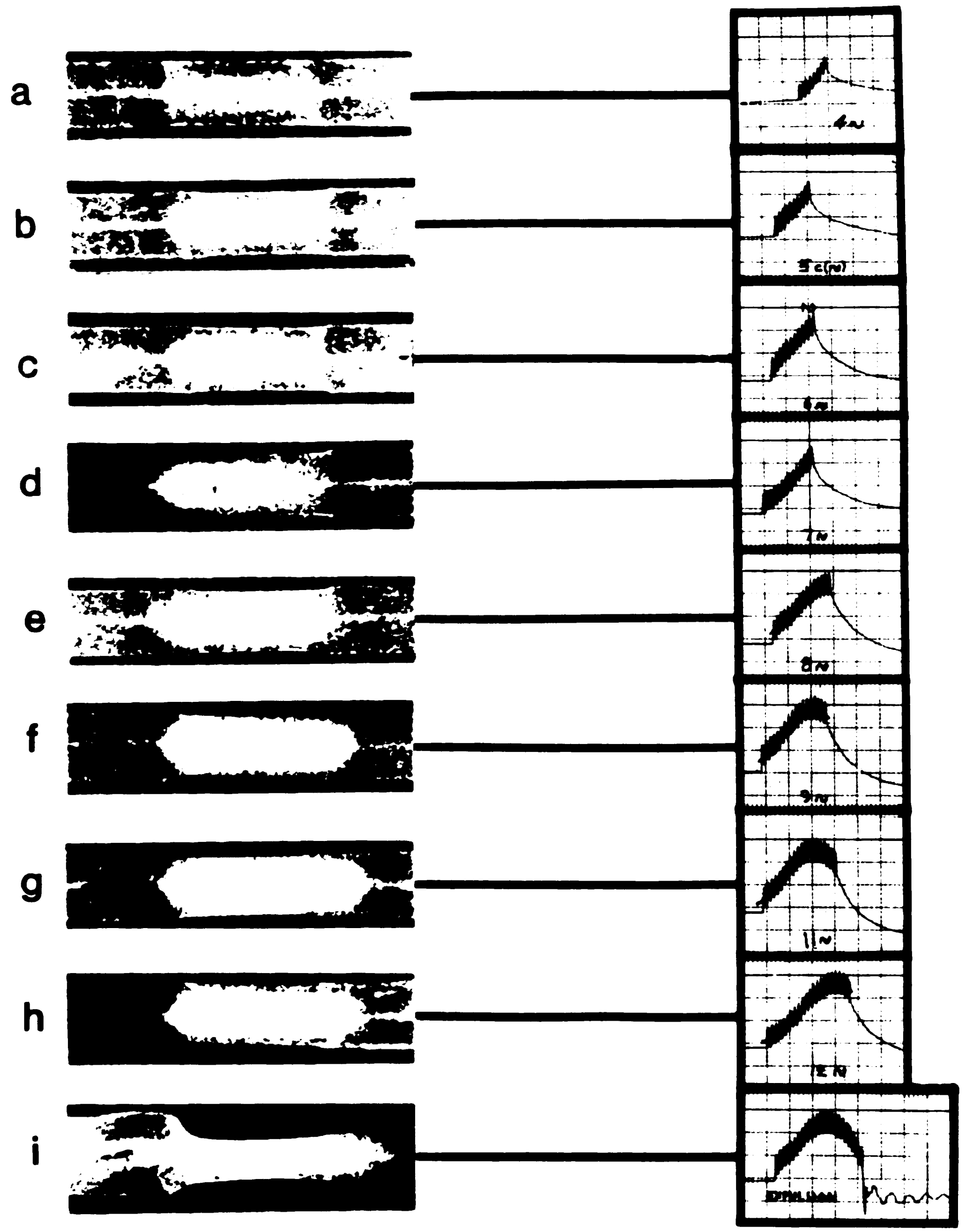

Figure 2.12 Nugget expansion profile as the weld develops, as a function of weld time, in cycles. The etched cross-sections (left side) show nugget development. The oscillograph data (right side) show vertical electrode movement during the weld. Notice the abrupt collapse at expulsion, letter i, (Ref 33).

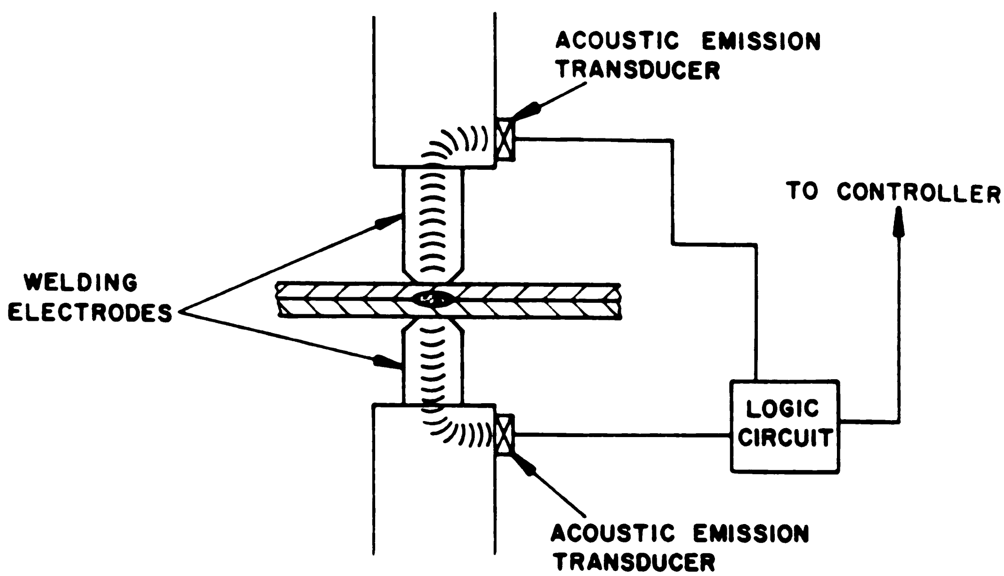

Figure 2.13 Schematic illustration of acoustic emission sensors on weld gun, (Ref 34).

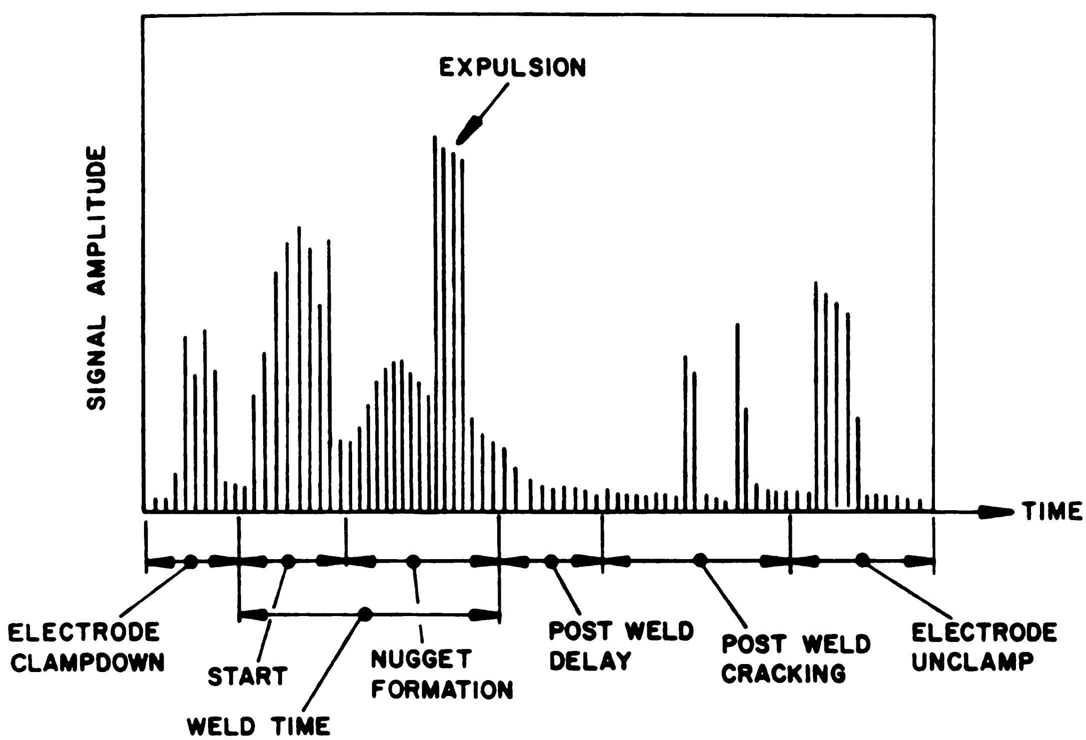

Figure 2.14 Schematic signature of acoustic emission during spot welding, (Ref 34).

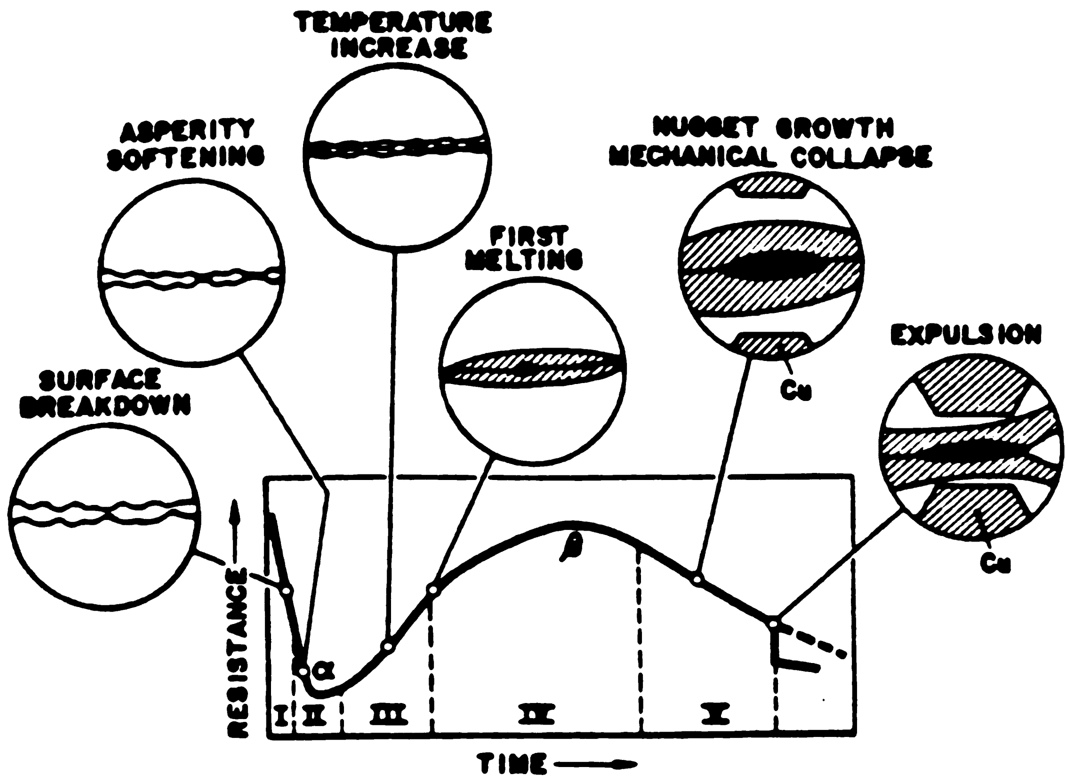

Figure 2.15 Classical dynamic resistance curve, (Ref 35).

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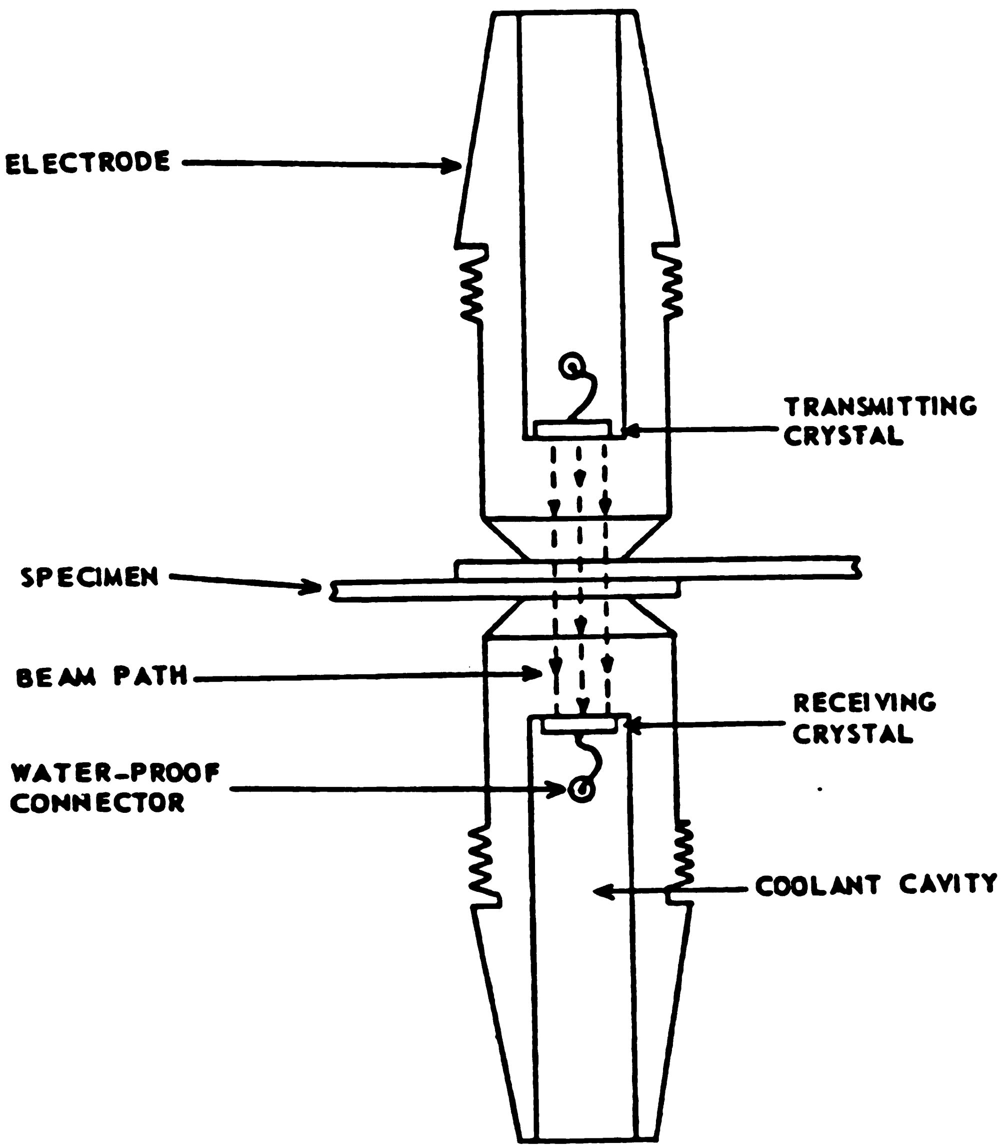

Figure 2.16 Welding electrodes containing ultrasonic transducers in a pitch-catch configuration, (Ref 37).

2-7-1 The Classical Dynamic Resistance Curve

Perhaps the most common feedback control method found in the literature is dynamic resistance (10,35,36,38-45). These systems usually employ voltage and current sensors in the secondary loop. V/I represents the measured resistance, taken at a point each half-cycle when dI/dt = 0, in order to eliminate inductive effects.

The classic dynamic resistance curve is shown in Figure 2.15. The curve has been characterized in terms of six key stages (35,36). Stages I and II include clamping of the workpieces by the electrodes and the passage of the first 1-2 cycles of current. During this time resistance is unstable and decreases rapidly to a minimum value which signifies the end of stage II. During stage III, resistance begins to rise due to bulk heating. Stage IV and V represent nugget growth, where resistance begins to taper off due to the increasing area at the weld interface. Stage V is also accompanied by some electrode indentation. Stage VI begins with expulsion of molten metal from the weld interface. During this time there is a rapid decrease in resistance due to an abrupt increase in weld area as the enclosed nugget ruptures. Resistance continues to fall after expulsion, due to additional electrode indentation.

This curve has been used in a variety of ways to provide meaningful feedback and control. Some adjust the cur

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current each cycle during stage III in order to control the rate of resistance change (41). Others observe the rate change during stage V (43). Still others terminate upon expulsion detection at the abrupt resistance drop (36).

2-7-2 A Theory for the Fundamental Changes at Expulsion

The existence of the resistance drop at expulsion (shown in Figure 2.15), is well documented (35,36,41-46). The reason for the R-drop at expulsion has been given by Lee and Nagel:

> "Because of the sudden spread of the molten metal, the current is no longer restricted to the hot region. This sudden change in the conduction mode is typified by a sudden drop in the resistance. Expulsion also signifies the maximum nugget size for that electrode size, geometry, and force. For all practical purposes the nugget growth process terminates at expulsion" (46).

Therefore, an abrupt increase in the faying interface contact area occurs at expulsion. When this happens, current density falls, which is why the nugget growth halts. So we see that expulsion can have a stabilizing effect upon the process since nugget size variation is less. The nugget size will be roughly the same even when input parameters vary, provided there is still enough energy for expulsion to occur. Of course, over welding severely could permit thermal runaway even after expulsion, but there should normally be a considerable current range in between

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expulsion and unacceptably hot welds. This range will be discussed further in Section 4-4-4.

Consistent with the fundamental resistance change at expulsion, the electrodes experience abrupt motion at this time (33,47-49). Figure 2.12 shows the classic pattern for electrode movement. The key here is the abrupt drop at expulsion.

In addition, the acoustic emission signal at expulsion has also been used to terminate the weld as seen from Figure 2.14 (8,34,50,51). Unfortunately, this method did not prove very reliable in the present study, as discussed in Section 4-5-2.

2-8 A Novel Technique for In-Situ Measurement of Temperature and Voltage

Measurement of data is an abiding problem in scientific research. Once in a while, a researcher will develop a truly clever and insightful way to collect data. One has to be impressed with the great effort some have given toward collection of hard-to-get data. This section mentions an interesting data collection scheme that has been used in the study of resistance welding.

Alcini (52,53) extensively developed the half weld technique, whereby electrodes were cut in half along their axis and arranged to make a weld on the sheet edge (Figure

2.17). This setup used a quartz "window" to contain the melt and allowed for wirebonding of micro thermocouples on an axial plane of the weld (Figure 2.18). Using an elaborate procedure, he was able to measure voltage and temperature from within the weld with significant accuracy. Some of his results are shown in Figures 2.19 through 2.21.

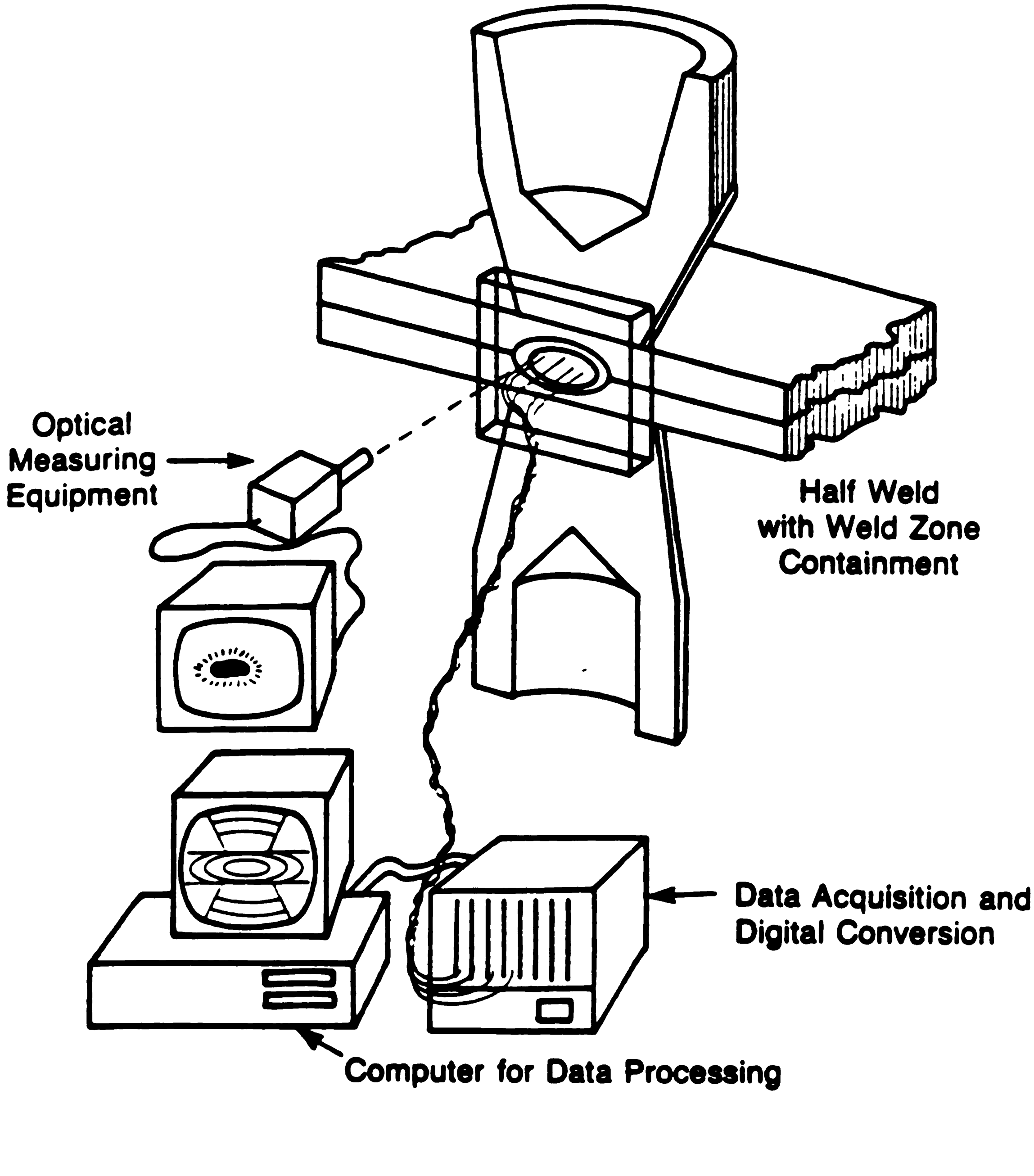

Figure 2.17 Schematic of the setup used for in-situ measurement of temperature and voltage, using half weld instrumentation, (Ref 52).

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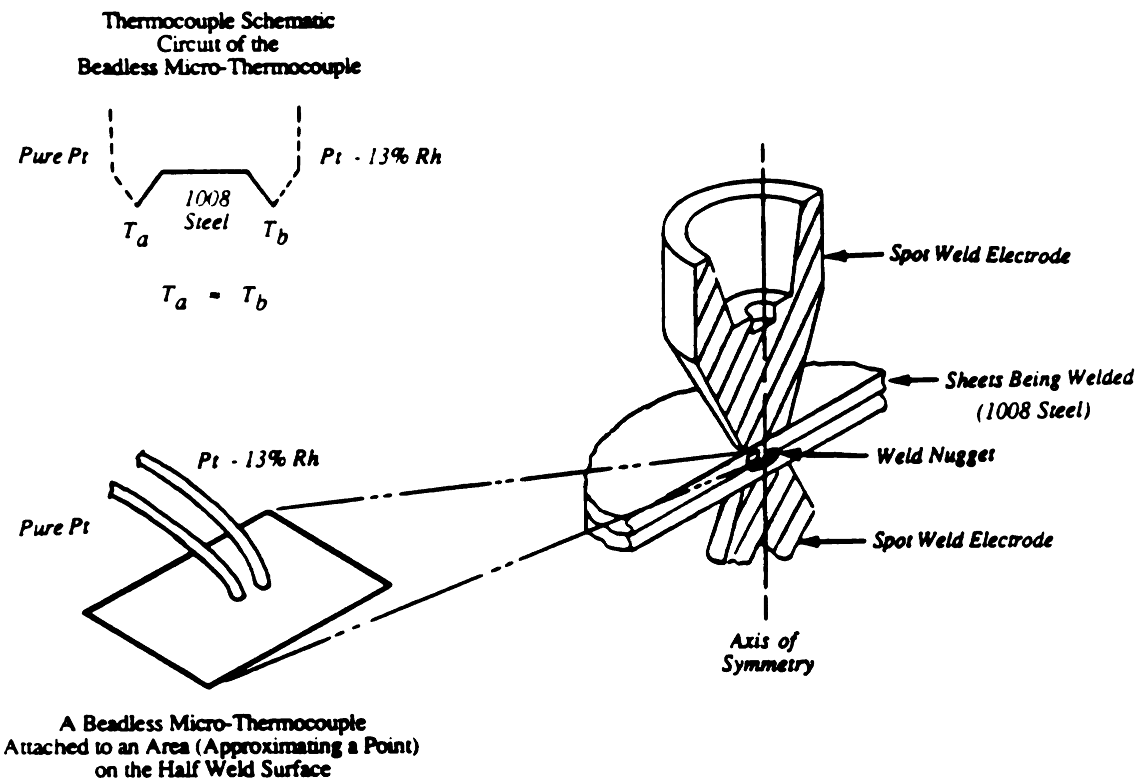

Figure 2.18 Schematic of beadless microthermocouple attachment used for in-situ measurement, (Ref 53).

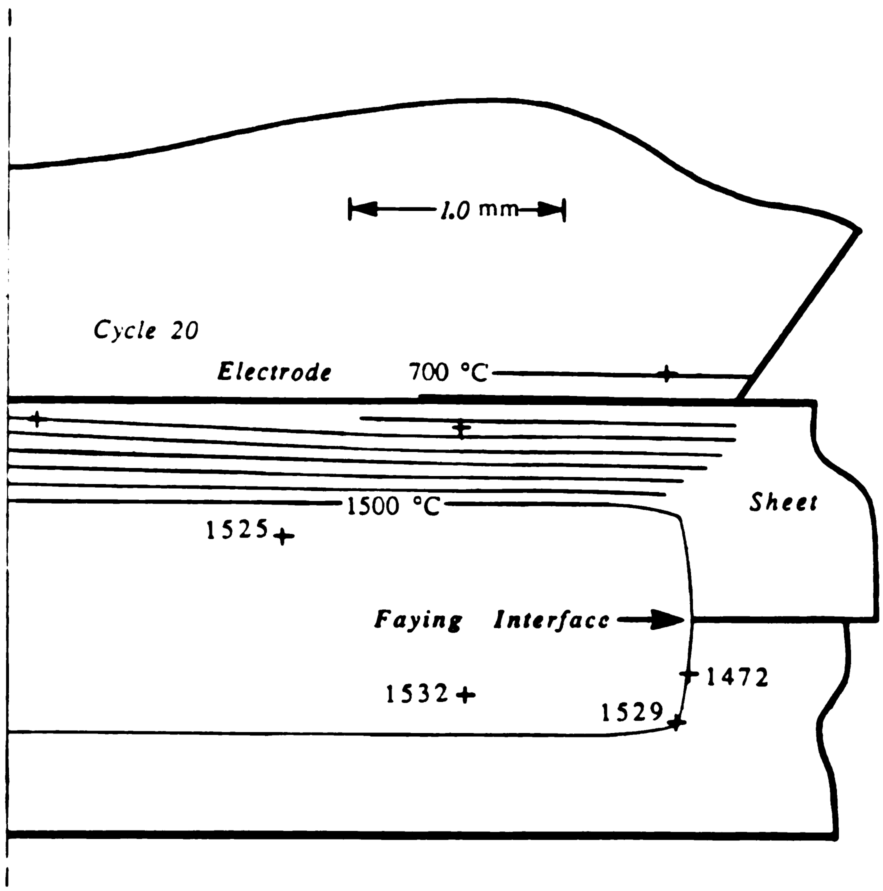

Figure 2.19 In-situ temperature fields in full-size weld nuggets. The temperature field was measured at the peak of nugget size by the half-weld technique, (Ref 53).

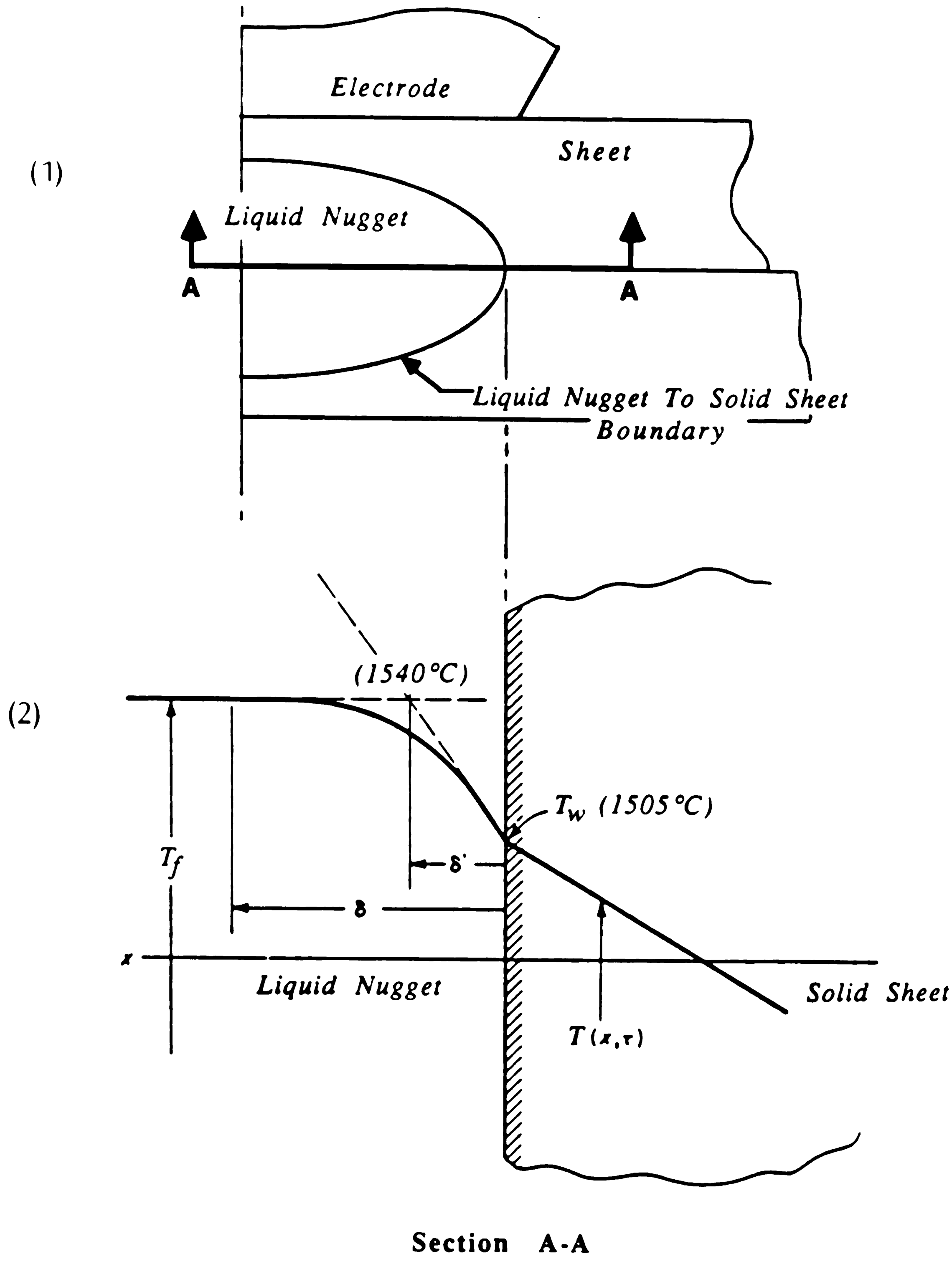

Figure 2.20 Convection in liquid nugget. Steady state convective heat transfer and heat conduction at a boundary surface, measured by the half-weld technique, (Ref 53).

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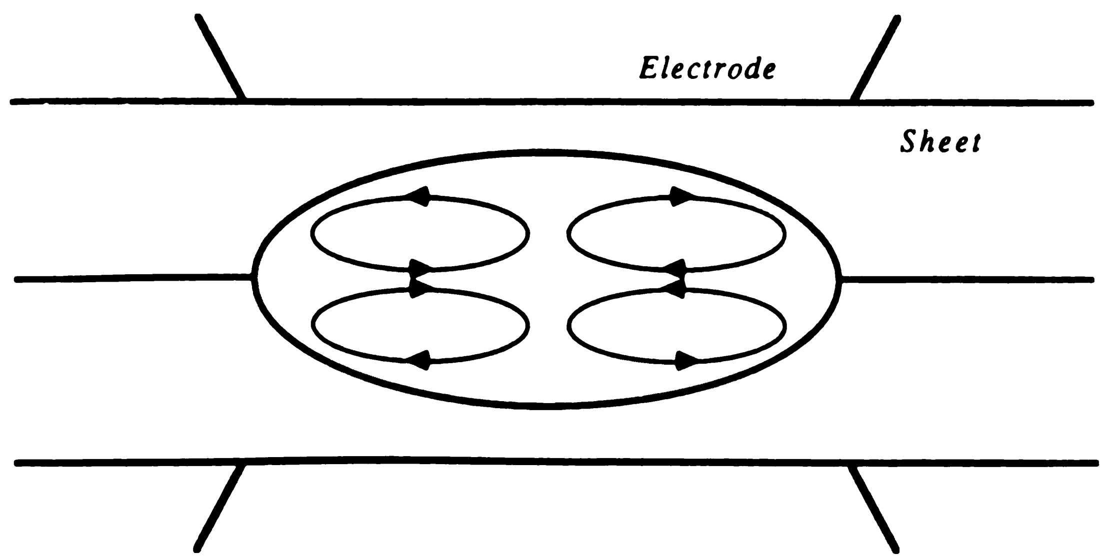

Figure 2.21 Convection swirling pattern proposed by Alcini, (Ref 53).

3. EXPERIMENTAL STRATEGY AND SETUP

3-1 Goals and Strategy

The goal of this study was to understand the spot weld process from the aspect of key variables, and then learn to control the process in spite of the many variables existing in the manufacturing environment. To achieve this goal it was necessary to conduct experiments to filter out key variables from less significant variables. Then, with the list of key variables and optimum setup conditions in hand, the next phase would be to implement a process control plan with measured performance feedback. The strategy used to achieve the goals may be summarized as follows:

1) Obtain management support to sustain project resources.
2) Develop laboratory facilities.
3) Conduct scientific studies, both in lab and plant.
4) Develop training courses.
5) Assemble trained preventive maintenance teams.
6) Bring every weld process under control (1600 guns).
7) Enhance program based on learned improvements.
8) Implement monitoring and preventive maintenance plans.

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3-2 Laboratory Apparatus

The laboratory welder consisted of a single gun spot welder as shown in Figures 3.1 and 3.2. The welder was custom manufactured as a laboratory model by the Resistance Welder Corporation of Bay City, Michigan. The important features were:

1) An air cylinder to extend and pressurize the electrodes.

2) A gun translation stage and sample holders (used for the electrode misalignment studies).

3) A fixture transformer driven by a 480 volt 60 Hz power line. The transformer was rated: 50 kVA at 440 volts, secondary voltage 3.2 - 5.0 volts, Girton Industries Model A 454.

4) A Legend weld control by Medar Corporation of Farmington Hills, Michigan (software program number 7181, revision 7).

5) An IBM personal computer used for data acquisition, as illustrated in Figure 3.3.

6) A Robotron toroidal current meter, model WS-20 from Robotron Corporation of Southfield, Michigan.

7) A digital low resistance ohmmeter, model 247001-11 by Biddle Instruments was used for static resistance readings of clamped sheets and machine circuits. A 10 amp current is supplied by the meter to take readings directly in micro-ohms.

8) A hydraulic force gage, range 0-1000 pounds (0-434 kg).

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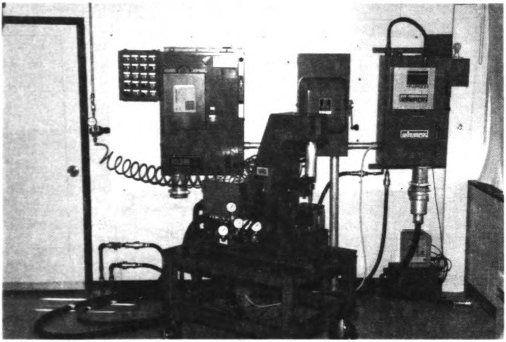

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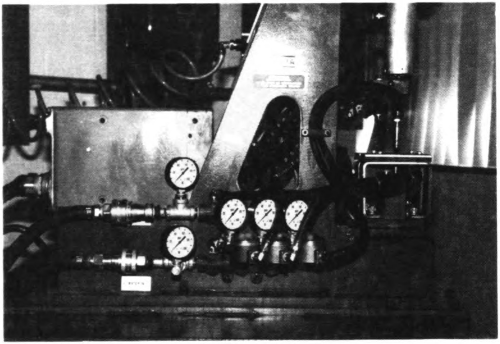

Figure 3.1 Photographs of laboratory spot welder.
a) overall setup, b) closeup view of welder.

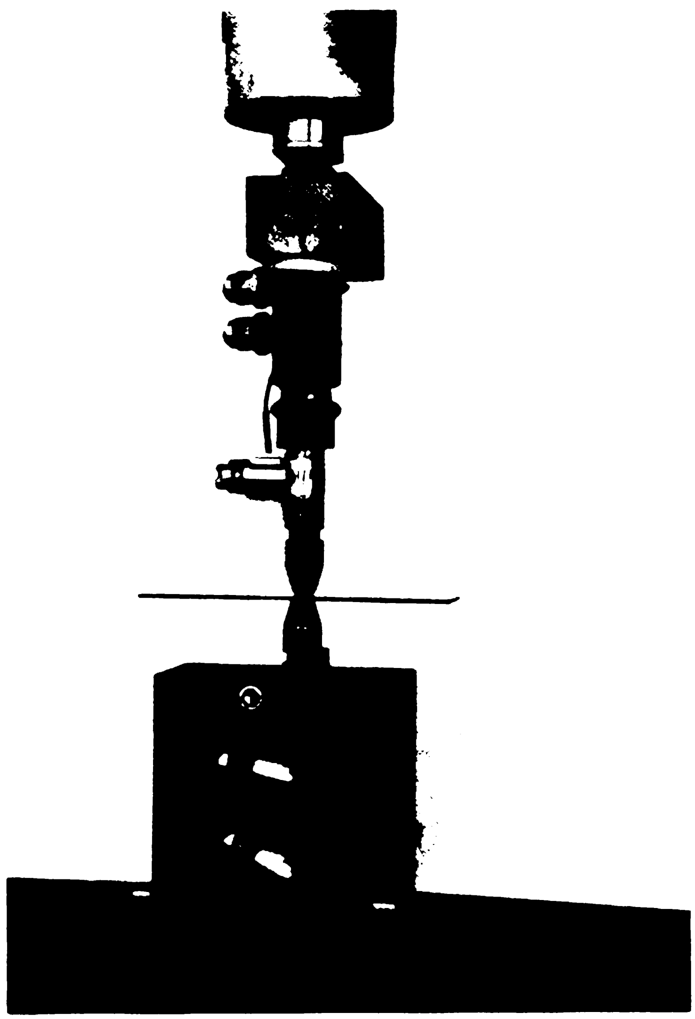

Figure 3.2 Photograph of laboratory welder, showing weld tip arrangement. The lower electrode is stationary. Notice the acoustic emission sensor on the upper electrode shank.

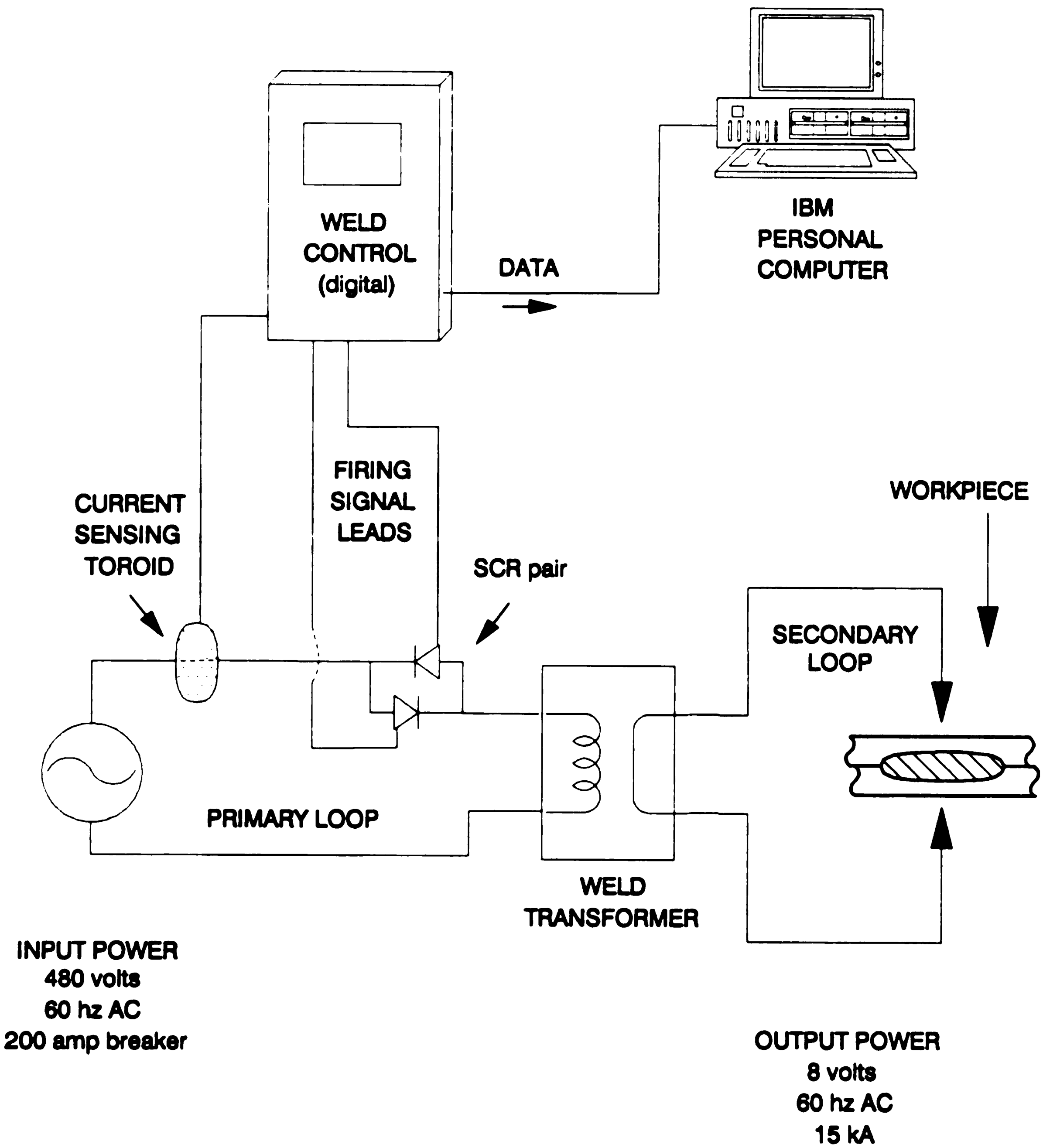

Figure 3.3 Electrical schematic of laboratory welder, with data acquisition computer.

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3-3 Production Apparatus

The primary apparatus used for production data was a hard automation fixture-type welder with a daily production rate of approximately 1000 automobile hoods per day. The weld control and data acquisition system were identical to the laboratory system shown in Figure 3.3.

The material welded was 0.024 inch (0.6 mm) hot dipped galvanized steel welded to 0.080 inch (2.0 mm) hot dipped galvanized steel.

3-4 Weld Microstructure Study Procedure

In order to study weld microstructure, samples were welded of the following steels:

1) Cold Rolled SAE 1005 welded to Quenched SAE 1080 Spring Steel.

2) Cold Rolled SAE 1005 welded to Quenched SAE 1005.

These welds were sectioned in the transverse direction along the weld centerline. They were metallurgically polished and etched. Photomicrographs and microhardness (Tukon) profiles were made.

3-5 Contact Resistance Measurement Procedure

To measure contact resistance before welding, the following procedure was used in order to create nearly ideal conditions:

1) Acetone-washed stainless steel coupons 0.030 x 1.5 x 5 inches (0.75 x 38 x 127 mm).

2) A-nose class II copper electrodes, 0.250 inch (6.35 mm) diameter face.

3) Misalignment eliminated by visual alignment of electrodes.

4) Tips made parallel by clamping lightly on a rotating file.

5) Tip to tip resistance (with no coupon) was 20 - 53 micro ohms.

6) Tips were allowed to impact the coupons as in actual welding.

7) Measurements taken 1 minute after clamping, to stabilize.

8) Five data points were collected at each pressure level.

9) The Biddle micro ohmmeter was used measure resistance.

3-6 Weld Lobe Procedure

The importance of current and time was confirmed using the laboratory welder. Data were gathered to plot a weld lobe of 0.030 inch (0.75 mm) bare steel. A weld lobe is a plot of iso-diameter lines on rectangular coordinates of weld time (ordinate) and weld current (abscissa). The procedure used was MDS-247 (General Motors), Appendix A, with the following modification. In this study, the lobe was plotted to the outer bounds of acceptable weld quality. This means minimum nugget diameter on the low current end, and electrode sticking or over-indentation on the high current end. These two extremes span the domain of acceptable manufacturing.

Experimental parameters were:

Force = 500 pounds (217 kg)
Electrode Diameter = 0.25 inches (6.35 mm)
Minimum Weld Diameter = 0.158 inches (4.0 mm)
Nominal Weld Diameter = 0.197 inches (5.0 mm)
Preconditioning welds = 100
Maximum Weld Indentation = 50%
Coupon Size = 1.5 x 5 x 0.030 inches (38 x 127 x 0.75 mm)
Material = Low carbon uncoated steel, SAE 1005 DQAK
Electrode Material = RWMA Class II copper, (1/2% Cr)
Electrode Geometry = Pointed "A" nose.

3-7 Electrode Misalignment Study

A simple gun translation device was added to the weld cylinder at its base in order to measure the effect of electrode misalignment. This device is shown in Figures 3.4 and 3.5. As the screw is tightened, the entire cylinder and the upper electrode are shifted 0.050 inches (1.27 mm) per revolution. During the contact resistance study involving electrode misalignment, a sample holder was used in order to prevent sheet rotation for highly misaligned conditions. This sample holder, shown in Figure 3.6, was made of

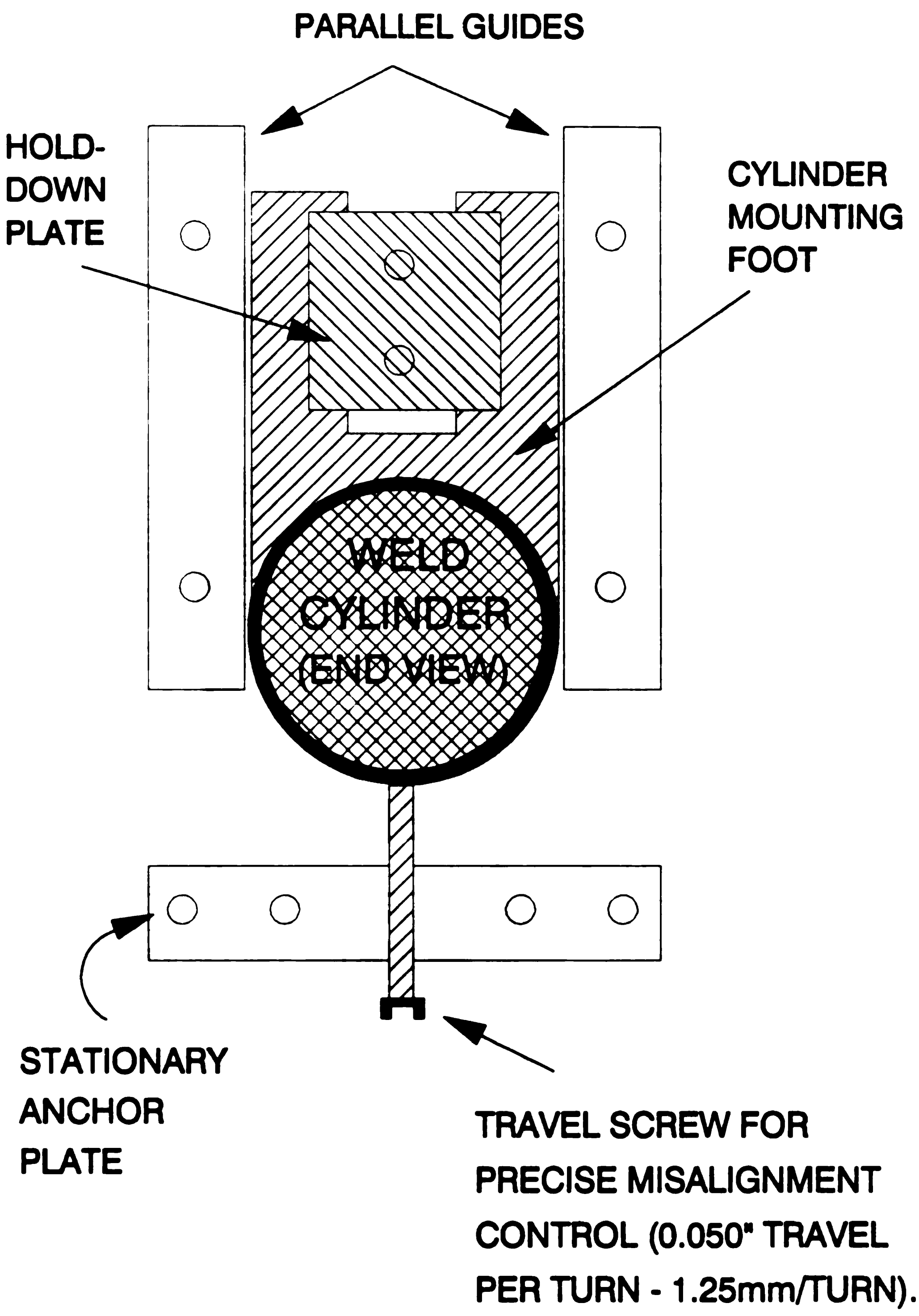

Figure 3.4 Sketch of gun translation device used for misalignment study.

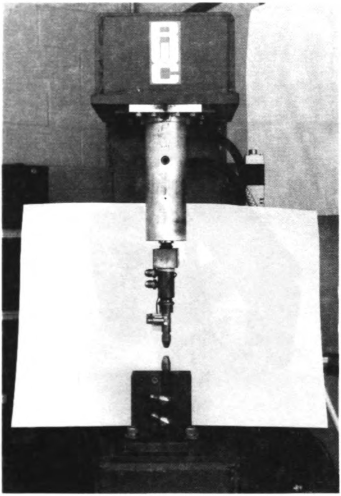

Figure 3.5 Photograph showing gun translation device installed on upper platon.

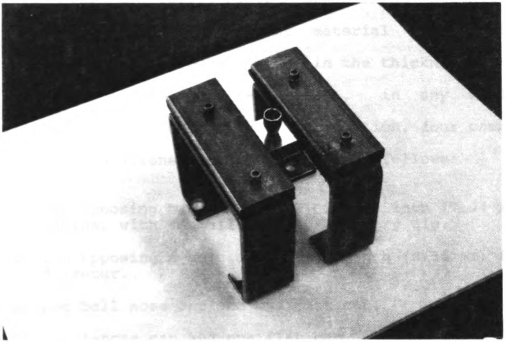

Figure 3.6 Holders used to prevent sample rotation during misalignment study.

non-magnetic stainless steel bar stock 0.25 inches thick by 2 inches wide (6.4 mm x 51 mm), and strips of fabric-reinforced rubber (conveyor belt material).

3-8 Materials and Electrodes Used in Plant Study

A practical setup guide was developed from the plant study. This guide was intended to identify robust weld parameters for a full range of common automotive applications. The nominal plant material was drawing quality aluminum killed (DQAK) steel in the thickness range 0.020 - 0.120 inches (0.5 - 3.0 mm), in any welded combination of bare or galvanized. In addition, four common electrode configurations were represented as follows:

Case A: Two opposing ball-nose caps of 5/16 inch (7.94 mm) radius, with a small flat at the very tip.

Case B: Two opposing A-nose caps, 0.250 inch (6.35 mm) face diameter.

Case C: One ball nose cap and one flat cap.

Case D: One A-nose cap and one flat cap.

4. LABORATORY RESULTS AND DISCUSSION

Laboratory data were gathered concerning the following topics:

1) **Weld microstructure and hardness.**

2) **Contact resistance.**

3) **Weld lobes.**

4) **Effect of mechanical considerations on the weld lobe.**

5) **Process monitoring and feedback control.**

These topics were also discussed in chapter 2, where the work of other researchers was acknowledged.

4-1 Microstructure and Hardness

Samples were welded of the following steel materials:

1) Cold Rolled SAE 1005 welded to Quenched SAE 1080 Spring Steel

2) Cold Rolled SAE 1005 welded to Quenched SAE 1005

Micrographs and Tukon micro hardness profiles were made (Figures 4.1 - 4.4). Hardness data are displayed in Rockwell C and B scales for convenience. Items of note in Figures 4.1 and 4.2 are:

1) Greater nugget penetration into spring steel (1080) due to lower electrical and thermal conductivity.

2) Nugget hardness is nearly constant, indicating a well-mixed melt from a carbon solution standpoint.

3) The HAZ of CR 1005 begins at the edge of the nugget at 26 Rc hardness. It smoothly tapers off to 46 Rb.

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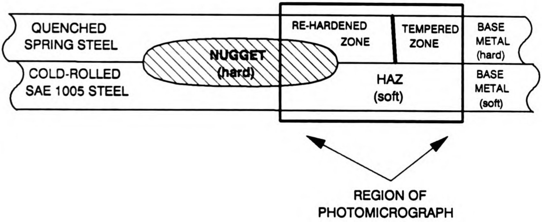

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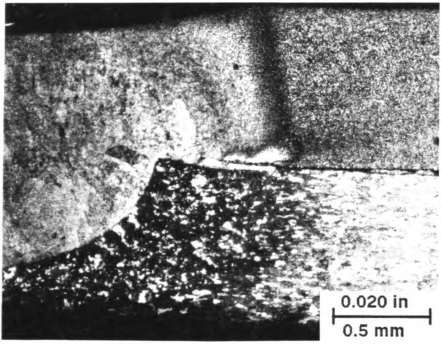


Figure 4.1 Coupon weld of hardened SAE 1080 steel welded to cold rolled SAE 1005, a) sketch, b) photomicrograph.

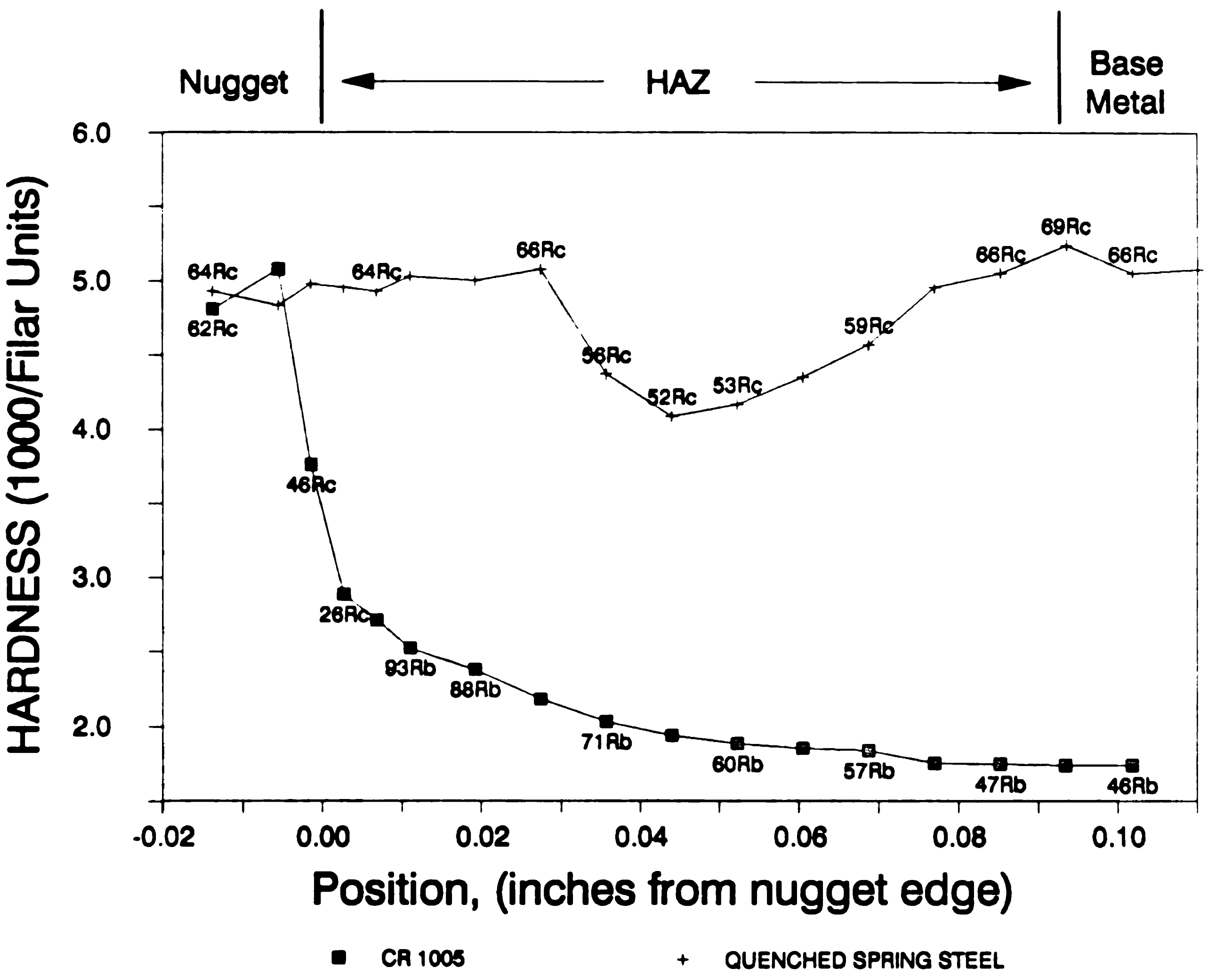


Figure 4.2 Tukon hardness profiles of sample from Figure 4.1.

4) The near HAZ of quenched spring steel consists of a wide re-hardened zone with full hardness equal to nugget hardness. The far HAZ consists of a tempered zone which appears to bottom out at 52 Rc. Outside the HAZ, the base material is fully hard at 66 Rc.

5) The boundaries of the prior austenite growth cells are plainly visible inside the nugget.

Items of note in Figures 4.3 and 4.4 are:

1) Nugget penetration is roughly equal in both materials.

2) Maximum hardness is only 26 Rc due to the low carbon content. Thus even the untempered martensitic nugget would still be quite tough from a brittle fracture standpoint.

3) Hardness gradually fades to 50 Rb for CR 1005, 87 Rb for Quenched 1005.

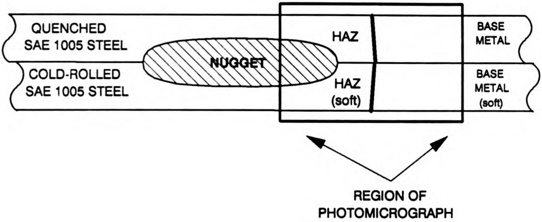
4) Base microstructure in CR 1005 is coldworked ferrite with an imperceptible amount of pearlite and carbides.

5) Base microstructure in quenched 1005 is grain refined equiaxed ferrite with imperceptible amounts of carbon products such as martensite, pearlite and carbides.

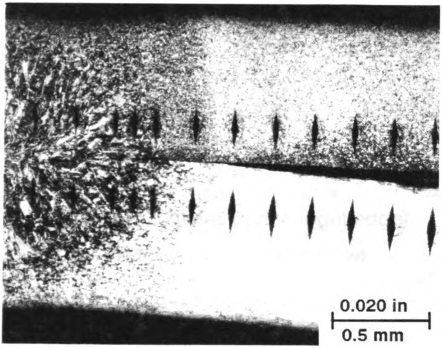
6) HAZ in both materials consists of a partially transformed far HAZ band and a fully transformed near HAZ band.

7) Remains of prior austenite growth cell boundaries are visible inside nugget.

Fortunately, microstructural discrepancies due to material variation (of approved materials) are rarely seen in practice. Therefore, common microstructural discrepancies are usually dependent upon welding conditions. This is good news since, by controlling weld conditions we will also control the microstructure. Thus as welding



a)



b)

Figure 4.3 Coupon weld of heat treated SAE 1005 welded to cold rolled SAE 1005. a) sketch, b) photomicrograph.

HARDNESS (1000/Filar Units)

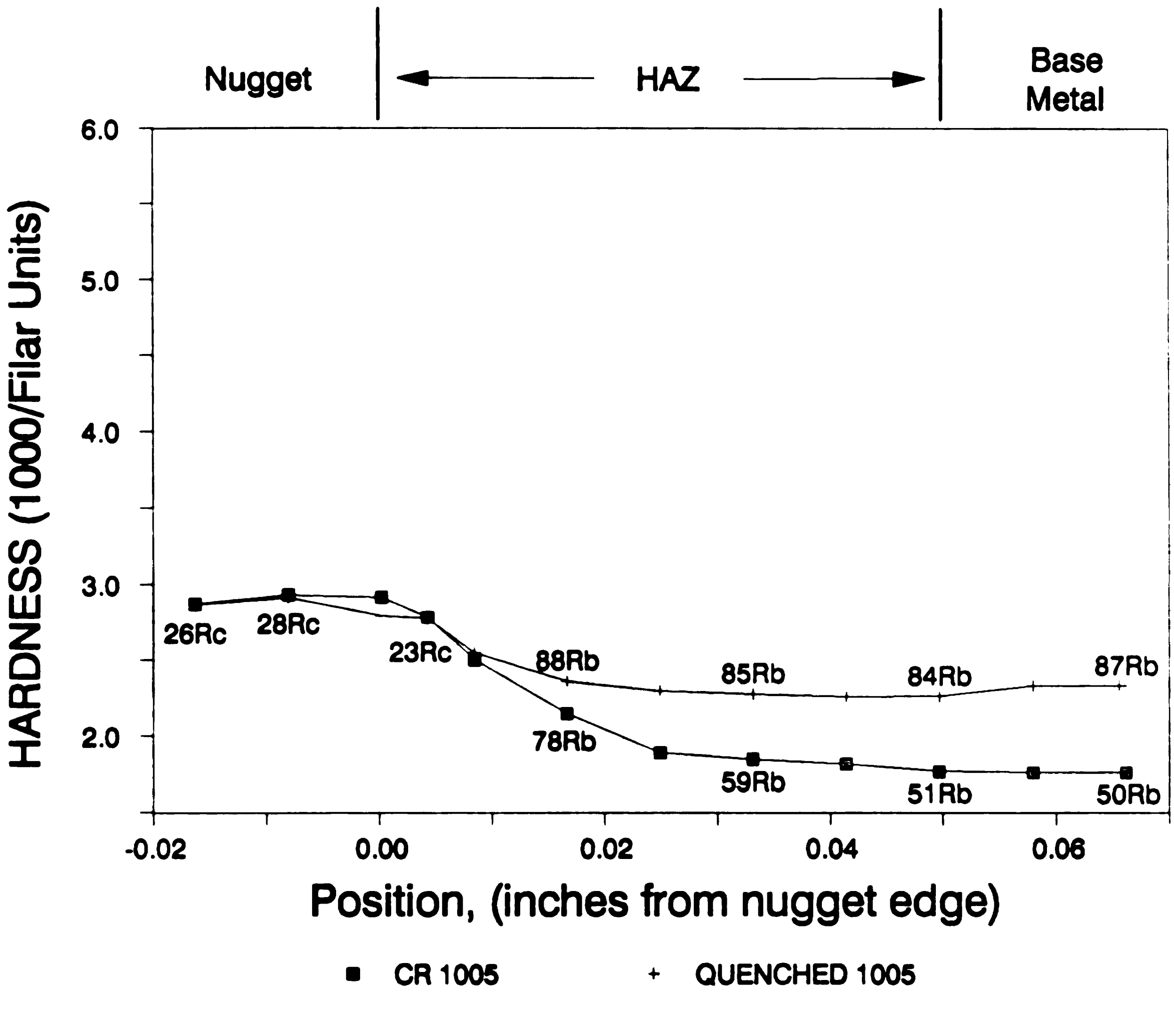


Figure 4.4 Tukon hardness profiles of sample from Figure 4.3.

fabricators, our destiny is in our own hands rather than someone else's. If we can control our process then we will be quite reasonably assured of the narrow boundaries of microstructural variation.

While it remains possible to generate microstructural discrepancies such as cracks and porosity by over welding, even the existence of these discrepancies does not necessarily constitute a structural problem. If the discontinuity is away from the load-bearing edges of the weld, it generally does not weaken the joint. The tolerance of spot welds for metallurgical unsoundness in the weld core is due to compressive cooling stresses around the weld which tend to prevent crack growth. That microstructure is not a significant factor in controlled spot welding of low carbon steel indicates how well-suited the material is for the process.

4-2 Contact Resistance

Figure 4.5 demonstrates the inherent pressure / resistance relationship for 304 stainless steel. The results show two significant conclusions:

1) Contact resistance is a significant function of electrode pressure, especially below 8 ksi.

2) Random variation decreases with increasing pressure, as seen in the range and standard deviation data.

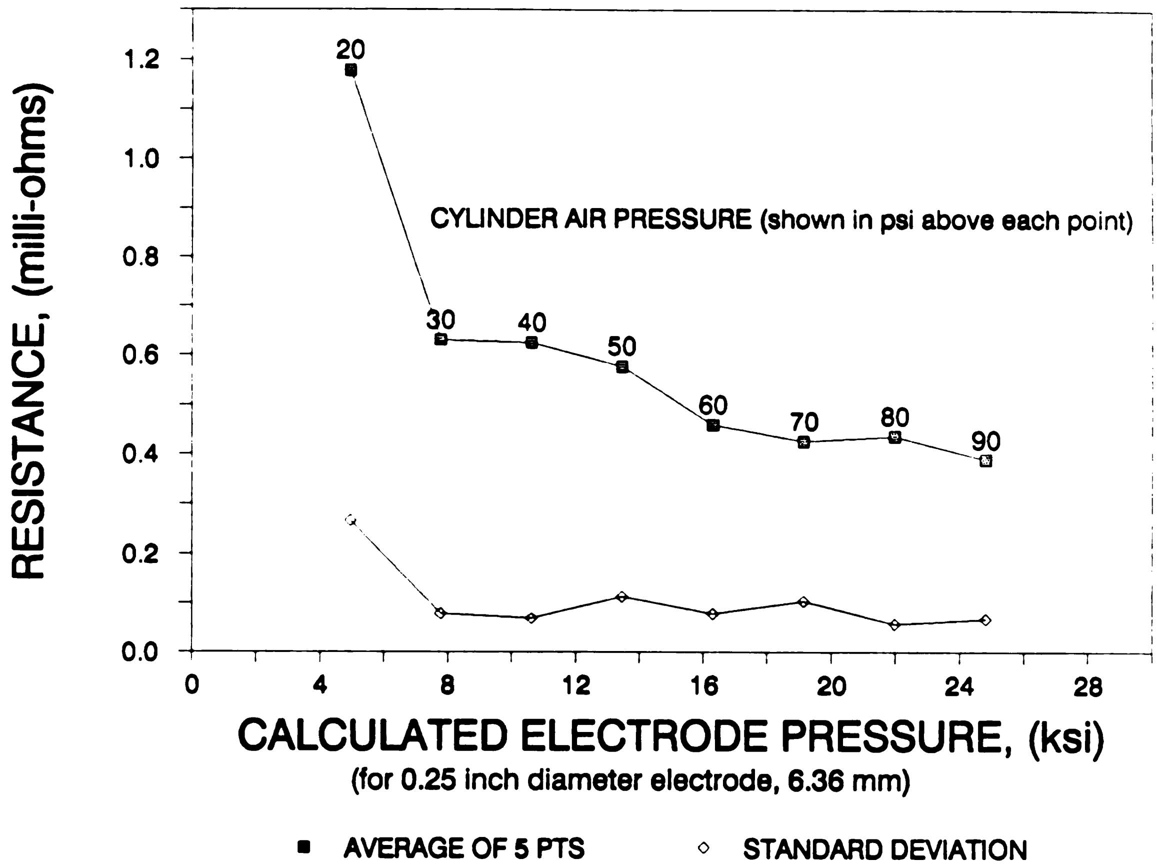


Figure 4.5 Preweld contact resistance versus pressure.

c

e

c

c

t

L

r

t

Se

m

m

The pronounced random variation indicates that operating a stable, production welding process would require either stabilization of contact resistance or minimization of its influence upon weld quality.

Although contact resistance varies widely at the start of spot welding, it is desirable to minimize the impact of this variation upon the final temperature distribution. Later in this study we will address the issue of contact resistance sensitivity.

4-3 Weld Lobe Data

The importance of current and time was confirmed using the laboratory welder. Using the lobe procedure outlined in Section 3-6, a weld lobe was generated for 0.030 inch (0.75 mm) bare steel. The following observations can be readily made from Figure 4.6:

1) The area enclosed by points A, B, C and D is the window of acceptable weld quality for this material under the conditions listed. Within this envelope, moving toward the right produces hotter, larger welds.

2) The curve connecting points A and B is the iso-diameter boundary for a weld diameter of 0.158 inches (4.0 mm). Welds along this boundary typically have a microstructure as in Figure 2.1.

3) Points E and F define the expulsion limit. Welds to the right of this curve consistently expel molten metal as shown in Figure 4.7.

4) The sticking / indentation limit is shown with endpoints C and D. A typical "hot" microstructure along this line is shown in Figure 4.8.

TIME (60 hz cycles)

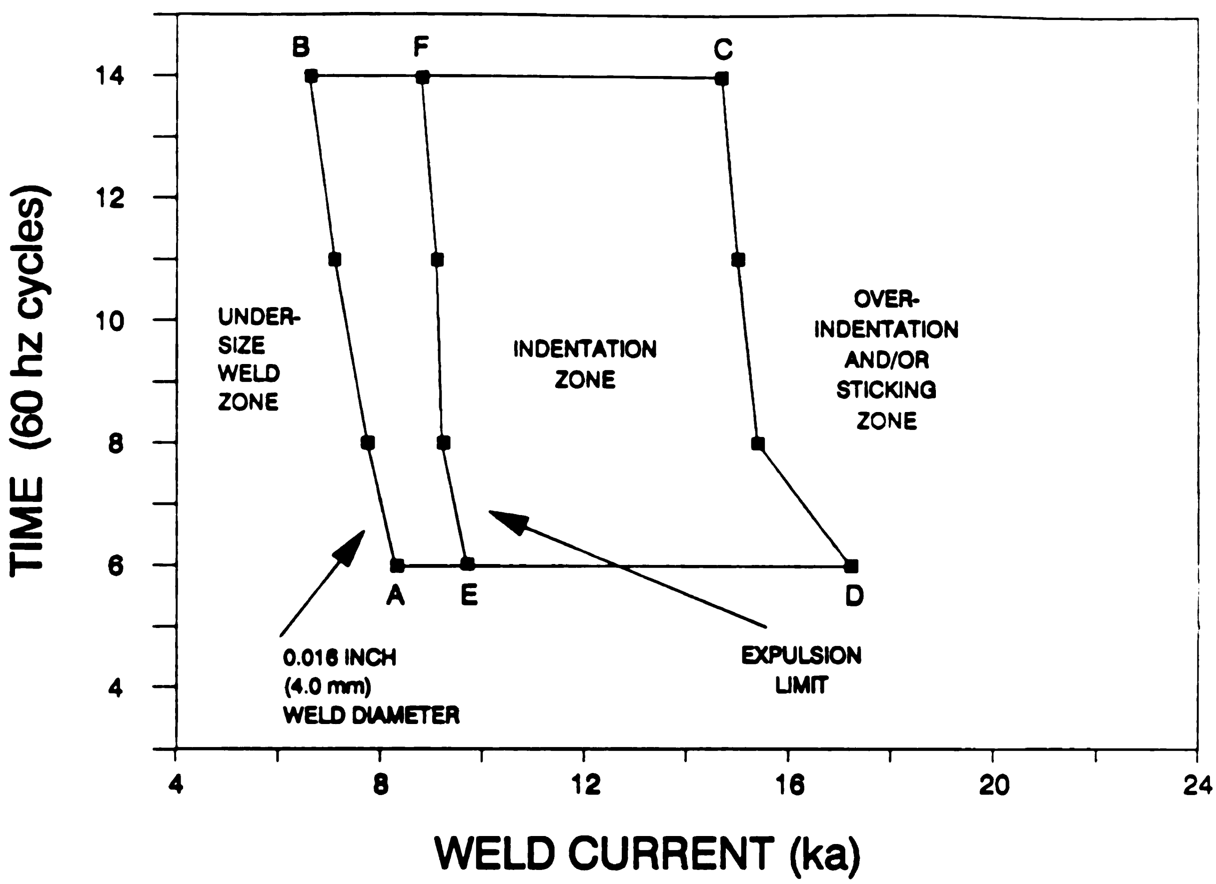


Figure 4.6 Weld lobe number 1 - a normal weld lobe for bare steel, under the conditions stated in Chapter 3. Electrode pressure = 10.2 ksi, (70 MPa). Force = 500 lbs, (217 kg).

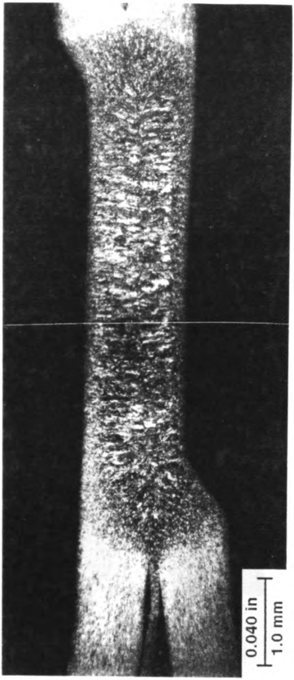


Figure 4.7 Photomacrograph showing the result of moderate expulsion. This is a laboratory weld, of 0.030 inch (0.75 mm) SAE 1005 uncoated steel. Parameters were 8.3 ka for 14 cycles at 500 pounds (217 kg). Notice the electrode indentation, and the expulsion "whisker" extruded from the weld interface, (sample no 544).

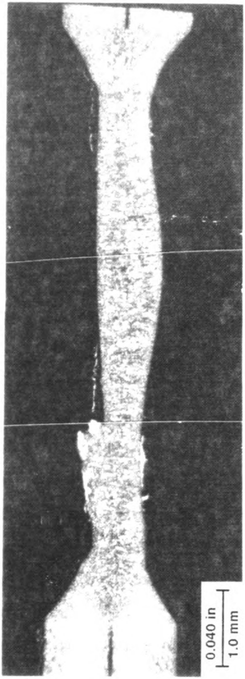


Figure 4.8 Hot weld showing over-indentation. The material and parameters were identical to Figure 4.7, except that current was 15.8 ka. The electrodes stuck to this sample and left behind pieces of copper on the surface, (sample no 333).

5) From Figure 4.6 it is apparent that current is a more influential parameter than time. This conclusion is consistent with Joule's Law, Equation 2.4

4-4 Misalignment and Force Effects

In order to simulate plant conditions concerning weld pressure in the laboratory, it was necessary to consider both electrode force and misalignment, since misalignment influences contact area as discussed in Appendix B. A simple modification to the weld lobe procedure provided adequate data to assess the relative importance of misalignment and force. The gun translation device, which was added to the welder, was shown in Figure 3.4. It provided a controlled means of inducing electrode misalignment. After translating the upper electrode 40% (0.10 inches, 2.54 mm) away from the axis of the lower electrode as shown in Figure 4.9, a new weld lobe was generated, using the same procedure. The results are shown in Figure 4.10.

In comparing lobe 2 with lobe 1, the following conclusions may be drawn:

1) All of the vertical curves are shifted left, by 100 to 1000 amperes.

2) About 80% of lobe 1 is common to both lobes. Only the rightmost 20% of lobe 1 is not shared by lobe 2. This means that if the process is initially set to the expulsion limit according to lobe 1, and then the electrodes should become misaligned by 40%, then the weld will still be acceptable according to lobe 2. Conversely, if the process begins with misaligned tips and is set to operate near the low current limit of lobe 2, then by

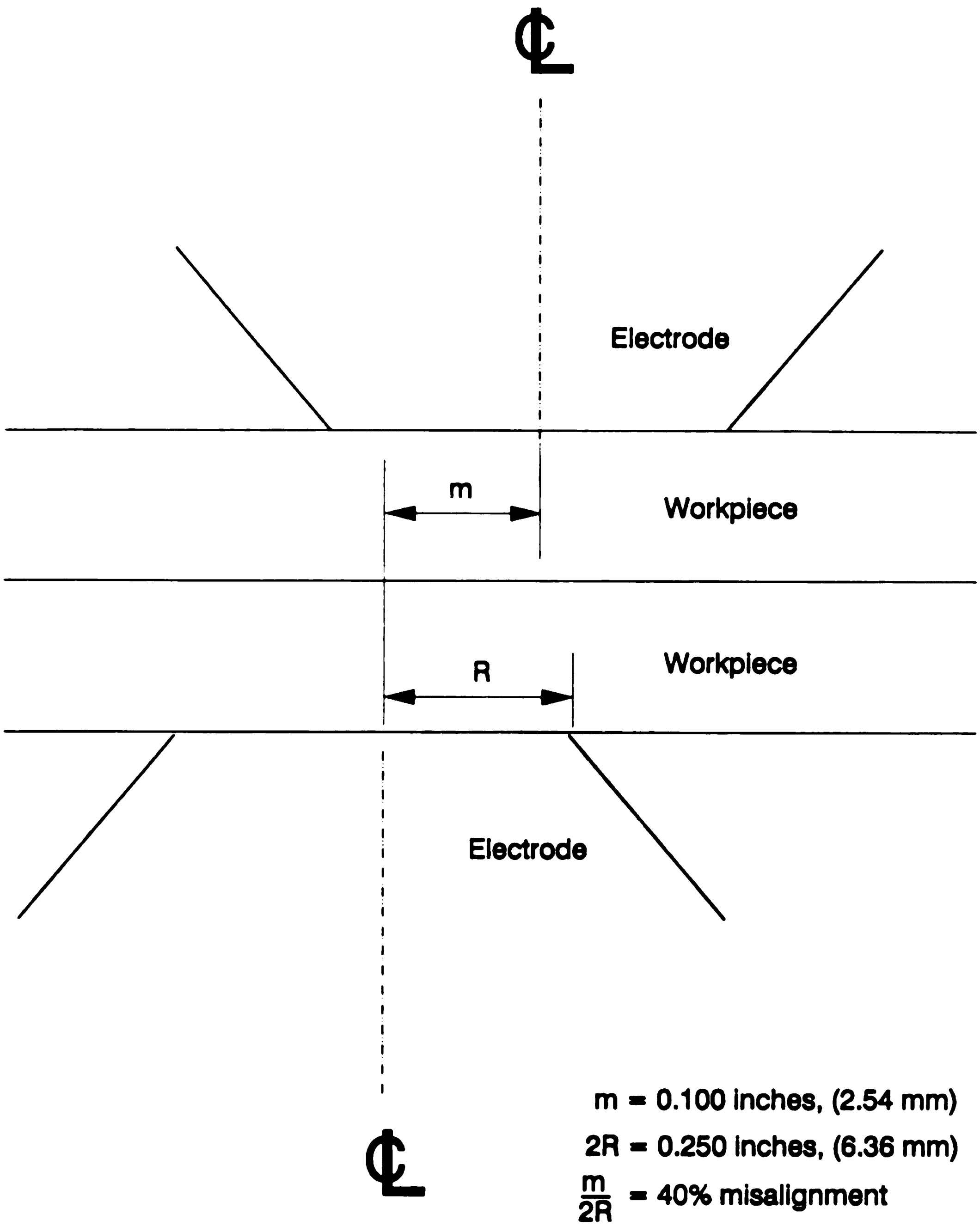


Figure 4.9 Schematic of the experimentally misaligned condition.

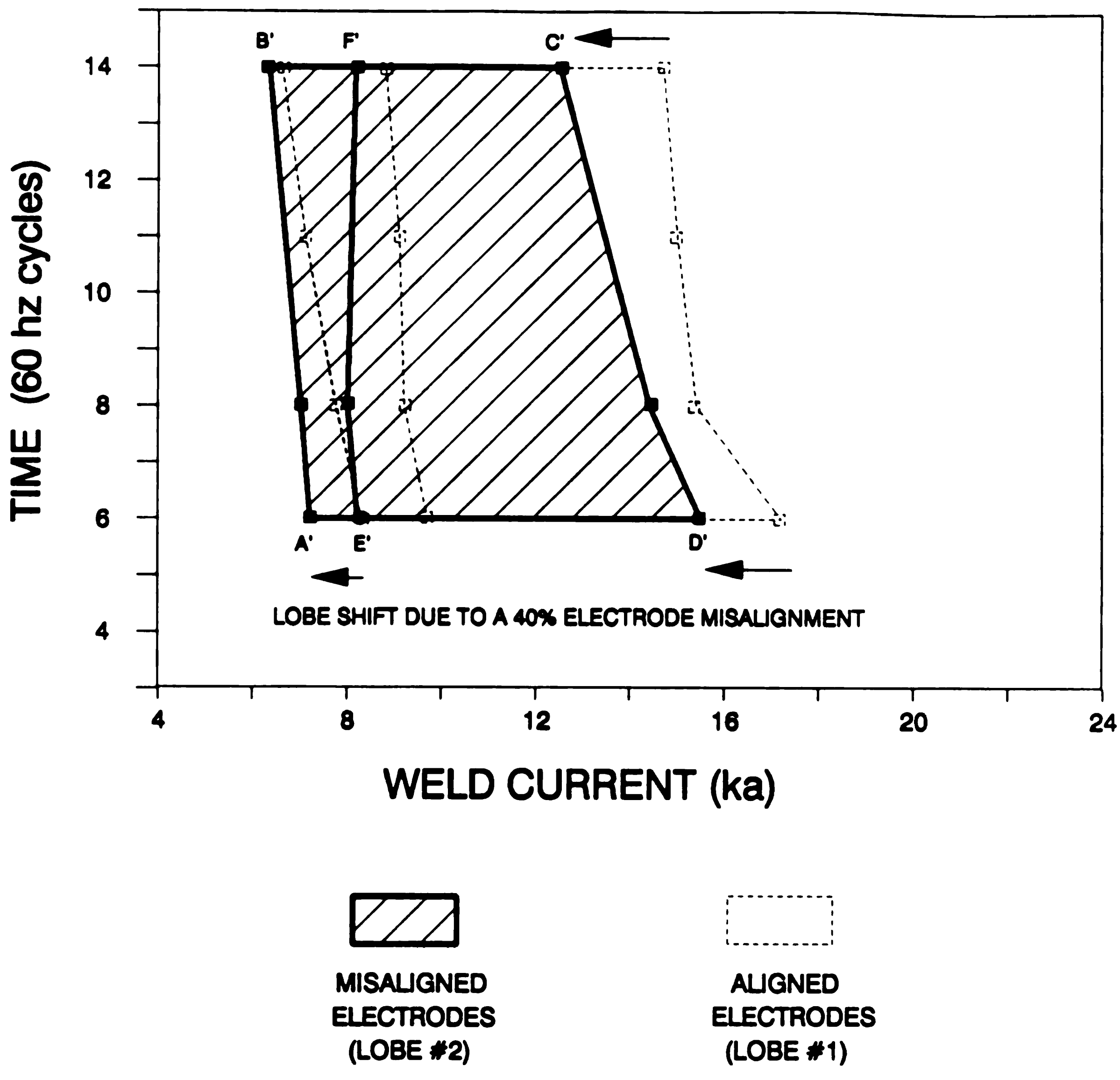


Figure 4.10 Weld lobe number 2 - 40% misaligned electrodes. Notice the leftward lobe shift caused by the misalignment. Still, lobes 1 and 2 share roughly an 80% overlap, when the upper limit is taken to the sticking/indentation point.

aligning the electrodes, the process will begin producing undersize welds. However, in either lobe 1 or 2, if the process is initialized at the expulsion limit then, regardless whether the electrodes become more or less aligned, the weld size should remain adequate.

4-4-1 Misalignment Effect

Ordinarily, under laboratory conditions, misalignment would be seen as a major variable. This is because within the spot weld research community, the upper current limit of the weld lobe has traditionally been the expulsion limit (Appendix A). Treating expulsion as the upper limit, lobes 1 and 2 do not exhibit enough overlap before and after misalignment. Thus, under the no expulsion rule, misalignment would not pass as a minor variable. However, since misalignment is difficult to control in manufacturing, we learned from this study how to desensitize the process, by disregarding the no expulsion rule.

Misalignment has been shown to be a minor variable, when it is less than 40% of the electrode diameter. For on the one hand, misalignment increases local pressure, which tends to reduce visual weld heat. On the other hand, misalignment also increases current density by an equal amount. These two changes nearly cancel each other, and the resulting lobe shift is relatively small. The trick which allows misalignment to be treated as a minor variable is to set the process to operate near the expulsion limit. In order to center the process at expulsion, we must redefine the upper limit of the weld lobe to include the hot welds, out to the point of over-indentation and/or electrode sticking. Then if some misalignment should occur, the process will still make acceptable welds, as per Figure 4.7, albeit with more expulsion.

4-4-2 Force Effect

A 40% misalignment reduces electrode contact area by 50% (for the mathematical solution to the common area of winking circles, see Appendix B). Since halving the welding area essentially doubles current density and pressure, the data of Figure 4.10 was replotted in Figure 4.11 in terms of average current density. Even though mechanical and electrical considerations imposed by the sheets have an impact on actual pressure and current density, these mechanics considerations are ignored here. Under the assumption that these considerations are negligible, Figure 4.11 simulates the effect of doubling the weld force.

Force has been shown to exhibit a strong influence upon the size and position of the weld lobe. As force increases, the weld lobe increases in width and moves to the right (compare lobes 1 and 3). Thus one may conclude that force is an unavoidable major variable. However, force is a very acceptable key variable from a practical point of view,

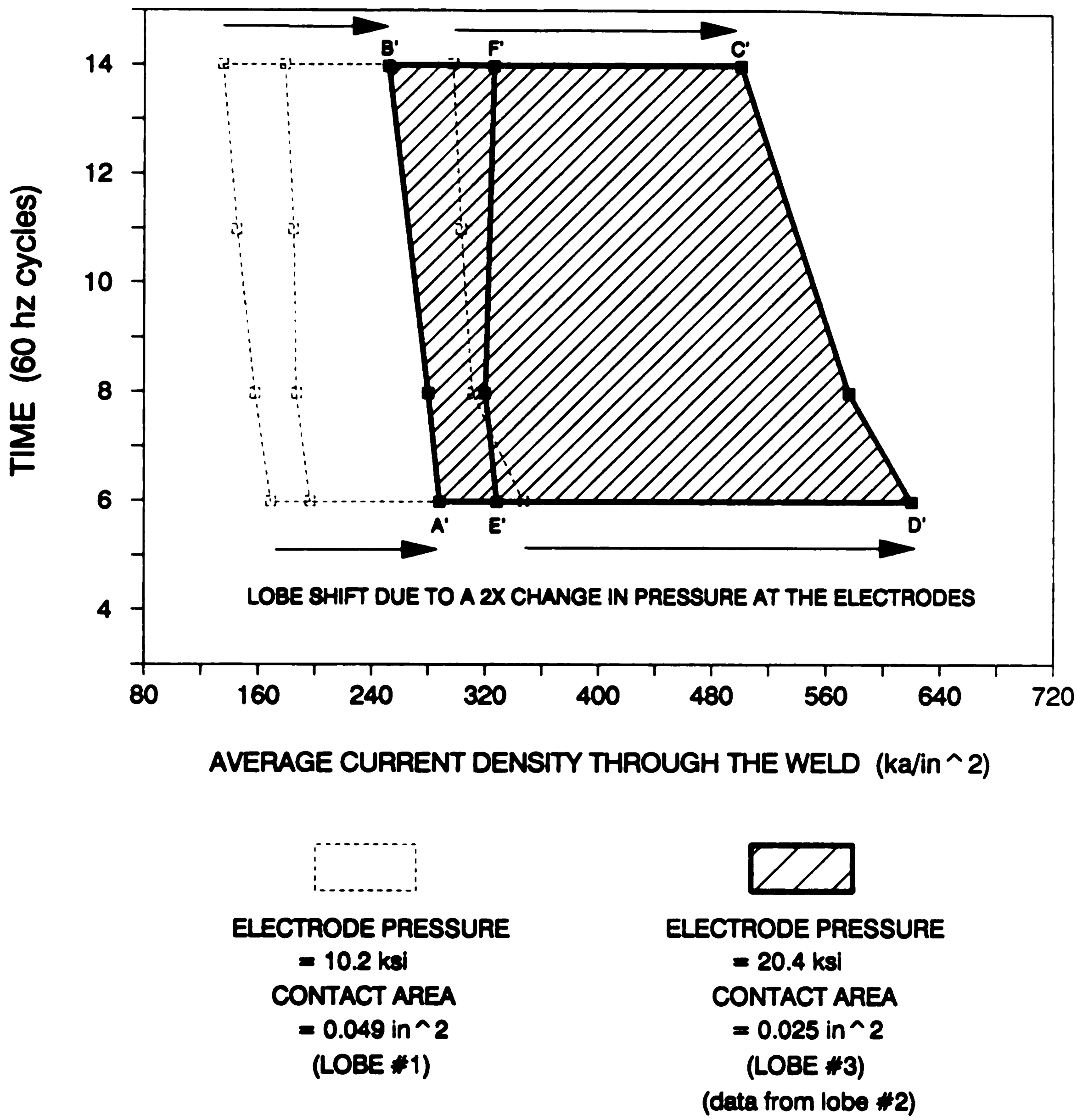


Figure 4.11 Data from lobes 1 and 2, showing average current density as the abscissa rather than current. Force = 500 lb (217 kg) in both lobes. These data show the significant effect of changing the average pressure at the weld. These data approximate the magnitude of lobe shift that would have been measured by a 2x increase in weld force, for aligned electrodes.

since it can be easily set, monitored, and maintained at the process. Remember, the stated goal in this study was to establish weld parameters which define a stable, robust process with as few key variables as possible.

4-5 Process Monitoring and Feedback Techniques

As a matter of common practice in industry, current steppers are used to compensate for tip wear according to a programmed boost schedule. Steppers are quite reliable. However, even with their use, there can still be a need for compensation of other types of process variation. Conventional steppers do not adjust for many significant variables such as current, tip alignment, cable wear, material and coating. One of the goals of this study was to identify static parametric regimes where the deleterious impact of process variables is minimal. Assuming that this can be done, there may still be practical situations where the magnitude of process variation exceeds that allowed by even the most robust static control scheme. In that case, one must either minimize the offending process variation, or compensate dynamically, so as to remain inside of a "moving" weld lobe.

4-5-1 Power Factor Drop (PFD)

Certain weld controls can empirically measure the power factor each half cycle. In this study a Medar Legend (tm) weld control was used with a data acquisition system, as described in Section 3. Power factor data for bare low carbon steel are shown in Figure 4.12. On first inspection, the power factor curve appears to resemble the dynamic resistance curve shown in Figure 2.15. The reason for this resemblance lies in the definition of power factor. Most commonly, power factor is defined as:

$$P.F. = \cos(\Phi) \qquad [\ 4.1\ ]$$

where Φ is the angle between voltage and current. This equation is true for sinusoidal waveforms. But in resistance welding, part of the sinusoidal wave is removed in order to regulate the weld current. In any case, a more appropriate definition is used to correlate power factor and resistance (54). That is:

$$P.F. = \frac{R}{\sqrt{R^2 + (X_L)^2}} \qquad [\ 4.2\ ]$$

where R = total circuit resistance, and X_L = inductive reactance of the circuit. Since X_L is mainly dependent upon

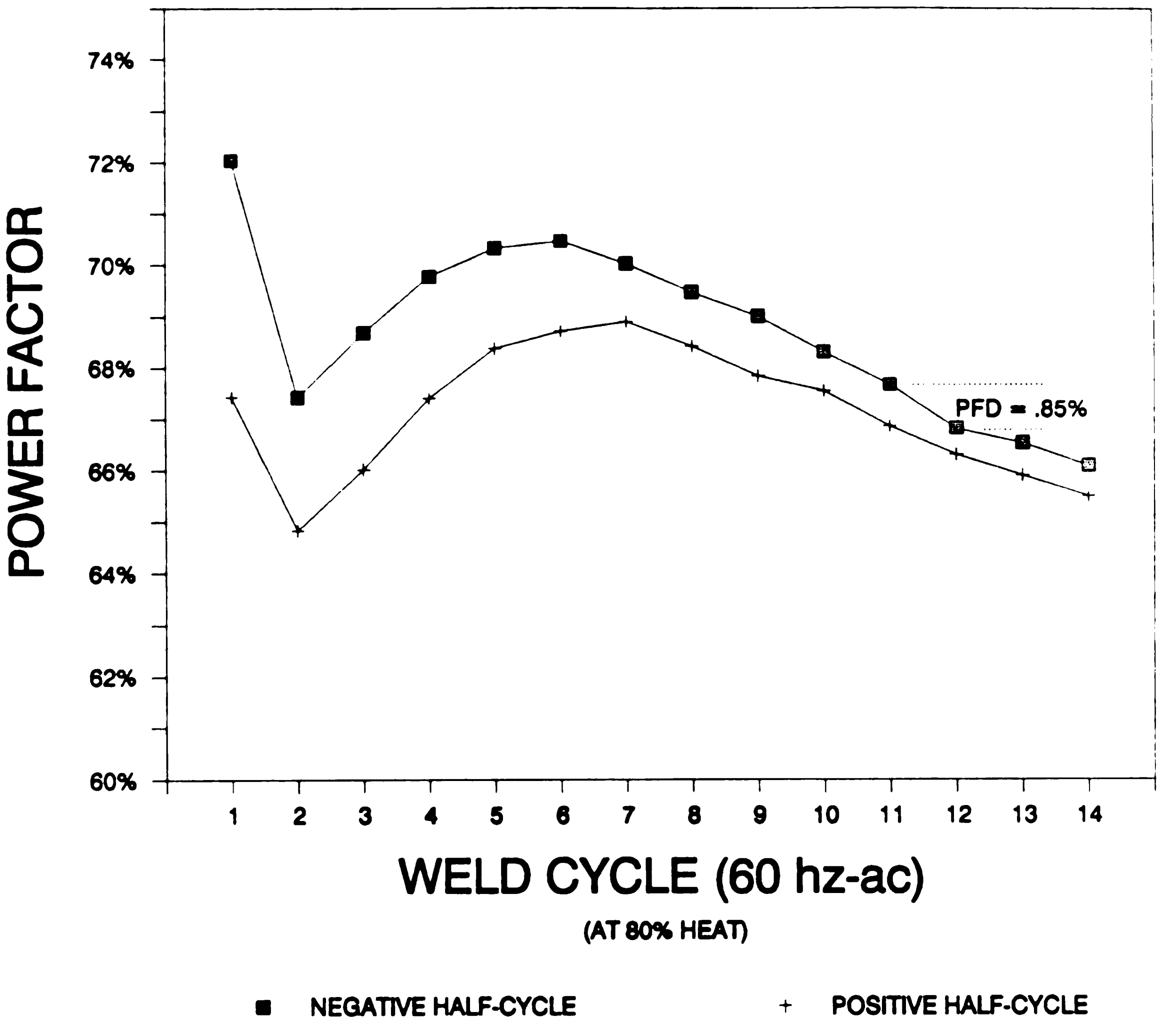


Figure 4.12 Dynamic power factor for a laboratory weld on SAE 1005 bare steel, 0.030 inches (0.75 mm). This weld did not have expulsion. The largest one-cycle drop in power factor near the end of the weld (when expulsion normally occurs), was 0.85%.

geometric and magnetic effects in the transformer and secondary loop which should normally not change during welding, it may be treated as a constant of the weld setup. Therefore, the most dynamic term in Equation 4.2 is resistance, and more specifically, the resistance of the weld.

Figure 4.13 shows Equation 4.2 for the practical range of resistance spot welding. And from Figure 4.12 we see that the laboratory welder operated in the range 61% to 72% power factor. Over small ranges such as this, a tangent on the curve in Figure 4.13 indicates only a small amount of nonlinearity between power factor and resistance. In addition, by comparing Figures 4.12 and 4.14, notice how expulsion produces an instantaneous drop in power factor.

There are two significant conclusions to state here:

1) As long as impedance is constant, power factor can be used to indirectly measure small resistance changes. This is important because of the ease with which power factor is measured, without the use of secondary leads or sensors.

2) The power factor drop (PFD) at expulsion essentially measures the resistance drop of Nagel and Lee (36), and therefore may be used as expulsion detection signal.

The second conclusion is very significant because it improves the economic opportunity for feedback control.

By having the weld control provide power factor data as a by-product of its own internal algorithms (54), it is essentially "free data". This data stream may be processed after each weld. Current adjustments can be made

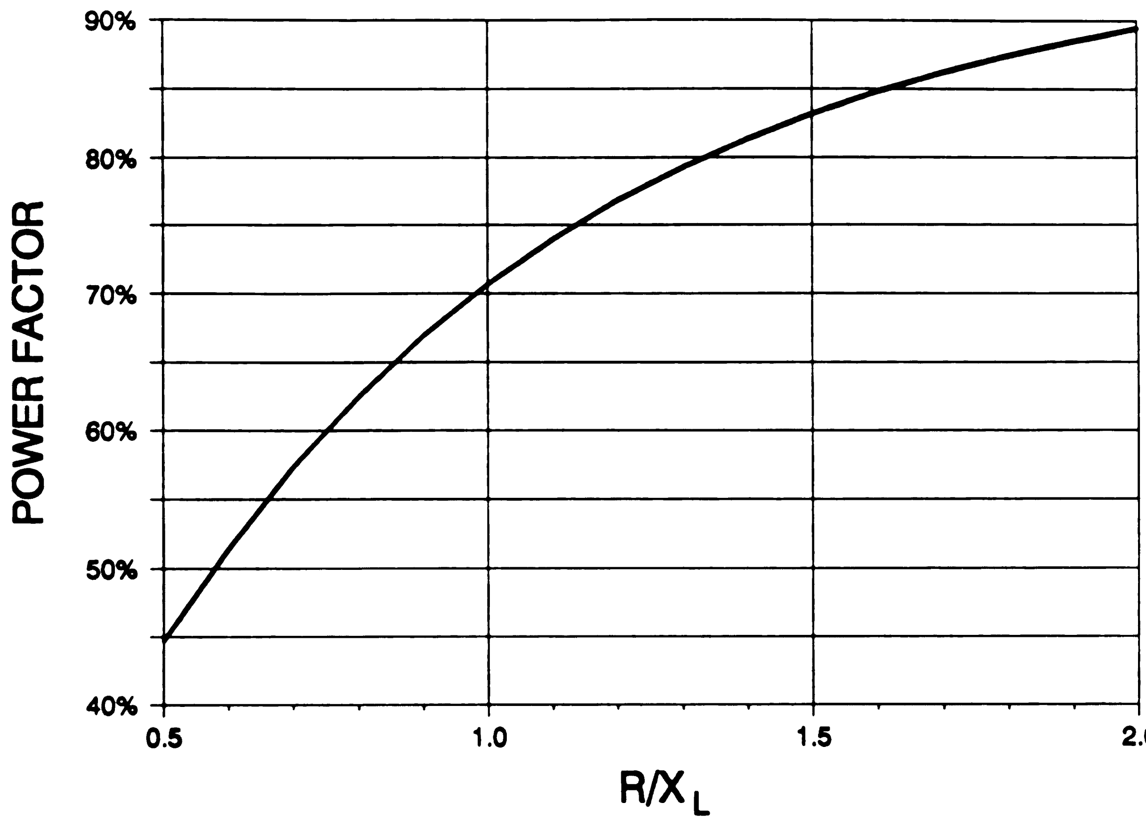


Figure 4.13 Theoretical relationship between power factor and R/X_L ratio. Tangents along short sections of this curve may be used to linearly approximate this relationship. In addition, since X_L is largely constant during welding, it explains why the power factor curve mirrors the resistance curve during welding.

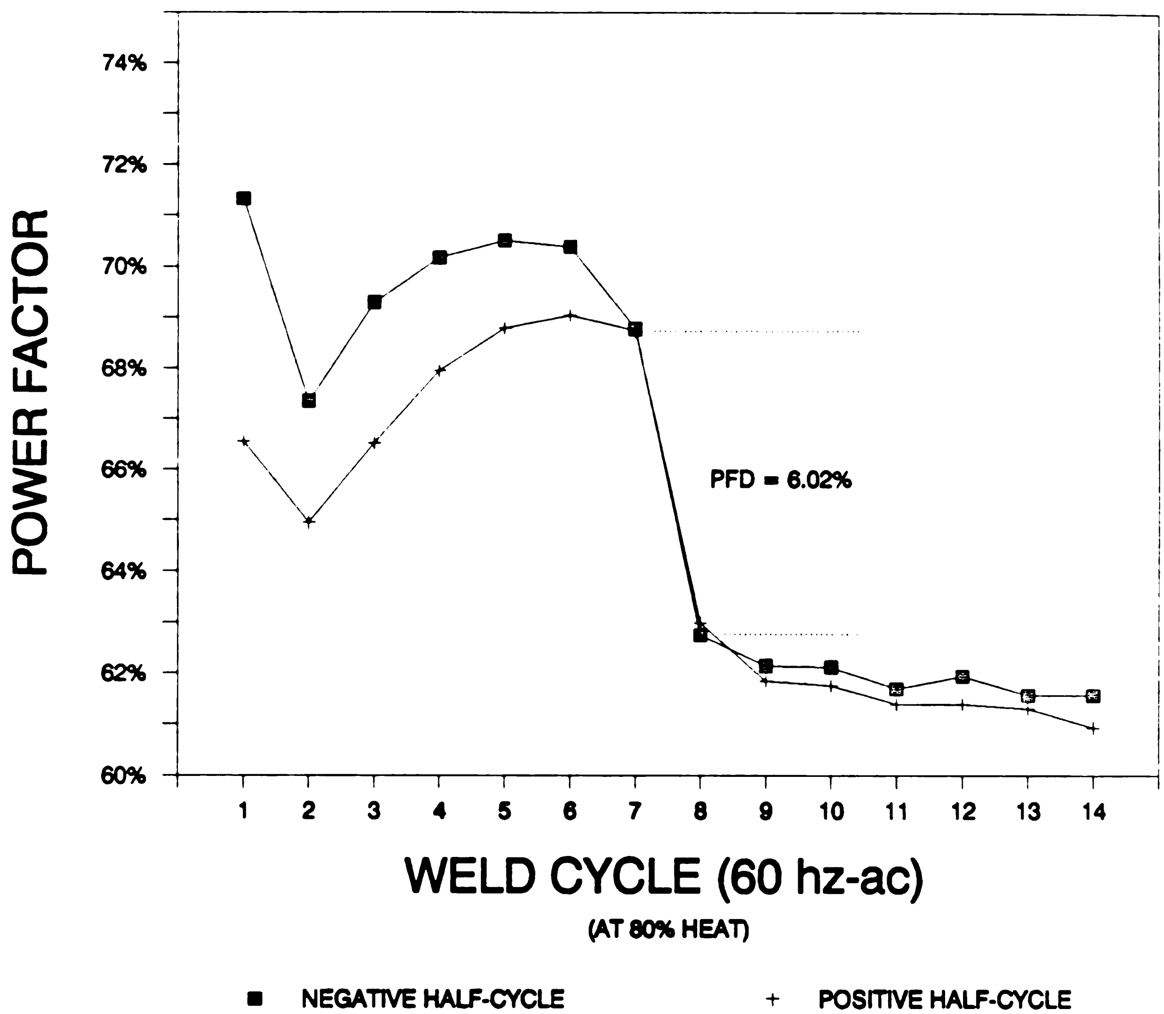


Figure 4.14 Dynamic power factor for a laboratory weld on SAE 1005 bare steel, 0.030 inches (0.75 mm). This weld had visible expulsion. The largest one-cycle drop in power factor near the end of the weld is 6.02%.

automatically, keeping the process operating as closely as possible to the expulsion limit. Fortunately, as discussed in Section 4-4, probably the most robust way to operate the process is at the expulsion limit, since it is close to the center of the weld lobe. Whereas a conventional stepper blindly compensates for tip wear alone, a dynamic stepper could compensate for any variable, including tip wear. The data presented in this report show that this system works, both in the laboratory and plant environments. Its practical limitations and advantages are explained in Section 5-6-1.

The power factor signal is processed for feedback as shown in Figure 3.3. First, power factor is internally measured and stored for each half cycle of current. These numbers are available for data collection at the printer port after each weld is complete. Table 4.1 shows an example of this postweld output. Next, the control identifies the largest decrease in power factor from one cycle to the next. Each polarity is considered separately, and the larger of the two results is reported as the PFD (power factor drop). PFD is also directly available at the printer port after each weld as shown in Table 4.2.

Next, the PFD is compared to a threshold (say 1%). If PFD is equal to or greater than the threshold, the control concludes that expulsion has occurred, as in Figure 4.14. Likewise, PFD less than the threshold means that expulsion

Table 4.1 Example of cycle by cycle output produced by the weld control. Each line represents one cycle during the weld.

CYCLE	VOLT	AMPS	PF+	PF-	%HEAT
1	475	113	6442	6551	40
2	474	104	6619	6818	40
3	474	104	6755	6920	40
4	474	103	6848	6963	40
5	474	100	6898	6987	40
6	475	107	6885	6415	40
7	474	115	6320	6294	40
8	474	109	6278	6321	40

Table 4.2 Example of end of weld summary output produced by the weld control. Each line represents one weld.

WELD	AMPS	VOLTS	%HEAT	PFD
1	63	476	80	00.85
2	66	476	80	06.02
3	66	476	80	05.57
4	64	476	80	01.07
5	64	475	80	00.98
6	64	475	80	00.93
7	64	475	80	01.31
8	64	476	80	00.92

did not occur, as in Figure 4.12.

For signal processing, there are counters which keep a running tally of expulsion welds and no expulsion welds. The counters are programmed to trigger a 1% heat change at a preset number of welds. If there are not enough expulsion welds the current is automatically increased. Conversely, if there are too many expulsion welds the current is decreased. After every automatic current change, both counters are reset and the tallying process restarts at the new heat setting. The flow diagram for this process is shown in Figure 4.15.

Laboratory correlation between PFD and visual expulsion was quite good when welding bare steel (Figure 4.16). Laboratory data for galvanized steel were not gathered however, plant data for galvanized steel is provided in Section 5-6-1.

4-5-2 Acoustic Emission (AE)

In this study, acoustic emission (AE) was considered in parallel along with PFD monitoring and visual expulsion monitoring. The PAC - 2250 system was attached to the lab welder for evaluation. It was set up and calibrated by the manufacturer, Physical Acoustics Corp. In initial testing, good correlation between acoustic emission energy and visual expulsion could not be obtained and the concept was dropped in favor of PFD monitoring, for the following reasons:

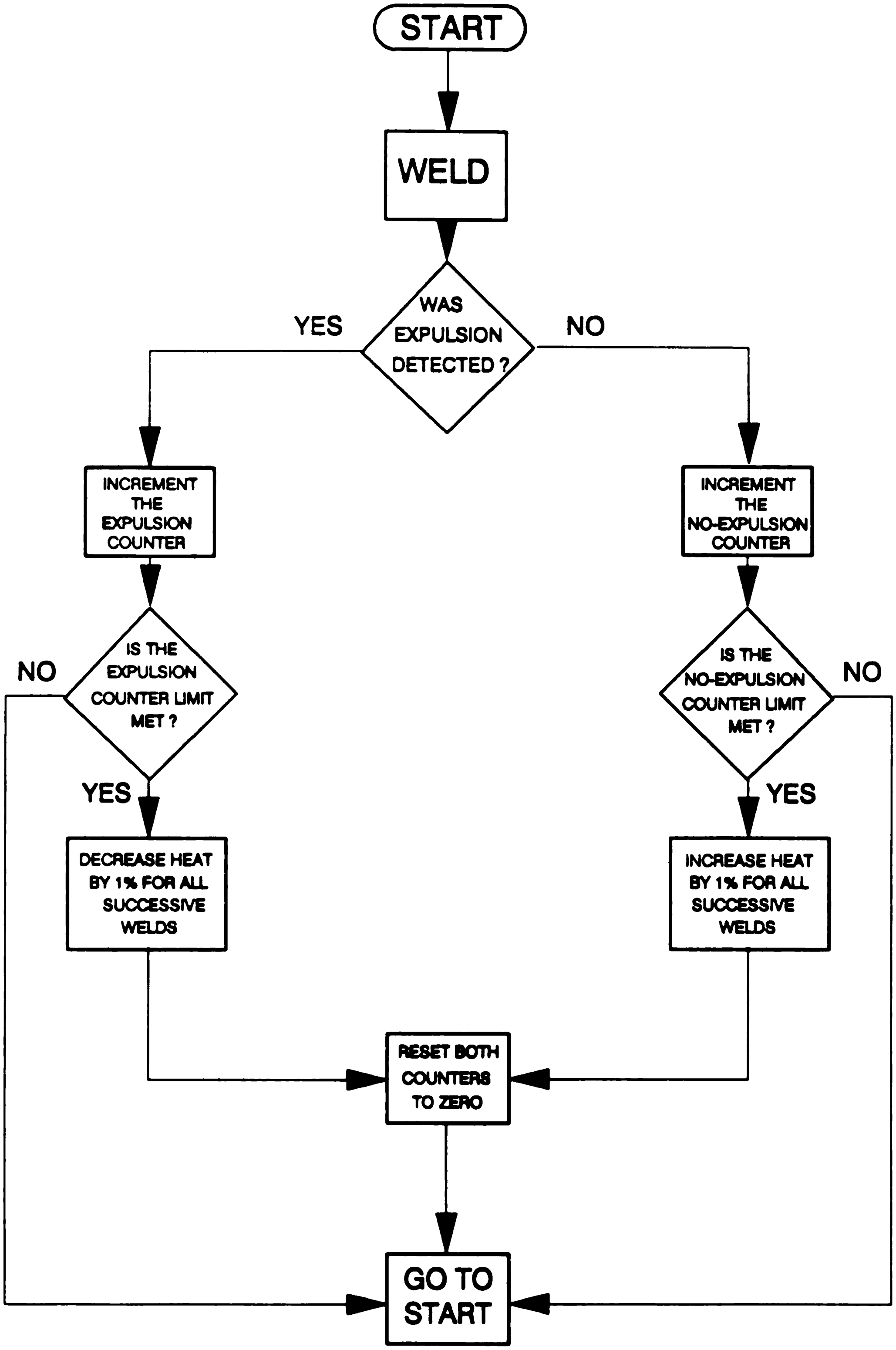


Figure 4.15 Logic flow diagram for automatic feedback stepping by the power factor drop (PFD) technique.

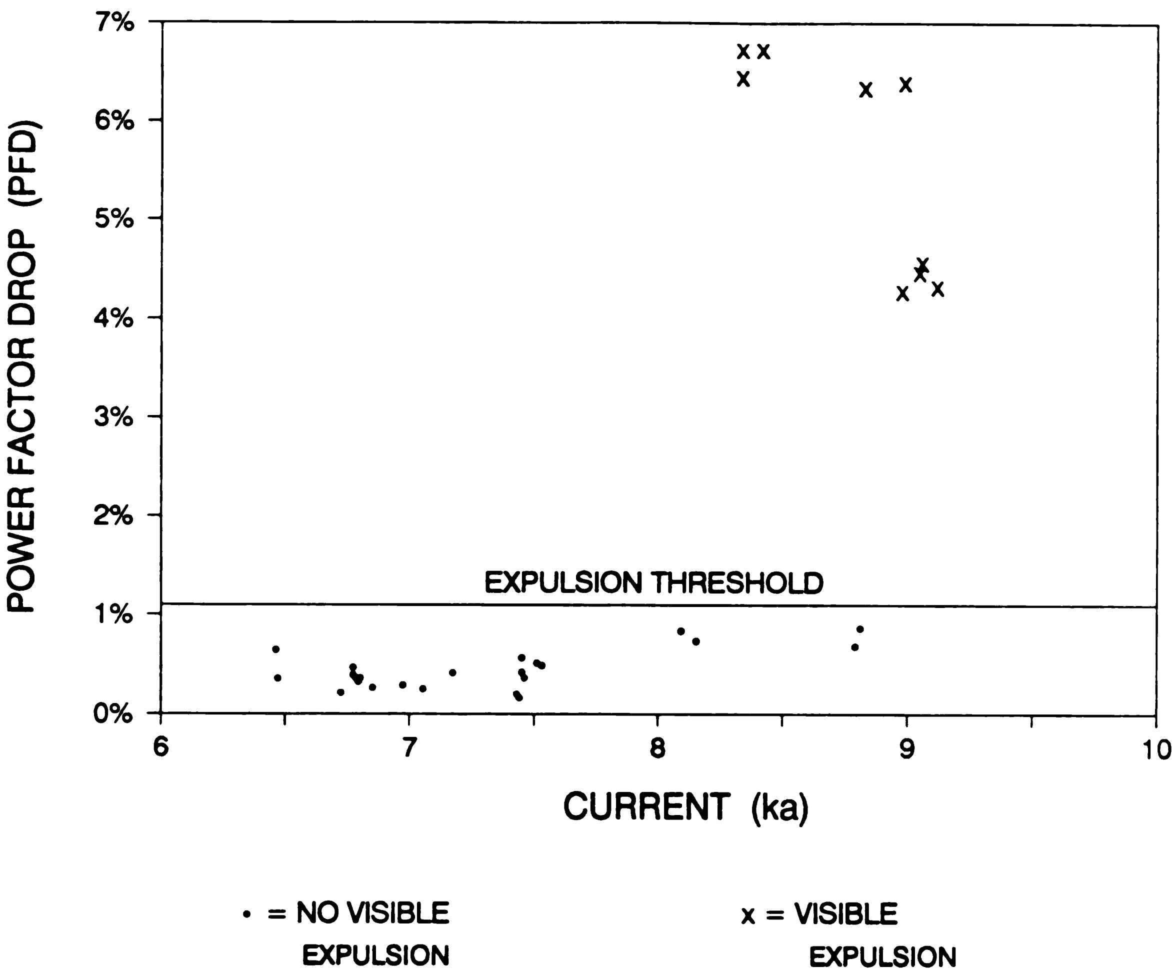


Figure 4.16 Correlation data between PFD signal and visual expulsion. These 32 data points were from 32 consecutive welds made under the conditions stated in Chapter 3.

1) PFD showed good statistical correlation with expulsion as per Figure 4.16.

2) PFD measurement is "free" data since it needs no sensors in the secondary loop, and adds no fundamental cost to the welding equipment.

While acoustic emission remains an interesting topic for resistance welding, it did not appear to be a viable solution to the feedback problem at this time in light of newer, competing technology.

4-5-3 Loop Efficiency

As a result of this study a simple method of automatically detecting significant process change was invented. Since there are measures of energy efficiency in the basic electrical data already resident in weld controls, a control can be inexpensively programmed to monitor the energy efficiency of the welding circuit. The controls used for data acquisition were altered to detect wear on the equipment, when that wear resulted in a change in the electrical load.

To understand this method, consider the welder for a moment simply as a current supply, programmable in increments of % heat, % current or amps. One could measure the relationship between the programmed (or expected) output and the actual output. In a well-behaved process, as the user calls for more output, the machine should respond by producing more current.

In the % heat system, as a consequence of Joule's Law, Equation 2.4, current should follow heat according to the formula:

$$I^2 = K \cdot \%H \qquad [\ 4.3\ ]$$

In this expression, I is either primary or secondary current, %H is the programmed value of percent heat, and K is a proportionality constant which lumps together the total load (inductive and resistive). K has been referred to as the K-factor. Rearranging for the K-factor,

$$K = \frac{I^n}{\%H} \qquad [\ 4.4\ ]$$

shown with the proportioning exponent n, which compensates for nonlinearity. Ideally, n = 2 and Joule's Law is obeyed. However, actual measured n values in this study ranged from 1.3 to 1.8 (see Figures 4.17 and 4.18). It is postulated that n values are not 2 because of measurement inaccuracies in the control, especially concerning how I(rms) and %H are determined.

In any case, K-factor is a process constant which reflects the empirical electrical efficiency of the welding circuit. It is useful for process control since it can be used to detect changes in the welder due to fundamental process changes, while remaining relatively insensitive to

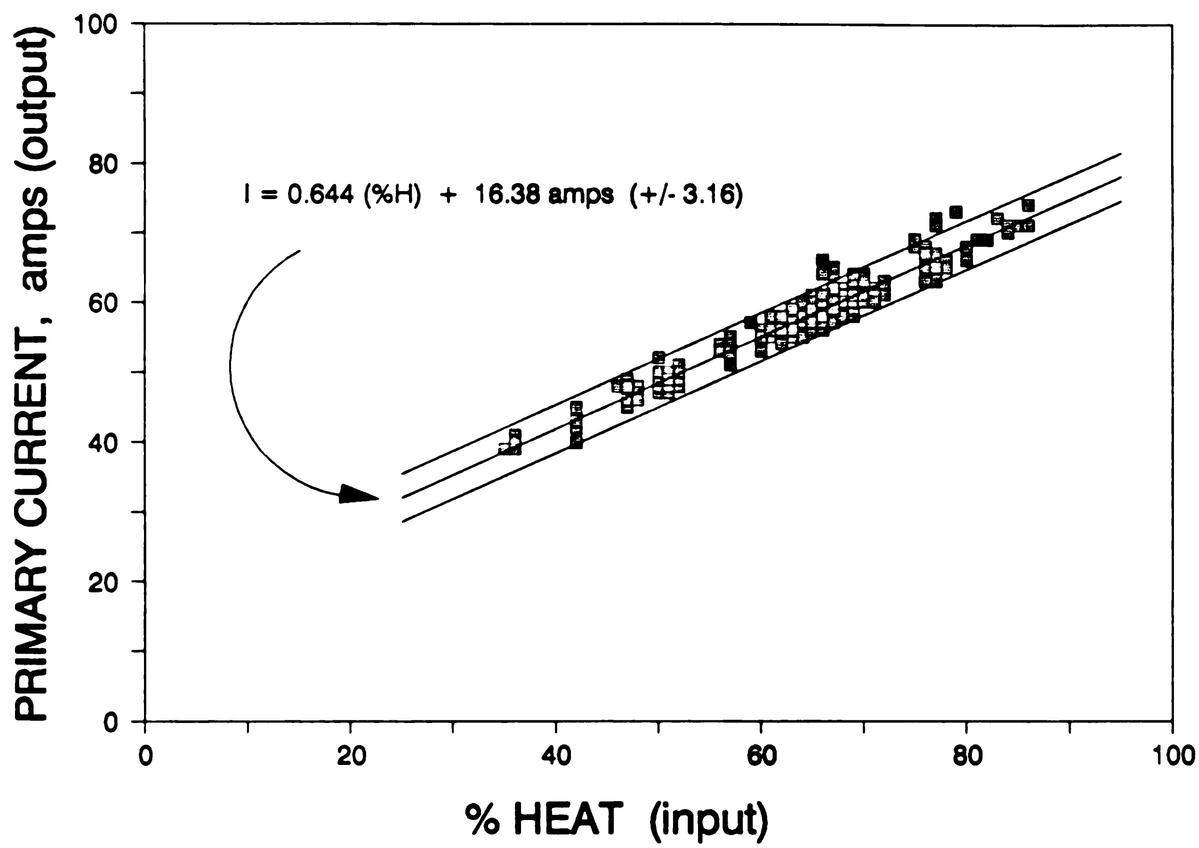


Figure 4.17 The measured relationship between primary current and percent heat, for the laboratory welder at tap 1 on bare steel. There are 455 separate data points shown; each point represents one cycle at the indicated heat. The tolerance band is calculated for the 95% confidence limits of the individual points. Joule's Law would imply a parabolic relationship; in reality however, the data do not agree with Joule's Law.

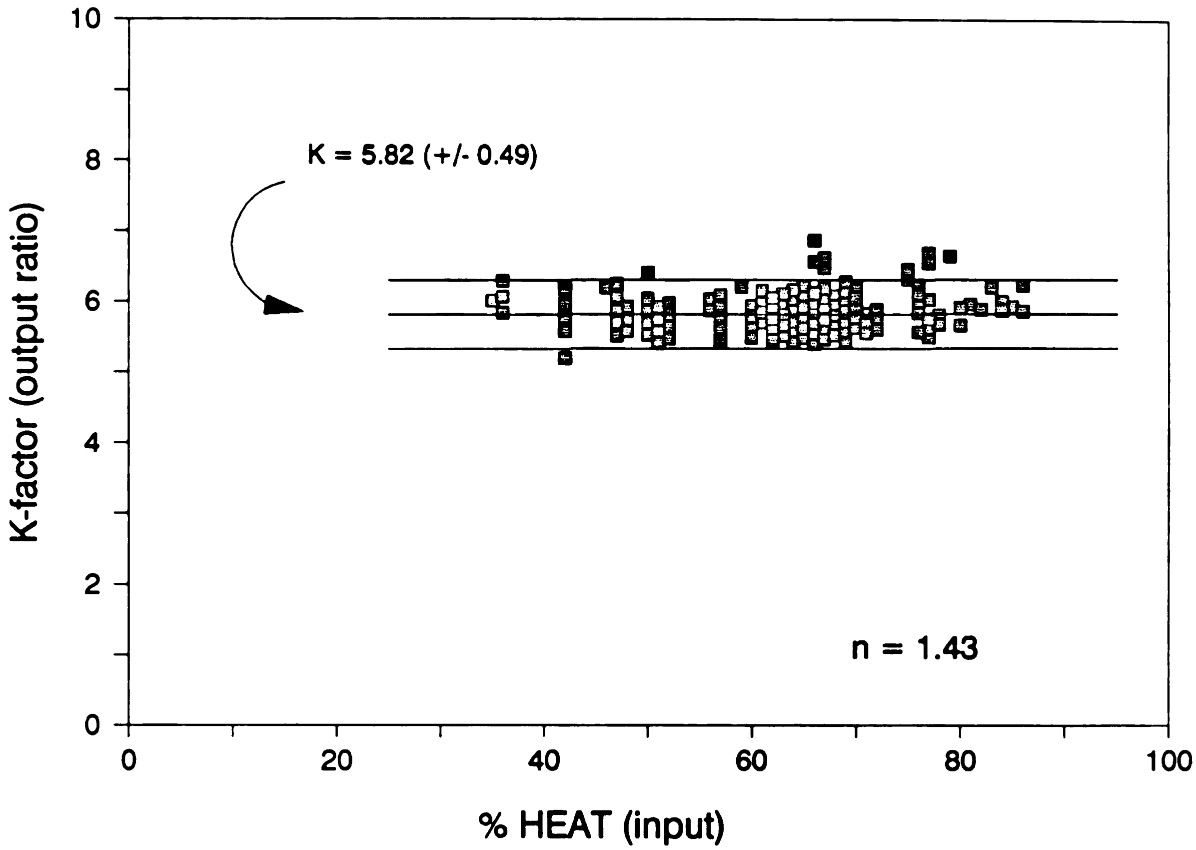


Figure 4.18 The empirical relationship between percent heat and primary current may be expressed for the data of Figure 4.17: $K = I^n/(\%H)$, where n = 1.43 and K = 5.82 (+/- 0.49).

parametric changes. In other words, a change in K-factor indicates that the process has changed in a significant way, such as cable wear, or a change in the transformer turns ratio. Simply changing the weld schedule or stepper schedule will not alter the K-factor.

Similarly, in % current systems, actual current should follow % current according to the formula:

$$\%I = 100 \cdot \frac{I}{I(max)} \qquad [\ 4.5\ ]$$

where Imax is the maximum current available when firing the SCR's at the full 180 degree conduction angle (minus a power factor or voltage compensation angle, if any). I and Imax can be either primary or secondary current. Equation 4.5 can be rearranged as was Equation 4.3 yielding,

$$C = \frac{I}{\%I} = \frac{I(max)}{100} \qquad [\ 4.6\ ].$$

C has been named the C-factor. Because the C-factor is a new concept, as of this writing its inventors Britton and Doede (55) had not yet tested its linearity. However being inherently simpler and more elegant than the K factor, if C-factor becomes a popular monitoring tool, it may steer the industry toward the %I programming convention. The C-factor will first need to be tested for linearity with respect to loop wear.

In the amperage programming convention, loop efficiency monitoring can be in done a variety of ways. K-factor can be used for a %H comparison (Equation 4.4), or C-factor for %I (Equation 4.6). It is important to note that in the amperage programming convention the system automatically compensates for loop wear. It becomes, by definition, a constant amperage power source, as discussed in Appendix D.

Because electrical efficiency is a product of controllable variables, a gradual change in inefficiency calls for preventive maintenance rather than feedback and automatic adjustment. Blind compensation for a maintenance need leads to further wear and loss of efficiency. It may best serve the user's interests to be passively alerted of the need for repair, so that the maintenance can be performed during a period of scheduled downtime. Methods like this are called passive monitoring rather than feedback monitoring because they do not compensate for changes they detect. If this particular system performed automatic compensation, it would be similar to the constant current system described in Appendix D. This technique is called loop efficiency monitoring because most of the wear on electrical components occurs in the (secondary) loop of the welding circuit.

5. PLANT RESULTS AND DISCUSSION

In addition to the variables studied in chapter 4, there is a host of additional variables imposed by the plant environment (see Figure 1.1). These variables range in their significance, and a complete study of each of them would require years of testing. In order to test the practical implications of the results obtained thus far, a change in research strategy was imposed at this point in the study. It was decided to take the conclusions of Chapters 2 and 4 to the factory floor in order to begin a pilot implementation study.

5-1 Floor-based Research Strategy

Conducting research on the factory floor involves coordinating activities among the many people who are connected with the processes. Communication is essential, both with those directly involved with the equipment, such as operators and maintenance personnel, and those more distantly involved, such as engineers and managers. To have a successful project with meaningful, fruitful results requires that all persons who can affect the research results be sufficiently aware and supportive so they may provide necessary assistance at whatever hour, day or night. Thus good, frequent, and friendly communications are extremely important to preserve rapport with the people on the floor. Because floor people are notoriously results oriented, it is also necessary to reward them for their efforts. Rewards vary from personal recognition to improved line performance, uptime, and part quality. See Appendix C for examples.

First, weld improvement teams were assembled to evaluate and recondition the plant equipment. Armed with the laboratory results that key variables were probably current, weld time, and force, we began to measure and record these variables on each weld gun. Knowing that electrode alignment was only a minor variable, we inferred that metal fit was also a minor variable (56). We used an infra-red viewer to detect hot areas in the tooling, and a micro-ohmmeter to measure the resistance of the secondary loops. Soon, we began to notice certain trends in the information:

1) Up to 50% of secondary current cables were found to be substandard by either the ohmmeter or the infra-red viewer.

2) Up to 30% of cooling water lines were found to be non-functional by the infra-red viewer.

3) Up to 25% of weld guns were in need of rebuilding, due to worn bushings or cylinders.

4) Weld current, time, and force varied widely throughout the plant. There seemed to be no single strategy for weld setup based upon either the material to be welded or the electrodes being used.

Because of the strength of these four trends, we began to refer to them as the four key variables. They were the root cause behind the majority of discrepant welds in the plant. Notice how all four key variables are maintenance related.

In order to address the above problem concerning parameter selection (trend number 4), a set of weld parameters was taken from the General Motors Resistance Welding Handbook (57) and adapted for easy floor interpretation on the shop floor (see Table 5.1). In setting up standard weld parameters without extensive lab testing there was a risk that the parameters would not be optimum. However, because weld lobes for low carbon steel are so large (as shown in Section 4-3 and 4-4), the opportunity to minimize process variation outweighed the risk that the actual parameters might not be exactly optimum for some applications. So as a first approximation, Table 5.1 values were implemented on all 1600 weld guns in the plant.

The decision to use standard parameters ended up helping the project in several important ways:

1) The bookkeeping and training were simplified, since only simple weld schedules were used, (eg. no current sloping or pulsing).

2) Once the reconditioning work was complete and the weld quality verified, if a later weld was not holding, the focus was not on the weld parameters themselves, but on the root cause for the discrepancy. People accepted the weld parameters and did not change them arbitrarily.

SPOT WELD PRODUCTION SETUP CHART FOR MILD STEEL

(adapted and refined from GM RESISTANCE WELDING HANDBOOK and GM-4488M)

"GMT"		WELD SIZE		WELD FORCE		SURFACE CONDITION: BARE to BARE						SURFACE CONDITION: BARE to GALV						SURFACE CONDITION: GALV to GALV					
GOVERNING METAL THICKNESS		MINIMUM DIAMETER REQUIRED		DESIGN FORCE		RECOMMENDED STARTING CURRENT (kA) (see legend below)				DESIGN MAXIMUM CURRENT	RECOM-MENDED	RECOMMENDED STARTING CURRENT (kA) (see legend below)				DESIGN MAXIMUM CURRENT	RECOM-MENDED	RECOMMENDED STARTING CURRENT (kA) (see legend below)				DESIGN MAXIMUM CURRENT	RECOM-MENDED
MM	INCH	MM	INCH	KG	LBS	A	B	C	D	(81%H)	CYCLES	A	B	C	D	(81%H)	CYCLES	A	B	C	D	(81%H)	CYCLES
0.6	0.024	3.5	0.14	260	600	5.0	7.0	7.5	8.5	10	8	6.0	8.5	9.0	10.0	12	10	7.0	10.0	10.5	12.0	14	14
0.7	0.028	3.5	0.14	260	600	5.5	7.5	8.5	9.5	11	9	6.5	9.0	10.0	11.0	13	11	7.5	10.5	11.5	13.0	15	15
0.8	0.031	4.0	0.16	260	600	5.5	7.5	8.5	9.5	11	10	7.0	10.0	10.5	12.0	14	12	8.0	11.0	12.0	13.5	16	16
0.9	0.035	4.0	0.16	260	600	6.0	8.5	9.0	10.0	12	10	7.0	10.0	10.5	12.0	14	13	8.5	12.0	13.0	14.5	17	17
1.0	0.039	4.0	0.16	260	600	6.0	8.5	9.0	10.0	12	11	7.5	10.5	11.5	13.0	15	13	9.0	12.5	13.5	15.5	18	18
1.1	0.043	4.0	0.16	260	600	6.5	9.0	10.0	11.0	13	12	8.0	11.0	12.0	13.5	16	14	9.5	13.5	14.5	16.0	19	19
1.2	0.047	4.0	0.16	260	600	6.5	9.0	10.0	11.0	13	12	8.0	11.0	12.0	13.5	16	15	9.5	13.5	14.5	16.0	19	20
1.3	0.051	4.0	0.16	260	600	7.0	10.0	10.5	12.0	14	13	8.5	12.0	13.0	14.5	17	16	10.0	14.0	15.0	17.0	20	21
1.4	0.055	4.5	0.18	390	900	7.0	10.0	10.5	12.0	14	14	8.5	12.0	13.0	14.5	17	16	10.5	14.5	16.0	18.0	21	22
1.5	0.059	4.5	0.18	390	900	7.5	10.5	11.5	13.0	15	14	9.0	12.5	13.5	15.5	18	17	11.0	15.5	16.5	18.5	22	23
1.6	0.063	4.5	0.18	390	900	8.0	11.0	12.0	13.5	16	15	9.5	13.5	14.5	16.0	19	18	11.5	16.0	17.5	19.5	23	24
1.7	0.067	4.5	0.18	390	900	8.0	11.0	12.0	13.5	16	16	9.5	13.5	14.5	16.0	19	19	12.0	17.0	18.0	20.5	24	25
1.8	0.071	4.5	0.18	570	1300	8.5	12.0	13.0	14.5	17	16	10.0	14.0	15.0	17.0	20	19	12.0	17.0	18.0	20.5	24	26
1.9	0.075	4.5	0.18	570	1300	8.5	12.0	13.0	14.5	17	17	10.5	14.5	16.0	18.0	21	20	12.5	17.5	19.0	21.5	25	27
2.0	0.079	5.0	0.20	570	1300	9.0	12.5	13.5	15.5	18	18	10.5	14.5	16.0	18.0	21	21	13.0	18.0	19.5	22.0	26	28
2.1	0.083	5.0	0.20	570	1300	9.0	12.5	13.5	15.5	18	19	11.0	15.5	16.5	18.5	22	22	13.5	19.0	20.5	23.0	27	29
2.2	0.087	5.0	0.20	570	1300	9.5	13.5	14.5	16.0	19	19	11.5	16.0	17.5	19.5	23	22	14.0	19.5	21.0	24.0	28	30
2.3	0.091	5.0	0.20	570	1300	9.5	13.5	14.5	16.0	19	20	11.5	16.0	17.5	19.5	23	23	14.5	20.5	22.0	24.5	29	31
2.4	0.094	5.0	0.20	570	1300	10.0	14.0	15.0	17.0	20	21	12.0	17.0	18.0	20.5	24	24	14.5	20.5	22.0	24.5	29	31
2.5	0.098	5.5	0.22	700	1600	10.0	14.0	15.0	17.0	20	21	12.5	17.5	19.0	21.5	25	25	15.0	21.0	22.5	25.5	30	32
2.6	0.102	5.5	0.22	700	1600	10.5	14.5	16.0	18.0	21	22	12.5	17.5	19.0	21.5	25	25	15.5	21.5	23.5	26.5	31	33
2.7	0.106	5.5	0.22	700	1600	10.5	14.5	16.0	18.0	21	23	13.0	18.0	19.5	22.0	26	26	16.0	22.5	24.0	27.0	32	34
2.8	0.110	5.5	0.22	870	2000	11.0	15.5	16.5	18.5	22	23	13.0	18.0	19.5	22.0	26	27	16.5	23.0	25.0	28.0	33	35
2.9	0.114	5.5	0.22	870	2000	11.0	15.5	16.5	18.5	22	24	13.5	19.0	20.5	23.0	27	28	17.0	24.0	25.5	29.0	34	36
3.0	0.118	6.0	0.24	870	2000	11.5	16.0	17.5	19.5	23	25	14.0	19.5	21.0	24.0	28	28	17.0	24.0	25.5	29.0	34	37
3.1	0.122	6.0	0.24	870	2000	11.5	16.0	17.5	19.5	23	25	14.0	19.5	21.0	24.0	28	29	17.5	24.5	26.5	30.0	35	38
3.2	0.126	6.0	0.24	870	2000	12.0	17.0	18.0	20.5	24	26	14.5	20.5	22.0	24.5	29	30	18.0	25.0	27.0	30.5	36	39

ELECTRODE LEGEND:

CASE	ELECTRODE COMBINATIONS
A	TWO BALL-NOSE CAPS
B	TWO A-NOSE CAPS
C	ONE BALL-NOSE CAP, ONE FLAT
D	ONE A-NOSE CAP, ONE FLAT

Table 5.1 Floor setup guide that was refined and used during the plant study. These are good empirical parameters for process control.

3) Because the parameters were derived from an official company handbook they were politically benign, and needed only a little "salesmanship" to gain acceptance plant-wide.

During the setup stage, whenever the standard parameters were found to produce discrepant welds, the standard was adjusted to reflect the latest information. It soon became obvious that the initial weld current for new electrodes was related to the electrode geometry. Empirically, this relationship is shown in the caption under Table 5.1. It is postulated that contact area is the most significant shape factor in assigning the starting current for a given electrode geometry. This is because contact area has a direct bearing on the average current density of the weld. Other factors which may be sensitive to initial electrode geometry are the distribution of current density and pressure across the electrode face. Therefore, a flat faced electrode will require more current than a ball faced electrode, even if the initial contact areas are similar (14,21,58).

5-2 Process Centering

Process centering has to do with adjusting a process to operate in the center of its parametric envelope. Ideally, a centered process uses parameters such that the measured average output equals the specification mean. In the case of spot welding, the measured output is nugget diameter, and a centered process operates at the center of its weld lobe, above the minimum diameter and below the electrode sticking point.

A few of the 1600 plant guns reconditioned still needed slight adaptation beyond the Table 5.1 requirements. This need surfaced during the first few production runs. These setups were finessed in order to achieve the required weld size for the entire electrode life. Usually only initial current and the stepper schedule were adjusted.

In our plant, electrodes are changed as a group. Therefore electrode life is considered to be the number of production shifts between tip changes. This practice is in contrast with a popular research technique of measuring the maximum number of welds obtainable, which has been shown to be a statistical variable (59). Thus it was not necessary to obtain every last weld from the electrodes, but only to make it safely to the next tip change interval. Typically this production interval is from one to four shifts (from 1000 to 10,000 welds).

One welding machine required a special deviation that is worth mentioning. Some sections of this machine ran at an extremely high production rate of 800 welds per hour. The air-cooled welding cables were heating up and oxidizing, which caused significant current losses within a few days' time. To cure the problem, the weld time was shorted from 16 cycles to 10 cycles in order to lower the electrical duty cycle, (the percent of time when the circuits are actually passing weld current) from 5.9% to 3.7%. In exchange for a shorter weld time, the starting weld current was raised from 9.5 ka to 10.0 ka. The material welded in this application was HSLA hot-dip galvanized sheet steel, approximately 0.030 inches (0.75 mm) thick.

Efforts to further optimize weld setups still exist in many areas of the plant. Nonetheless Table 5.1 served as a very good first approximation for the vast majority of plant applications. At present, continuing studies focus mainly on electrode shapes, electrode materials, and preventive maintenance systems rather than on process fundamentals, as was done in this study.

5-3 Process Desensitization

As a rule of thumb, operating near expulsion decreases process sensitivity and decreases the number of key variables. Running with the welds hot makes resistance spot welding easier to control because there are fewer sources of critical variation. When using this strategy, one usually only needs to monitor cable wear, water flow, force, and current. Variation in material, fitup, thickness, coating, dirt, voltage, water temperature, alignment, etc. can be largely ignored.

However, a price for the extra robustness of running hotly is shorter electrode life. Intuitively, the hotter the welds, the worse the electrode life will be. The upper limit to weld heat is defined by the following factors:

1) The minimum electrode life required to operate economically, which is measured conveniently in even multiples of the number of parts in a standard production interval (eg. the number of shifts).

2) The appearance requirements (if any) for the weld. Hot welds generally leave an indentation mark from the electrodes when significant expulsion occurs.

3) The absolute upper limit of weld heat is electrode sticking, when the electrode bonds to the workpiece. Sticking is totally unacceptable, since it halts the process and sometimes leads to equipment and part damage.

Another price for running hot is dirtier equipment, which will require deslagging and washing on a scheduled basis. Although some have claimed that running hot wastes electricity (60), the automotive community has regarded electricity as a minor cost of spot welding, since each weld uses only 0.0005 kw-hr of energy as described in Appendix D.

5-4 Remaining Variables

The question was raised by plant personnel about what to do once the variables were optimized if the process still failed at some future point to produce acceptable weld quality. (In all of the 1600 guns included in this study, less than 1% failed to yield acceptable weld quality after optimization). This section focuses on this group of exceptional welds. In almost every case there was an obvious and direct assignable cause to the problem.

Most of the exceptional welds were in extremely poor metal fit areas, where the electrodes and workpieces would not seat, even under full electrode force. When the clamped workpieces either do not contact each other or do not contact one of the electrodes, the current path through the workpiece becomes disturbed and current density will be low. In this case the gun must crush the sheets together in order to establish good thermal and electrical contact for welding. Over welding and using a pulsation weld schedule has worked with some success, although electrode life suffers accordingly. A better solution to metal fit problems is to eliminate them ahead of time, in the metal forming operations.

Occasionally electrodes become coated with organic buildup from oil, paper, or cloth from the manufacturing environment. This type of coating acts as an insulator and will suddenly cause weld current to drop to zero in the middle of a production run. There are several practical strategies for dealing with this annoying problem:

1) Lightly file the contamination off of the electrodes, taking care not to change the face diameter, which by this point in the stepper is at a particular size which is appropriate for this number of welds.

2) Replace the electrode with a used one that is worn to about the same diameter.

3) Program a minimum weld current limit into the weld control. The limit will halt the machine when minimum current is not detected. This "low current fault" condition effectively alerts personnel and prevents the manufacture of any discrepant welds due to this problem.

Other common causes of low current during welding are:

1) An open condition in one of the primary or secondary circuit connections.

2) Any source of extra resistance in the secondary loop such as a worn cable or loose connection.

3) An increase in the inductive reactance of the secondary loop due to a change in loop area or a change in the amount of magnetic material in the secondary loop.

4) A large drop in supply voltage.

5) A change in the weld schedule.

These considerations are discussed in Appendix D.

As observed from Figures 4.6 and 4.10, operating at or above the expulsion limit reduces the susceptibility to critical loss of current density. This susceptibility is due to variation in pressure or weld area. In fact, over welding in this way reduces the influence of many minor variables, such as metal thickness and coating (see Figure 1.1 for an extended list of variables). Making use of the full width of the weld lobe as defined in Section 4-3, one can center the process and operate the furthest from quality problems. This is done by setting the current near the middle of the weld lobe, at the expulsion limit.

While operating at expulsion, the degree of process robustness enjoyed depends upon:

1) The width of the weld lobe,
2) the chosen setup conditions, and
3) the range of variation encountered among the major and minor variables.

Although welding hotly increases the system's tolerance for variation, excessive heat produces negative results, such as over-indentation, poor electrode life, and worst of all, electrode sticking. Electrode sticking is most often observed with new electrodes. The system with the widest weld lobe will show the least tendency toward electrode sticking and the greatest insensitivity to normal process variation.

To increase the lobe width of a process one might consider changing electrode shape, diameter, material, or force. The shape of the electrode is expected to affect lobe width because of its effect on current profile (58). The electrode material is expected to affect lobe width because of its effect on heat flow out of the workpiece and because of alloying, pitting and contamination (61). The electrode force was shown to affect lobe width in Figures 4.6 and 4.11. The reasons for this force - lobe width relationship are complex, including a relationship between force and thermal and electrical coupling at the electrode-sheet boundary, and the effect mechanical deformation has upon the contact area and the current path (14,17,18).

5-5 Setup Guide

The parameters used to set up weld guns during the plant implementation study are shown in Table 5.1. The parameters were tested and refined empirically on 1600 production weld guns. In practice, the tabular values place the process very near to the expulsion limit, at a force where the process is robust and well-behaved. To complete the setup, we only fine-tuned the current to the expulsion limit and measured weld size destructively to demonstrate that the minimum bond diameter requirement had been met.

The column in Table 5.1 labeled "design maximum current at 81% heat" was used to test transformer capacity. The transformer must be suitably overdesigned to provide head room for the stepper to compensate for electrode wear over thousands of welds.

5-6 Process Monitoring and Feedback Techniques

5-6-1 Power Factor Drop (PFD)

Under plant conditions, production tests of the PFD stepper described in Section 4-5-1 were run using galvanized steel (0.024 inch [0.6 mm] welded to 0.079 inch [2.0 mm]). These results are shown in Figures 5.1 and 5.2. From these data one may conclude the following:

1) When in automatic feedback mode, the weld heat will step either up or down to balance the amount of expulsion obtained.

2) There is sometimes a rapid rate of stepping initially to compensate for incorrect starting current. An example of this heat correction is shown in Figure 5.2a. Once the current is adjusted to the expulsion limit, the current steps are more randomly up and down, with only a long term upward trend.

3) The feedback process is in control. Figure 5.1b shows a classic pattern of control for this application. About 78% of the welds exhibit PFD less than the expulsion threshold. Ideally, we expected approximately 75% of the welds to be below expulsion, since the counter limits were set to 6 no-expulsion welds and only 2 expulsion welds, (a ratio of 3:1). Figure 5.2b shows a higher percent of welds below expulsion (85%) due to the initial warm up adjustment during the first 150 welds (Figure 5.2a).

4) The long term stepper trend may be approximated by a straight line. This means that generic stepper gradients might be characteristically linear throughout electrode life. This trend would be a worthwhile subject for future study, perhaps using a similar data collection scheme. However, just knowing that the process naturally may want to step at a linear rate throughout the electrode life helped to simplify our plant's stepper schedules for non-feedback applications. As a result, in most cases they were shortened down to one or two steps, as characterized in Figure 5.3.

Certain interesting problems were identified whenever the feedback system failed. The biggest problem was false PFD's. A false PFD tricks the control into reading the weld as hotter than it is. This condition was initially prevalent when welding with galvanized steels. There is a false PFD associated with expulsion of the zinc coating early in the weld schedule. If the control reads this as the PFD for iron expulsion, it will incorrectly turn down the

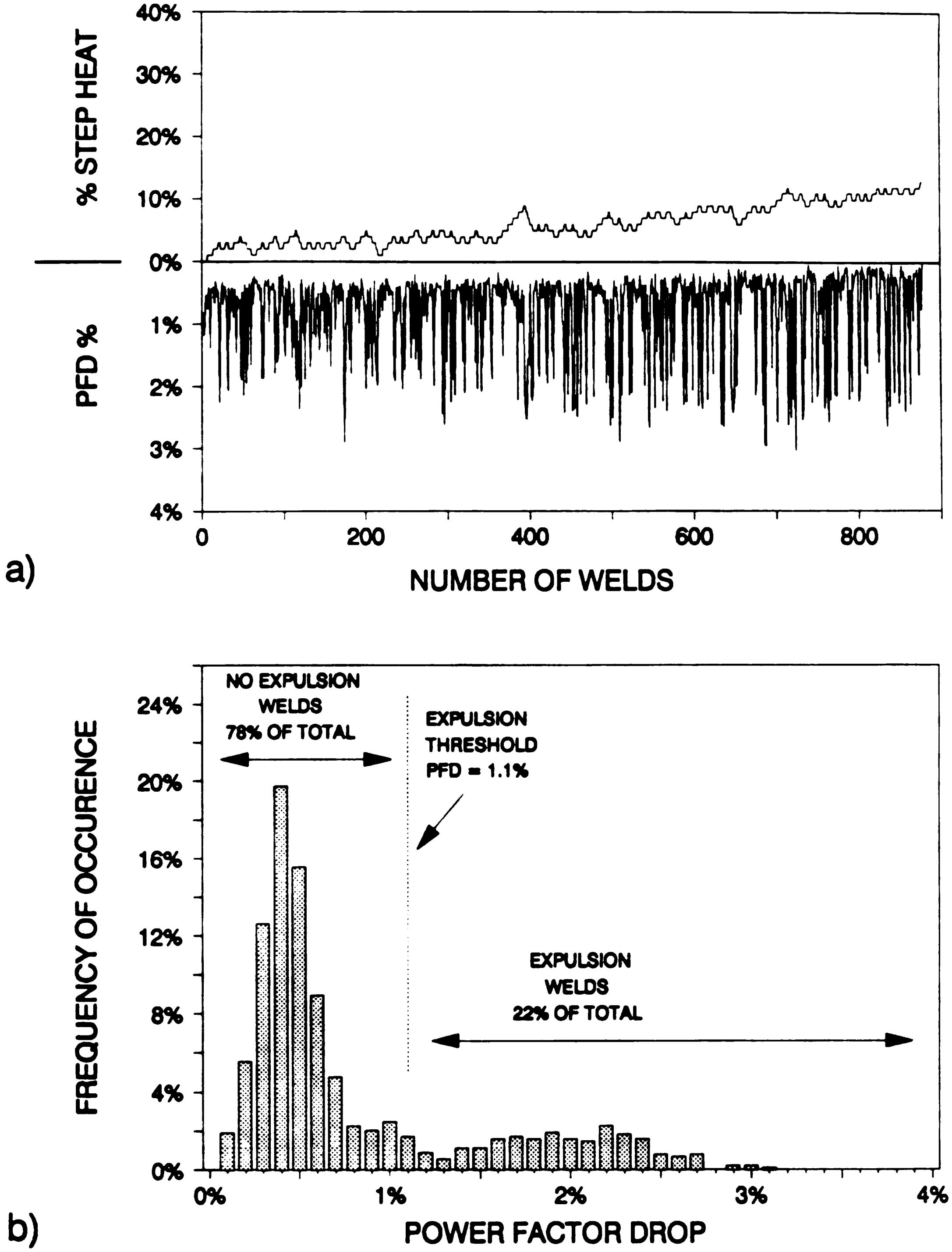


Figure 5.1 Actual production data using the PFD feedback control. The material was hot-dipped galvanized steel 0.024 inch (0.6 mm) welded to 0.079 inch (2 mm). The weld tool was of the press/fixture type, with a large secondary loop. Notice how the stepper stepped both up and down, in order to maintain an average of 22% expulsion. a) individual data, b) histogram.

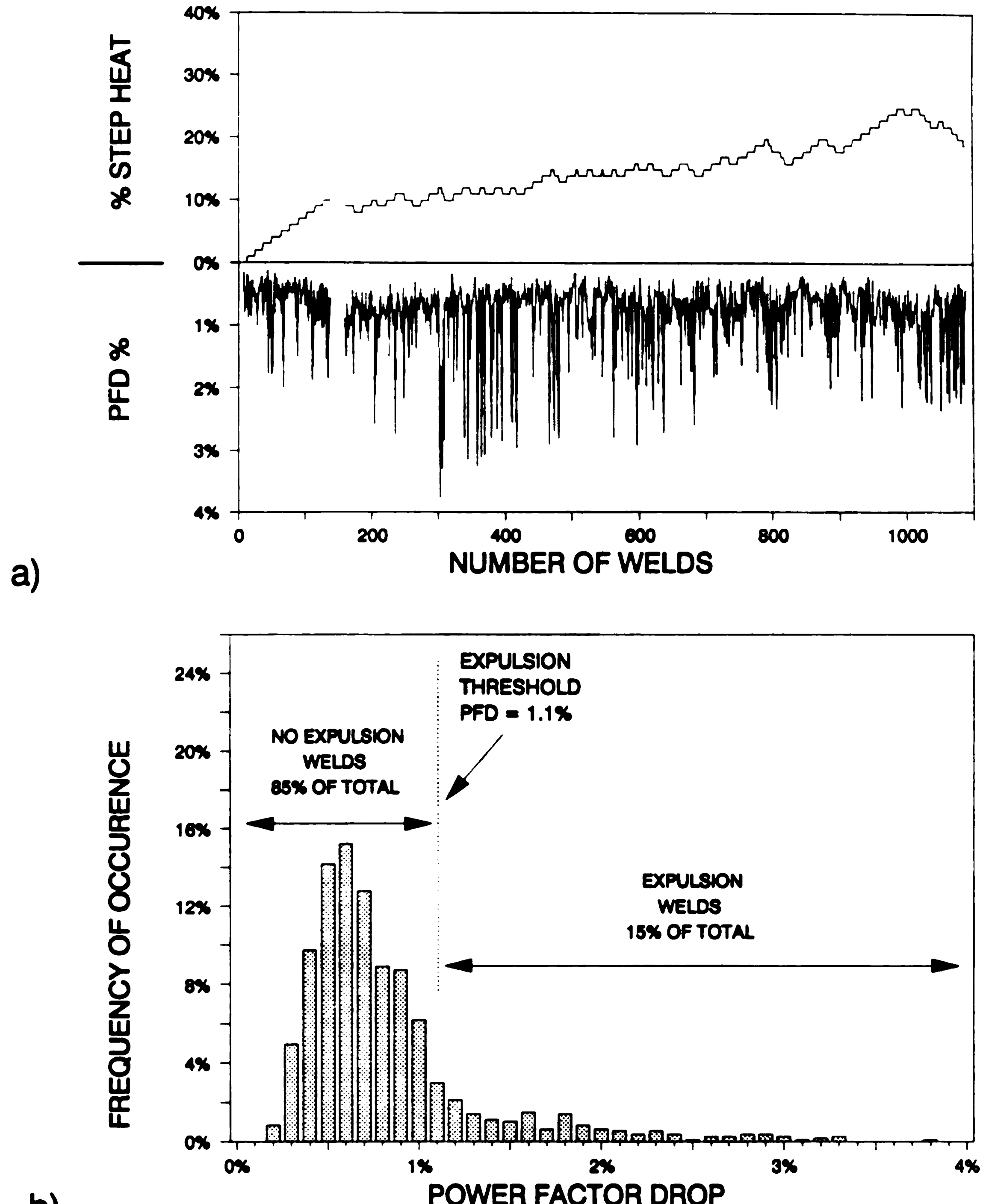


Figure 5.2 Actual production data using the PFD feedback control. The materials were identical to those in Figure 5.1. The weld tool was also similar. Notice how active the stepper was for the first 125 welds. Because the initial heat setting was too low, there was little expulsion. Later the system balanced, for a total of about 15% "expulsion welds". a) individual data, b) histogram.

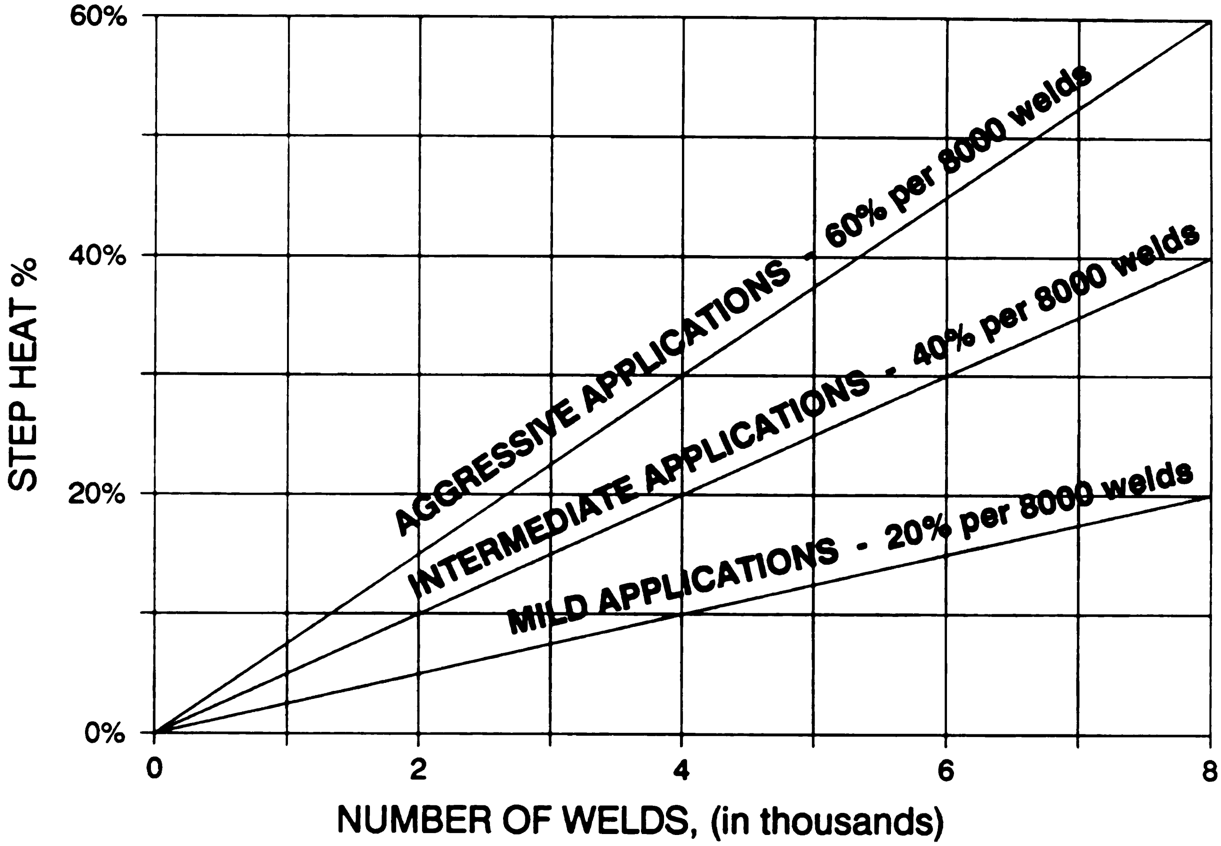
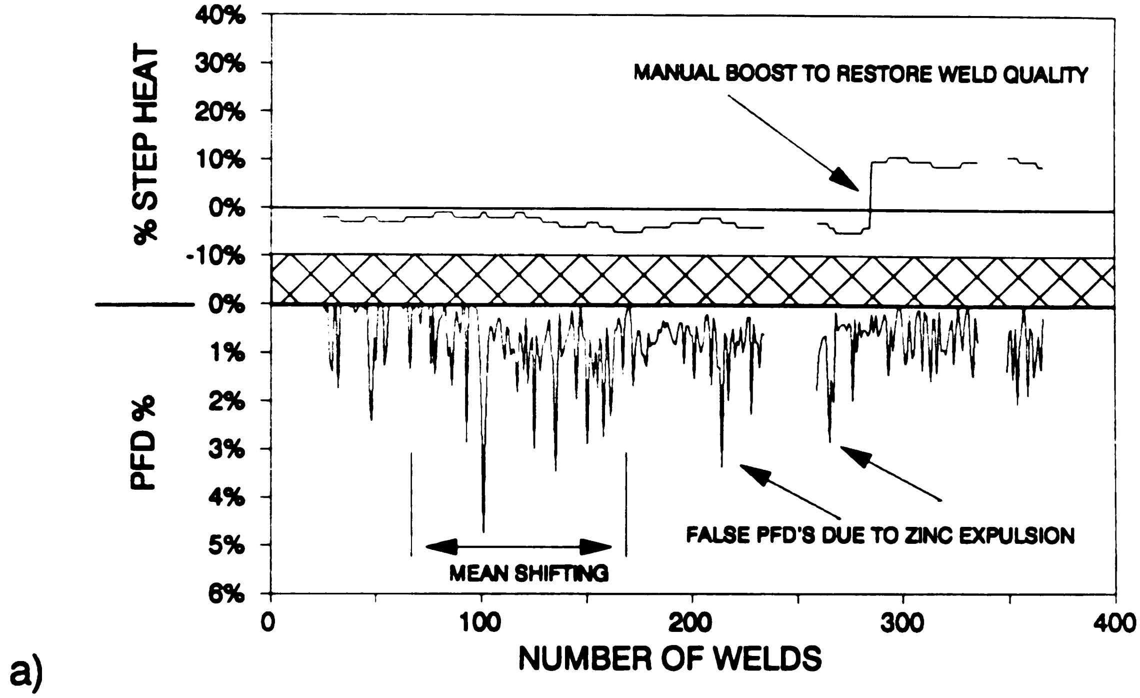


Figure 5.3 Standard, simplified stepper curves deployed in the plant for non-feedback applications.

heat in order to try to eliminate the perceived expulsion. Unfortunately, false PFD's can lead to cold welds. Through trial and error, we found in the plant that PFD's at zinc expulsion could be filtered out with pre-pulse welding and initial data blanking. This way, the control is set to look for PFD only after the zinc has expelled.

Other false PFD's can arise from dirty, arcing ground blocks, from loose, arcing secondary cables, or from poor water flow. False PFD's must eliminated or filtered, otherwise the noise will be interpreted as expulsion.

Another area of difficulty for PFD feedback control is welding very thin galvanized steel to itself. In the case of Figure 5.4, the material as specified is too thin to allow bulk resistance and heat flow to stabilize as discussed in Section 2-4-3. Therefore, even without feedback control this material will fluctuate in and out of expulsion. On light gauge steel, the window for quasi steady-state welding is much smaller and harder to hold. In practice, when the steel is thinner than 0.028 inches (0.7 mm), the process is subject to excessive variation due to coating variables. There was insufficient time in the present work to resolve this problem. Consequently, it remains for future study. The problematic data are shown in Figure 5.4.



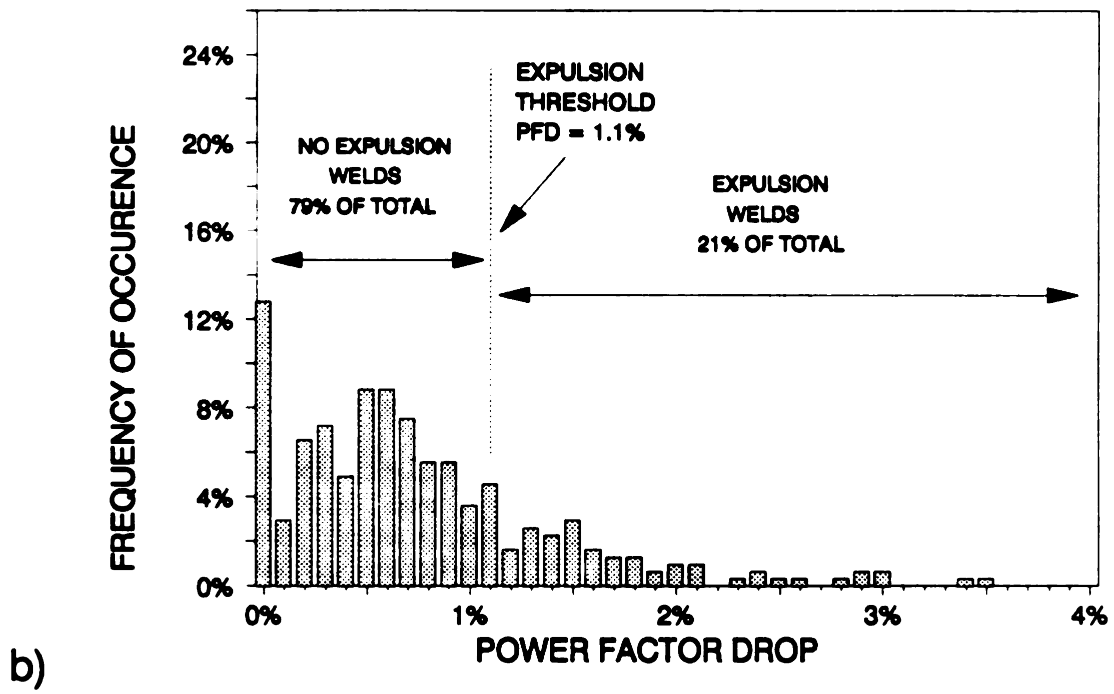


Figure 5.4 Actual production data showing PFD feedback out of control. The material was hot-dipped galvanized steel 0.024 inch (0.6 mm) welded to itself. The stepper was initially disturbed by frequent false PFD's, until the operator intervened at about 275 welds. a) individual data, b) histogram.

6. CONCLUSIONS

1) Weld force affected both the size and position of the weld lobe. Therefore force is a significant process variable.

2) Weld time was found to be a less sensitive variable than weld current.

The reader should note that the following conclusions are original contributions to the field of resistance spot welding:

3) Figure 1.1 showed a list of many variables commonly believed to be important in the control of resistance spot welding. They were arranged into the categories known as the four "M's": Material, Method, Machine, and Maintenance. However, as a result of this study, it was learned that the true key variables which actually control automotive resistance spot welding are:

   1) Loop resistance
   2) Water flow
   3) Gun condition
   4) Setup current

   It was observed that when these four variables were optimized and maintained, welding problems nearly disappeared. Optimum current was found to be at, or slightly above, the expulsion point. Table 5.1 shows the setup guide which evolved from this study, applicable for a wide range of common automotive applications.

4) Misalignment up to 40% of the electrode diameter had little impact on quality, provided the process was operating at expulsion before the misalignment occurred.

5) The power factor drop (PFD) at expulsion was a useful feedback signal for keeping the process centered at the expulsion limit. Heat schedules were automatically adjusted for misalignment, metal fit, edge welds and cable deterioration, on both uncoated and galvanized steels. On galvanized steel, special double pulse weld schedules were necessary to filter out zinc expulsion from the feedback signal.

6) An inexpensive, online method of monitoring electrical efficiency was invented. This system compares % heat and primary current against a preset number, (the K-factor), which is characteristic of the loop efficiency of the tool. The advantages of the technique are:

   1) no sensors on the weld gun,
   2) low cost (a one-time software change),
   3) direct, online monitoring while welding, and
   4) no more need for routine, hands on resistance testing of the weld circuit with a microhmeter.

7. RECOMMENDATIONS FOR FUTURE WORK

The following are suggested topics for future work in resistance spot welding:

1) Further characterization of ideal stepper profiles, as discussed in Section 5-6-1. Is I/D constant throughout tip life?

2) Process control of thin to thin welding of galvanized sheet, as discussed in Section 5-6-1.

3) Mass production welding of new automotive materials, such as aluminum.

4) Development of long-life electrode materials.

5) Why are power factor values different for the plus and minus half cycles? See Figure 4.12.

6) Performance of the PFD feedback control on a variety of weld tool configurations. For example, a large loop versus a small loop, or a high power factor circuit, such as with a long kickless cable and a small gun.

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APPENDICES

APPENDIX A

General Motors Weld Lobe Procedure MDS-247

APPENDIX A - 1

General Motors Weld Lobe Procedure MDS-247

MDS-247
SPECIFICATIONS AND PROCEDURE FOR DETERMINING THE WELDABILITY OF BODY STEEL MATERIALS

1. Scope

1.1 This specification establishes the requirements and procedures used to determine weldability by the resistance spot welding method for coated and uncoated low carbon mild steels, medium strength steels, high strength steels and high strength low alloy steels. The procedure is used to determine the practical limits of weldability by the resistance spot welding method, utilizing weldability lobes in conjunction with data from physical destructive test methods.

1.2 Details are contained herein for determining the selection of test conditions, equipment and instrumentation, for developing interpreting and evaluating weldability lobes.

1.3 Several formulas have been developed to obtain the various process parameters and constants that take into account the metal thickness, yield strength and coating of the test material.

2. Apparatus

2.1 Equipment Required.

2.1.1 Single point, single phase resistance spot welder with air operated cylinder, capable of developing at least 2,000 pounds of electrode force.

2.1.2 A suitable welding transformer that is capable of delivering the required weld current at the electrode tips for the specific machine secondary circuit and throat opening.

2.1.3 A suitable welding control with phase shift heat control and NEMA Type 5B timer functions.

• 2.2 Electrodes

RWMA Class II zirconium copper (WW 2) materials, size 2 (5/8-in. o.d.) and size 3 (7/8-in o.d.) closed shanks with "A" nose or ballnose caps dressed to the specified tip contact diameter for the test material. The ballnose cap when used must be dressed to a truncated cone with a 45 degree angle utilizing the tip dresser specified in paragraph 2.3.5. The electrodes require a cooling water flow rate of 0.5 gal/min with cooling tubes set 1/4-inch from inside surface of electrode shank (Figure 1).

2.3 Instruments

2.3.1 Model 273 Duffers Current Analyzer or equivalent for measuring weld cycles and secondary current.

2.3.2 Lebow Transducer, Model 3404-3K and Daytronic Strain Gauge Conditioner/Indicator, Model 3270 or equivalent for measuring the electrode force.

2.3.3 Brooks flow meter, Model No. 1355B01BICES or equivalent to measure water flow through each electrode.

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2. Apparatus (cont'd.)

2.3.4 Dial Caliper - Mitutoyo Model 505629 or equivalent to measure weld nugget diameters.

2.3.5 Electrode Tip Dresser - Tipaloy No. T-361AC-B or equivalent.

3. Material Requirements

A minimum of 30 square feet of test material is required. Material must be clean, rust-free and flat.

4. Weld Lobe Interpretation

A weldability lobe is a means of graphically expressing the numerous combinations of weld current and weld time which will produce satisfactory welds with a specific set of conditions. Weld current values are plotted on the "X" axis and weld time values on the "Y" axis (Figure 5). The left most boundary of the lobe defines the combinations of weld current and weld time which will produce minimum acceptable nugget diameters. Points to the left of this curve will produce nugget diameters less than the minimum specified. The right most boundary of the lobe defines the flashing point. Points to the right of this curve results in welaments with excessive heat energy evidenced by heavy expulsion, electrode indentation, and/or electrode sticking. Points between the two curves result in welds of satisfactory quality. The distance between these two boundaries at a given weld time is referred to as the "weld range." A wide weld range is very desirable and indicative that the material would be tolerant to changes of the manufacturing process variables such as tip geometry and voltage fluctuations. For convenient reference there is a third curve (shown as a dashed line) which indicates the currents and weld times which will produce a nominal diameter weld nugget. A point on this line may be selected for a nominal weld schedule.

5. Procedure

5.1 Selecting of Process Constants

5.1.1 Tip Contact Diameter

Measure the test material thickness accurately with a micrometer and insert the thickness value in the formula (Table I) to determine the tip electrode contact diameter required.

5.1.2 Nominal Nugget Diameter

From the formula (Table I) the nominal nugget diameter is equal to 0.86 times the tip contact diameter.

5.1.3 Minimum Nugget Diameter

By formula (Table I) the minimum nugget diameter is equal to 0.69 times the tip contact diameter.

5.1.4 Force

The electrode tip force is calculated by the formula shown in Table I.

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5. Procedure (cont'd.)

5.1.5 Weld Time

The weld time requirements are obtained from the formula shown in Table II.

5.1.6 Governing Material

When spot welding the test material to mild steel, determine the force required (from formula) for each material and use the weld schedule that is commensurate with the lower electrode force.

5.1.7 Weld Lobes Required

Resistance spot weld lobes are required for the following conditions:

Welding the test material to itself.

Welding the test material to a nominal 0.89mm (0.035 inch) mild steel (FBMS16-5E or FBMS 16-5U).

Welding the test material to a nominal 1.91mm (0.075 inch) mild steel (FBMS 16-5E or FBMS 16-5U).

5.1.8 Minimum Spot Spacing

Select minimum spot spacing for the metal thickness and welding combinations as shown in Table III

5.2 Setup of Equipment

5.2.1 Electrode Tip Tuning

Reduce the electrode tip force sufficiently to allow a file (parallel in thickness, smooth or dead smooth, double cut) between tips to be rotated through a plane perpendicular to the center line of electrodes. This operation will create parallelism between the electrode faces and adjust the tip diameters. Check contact diameter by measuring the carbon imprint per Section 5.2.4.

5.2.2 Tip Alignment

Check by carbon imprint (Section 5.2.4). Both electrodes should indicate the required tip diameter if in alignment. The metal panel is removed from between the carbon to determine alignment.

5.2.3 Tip Dressing

If the tip diameter is larger than required, use the electrode tip dresser at low electrode force to dress the tips to the proper diameter by rotating the dressing tool between electrode tips. Measure carbon imprint to verify correct diameter.

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SPECIFICATIONS AND PROCEDURE FOR DETERMINING THE WELDABILITY OF BODY STEEL MATERIALS

5. Procedure (cont'd.)

5.2.4 Carbon Imprint

Place a sheet of carbon paper over a sheet of plain paper with carbon side down. Fold the combination in the center over a metal panel. Place this combination between the electrodes. Make the carbon imprint at the electrode force required for the weld test (Figure 6). The carbon imprint indicates the electrode contact area. Measure to verify the proper tip diameter.

5.3 Sequence of Tests

5.3.1 Conditioning Welds

After the electrodes are aligned, tuned and dressed, one hundred conditioning spot welds are made at a weld schedule that would produce a nominal size weld nugget at the nominal weld time (per formula Table I). This stabilizes weld results and reduces the scatter of test points.

For galvanize coated metal the weld current should be adjusted from some lower heat value that does not result in sticking, gradually increasing the heat after several welds to obtain a brassing condition on the test coupons.

5.3.2 Hold Time Sensitivity Test

Weld tests are initially conducted on the test material to determine whether any embrittlement of the weld zone occurs due to the rapid quenching (60 cycles hold time). Hold time sensitive materials exhibits shear-type weld failures when peel tested.

At five cycles of hold time, spot weld together three sets of coupons (Figure 4A) at the maximum weld time determined (per formula Table II) for the test material. Peel test the second weld Per Figure 4B to determine the heat setting required to obtain the minimum weld nugget diameter (per formula Table I). Next, readjust the hold time to 60 cycles. At the same heat setting that produced the minimum size weld nugget at five cycles of hold time, spot weld together three more sets of coupons and examine the weld zone. If shear type weld failures occur, the test material is considered to be hold time sensitive. Slightly higher heat settings (8 percent maximum increase) may be used at 60 cycles hold time to obtain the proper nugget size. If good full size minimum nuggets are developed, the material is considered not to be hold time sensitive.

5. Procedure (cont'd.)

5.3.3 Weld Lobe Generation

5.3.3.1 A minimum Nugget Diameter Boundary

With the weld time set at maximum per formula, adjust the current to obtain the minimum nugget size per formula and peel test three coupons to verify (Figure 5, Point 1). Repeat this procedure for Points 2, 3 and 4, for intermediate, nominal and minimum weld times, respectively (Table II). Connect these points to establish the minimum weld nugget boundary of the weld lobe.

5.3.3.2 Nominal Nugget Diameter Curve

With the weld time reset to maximum as above, adjust the weld current to obtain the nominal nugget size (per formula) and peel test three sets of welded samples to verify the nominal weld nugget sizes (Figure 5, Point 5). Repeat this procedure for points 6, 7 and 8 of the weld lobe. Adjusting the weld times as per 5.3.3.1. Connect these points with a dashed line to establish the nominal nugget diameter curve of the lobe.

5.3.3.3 Tensile Test and Chisel Samples

Tensile and chisel samples are made at the nominal nugget diameter and only at the nominal weld time. Five tensile samples are made (Figure 2) first, followed by five chisel samples. The sequence of spot weld placement on the chisel samples are A, B and C per Figure 3. These samples are required to verify the weld quality at the nominal schedule (Section 6.6).

5.3.3.4 Expulsion Boundary

To obtain Point 9 (Figure 5) increase the weld current slowly at maximum weld time to obtain a flashing condition on the second spot weld of the peel test coupon. Make only one weld sample at the flashing condition to determine this point. Repeat this procedure to obtain Points 10, 11 and 12 of the weld lobe. Adjusting the weld times as Per 5.3.3.1. Connect the points to obtain the expulsion boundary of the weld lobe. Connect all upper and lower points to complete the weld lobe.

5. Procedure (cont'd.)

5.3.4 Procedure Variations

Due to material processing, carbon content, nitrogen and alloying material differences, variations in procedure may be required. Difficulties may arise in obtaining the desired points on the weld lobe. It may be necessary to increase the mimimum weld time by several cycles above that specified per formula to obtain weld nuggets.

Different interpretations of the high side of the weld lobe may be necessary because of the material characteristics. Flashing may occur prematurely and would indicate a narrow weld range. However, a moderate amount of flashing may be tolerable and acceptable. In this case, excessive flashing and/or sticking of the electrode to the test material may be taken as the high side of the lobe.

For galvanized steel, heavy brassing may be the criteria for determining the high side of the lobe if flashing is not obtained before excessive indentation. Mimimum nugget diameters may be difficult to obtain. The weld nuggets formed may be oval. For this situation the average diameter should be used. The average diameter may be obtained by measuring the major and minor diameter and computing the arithmetic average.

6. Reasons for Rejection

6.1 Hold Time Sensitive

Material that is found to be hold time sensitive to itself is rejected and terminates any further testing.

6.2 Brittle Welds

If during peel tests, brittle or erratic weld nuggets are obtained, the material is rejected and terminates further testing. Enough data shall be taken to substantiate this condition.

6.3 Laminated Base Metal

If during peel tests of the spot welds, lamination of the base material is observed, the material is rejected.

* 6.4 Narrow Weld Range

Minimum weld range requirements at the nominal weld times are listed below for the various metal thicknesses:

2000 amperes for 0.041 inch and larger.
1800 amperes for thicknesses less than 0.041 inch.

Materials with less than the minimum weld range requirements for the specific metal thicknesses is caused for rejection.

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6. Reasons for Rejection (cont'd.)

6.5 Weld Lobe Position on Graph

Weld lobes that do not overlap sufficiently with those previously developed for approved sources may also be rejected.

6.6 Chisel Test Samples

The material may also be rejected if two or more of the 15 spot welds on the chisel samples shear at the interface.

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TABLE I

PROCESS CONSTANTS FOR WELDABILITY LOBE DEVELOPMENT

t = Metal thickness (inches).

y_s = Yield strength of steel (KSI).

d = Contact tip diameter (inches).

A = Contact tip area (square inches).

n = Nominal nugget diameter (inches).

m = Minimum nugget diameter (inches).

P = Welding pressure (psi).

F = Weld force (pounds).

$$t = \frac{d^2 + .007}{1.65}$$

d = $1.65t - .007$

n = $.86 \quad 1.65t - \quad .007 \quad = \quad .86d$

m = $.69 \quad 1.65t - \quad .007 \quad = \quad .69d$

A = $1.296t - .00555$

P = $60Y_s + 10200$

F = AP

NOTE: For all materials less than 0.041-inch thick, use the following process constants:

500 pounds	Force
0.25"	Tip Contact Diameter
0.20"	Nominal Nugget Diameter
0.16"	Minimum Nugget Diameter

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TABLE II

SINGLE PULSE

Bare		Galvanize	
Min. W.T.	= .009F + 1.2	Min. W.T.	= .009F + 6.2
Nom. W.T.	= .013F + 1.9	Nom. W.T.	= .013F + 6.9
Int. W.T.	= .017F + 2.5	Int. W.T.	= .017F + 7.5
Max. W.T.	= .022F + 3.1	Max. W.T.	= .022F + 8.1

DUAL PULSE - 4 CY. COOL
(For Thicknesses Above .089")

Bare		Galvanize	
Min. W.T.	= .007F + 0.9	Min. W.T.	= .007F + 5.9
Nom. W.T.	= .009F + 1.2	Nom. W.T.	= .009F + 6.2
Max. W.T.	= .011F + 1.5	Max. W.T.	= .011F + 6.5

Bare Schedule - Bare to Bare and Bare to Galvanize When Bare is Governing.

Galvanize Schedule - Galvanize to Galvanize and Bare to Galvanize when Galvanize is Governing. Also one side Zinc at Interface.

Dual Pulse - .089-In. thick and over.

NOTE: Governing material is determined by the force required, whichever is lower.

NOTE: In general the lower force determined by formulas for materials would result in being the governing material. However, for all materials less than 0.041-in. thick—use 500 pounds.

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TABLE III

Required Spot Spacing -- Peel Test Coupons

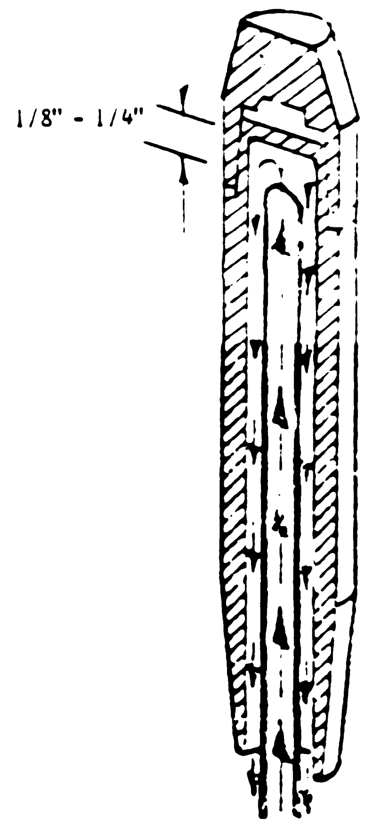
Thickness	Minimum Spot Spacing -- Inches		
Inches	Bare/Bare	Galvanize/Bare	Galvanize/Galvanize
.030	1/2	5/8	3/4
.035	5/8	3/4	7/8
.041	3/4	7/8	1
.047	7/8	1	1-1/8
.059	1-1/8	1-1/4	1-3/8
.067	1-1/4	1-3/8	1-1/2
.075	1-3/8	1-1/2	1-3/4
.089	1-5/8	1-3/4	2
.105	1-3/4	2	2-1/4
.120	2	2-1/4	1-1/2

NOTE:* 1400-pounds force or above--use size 3 shanks and electrode caps (MWZ 6146).

Metal thicknesses above 0.089 in. requires dual pulse weld schedules.

Tensile test coupon size for metal thicknesses above 0.089 in. should be 2" x 6".

* For electrode tip contact diameters above 0.290 in.--use MWZ 6006 Caps--Reworked--45 degree taper.



NOTE: Top of water deflection tube to be cut at 45-degree angle.

FIGURE 1 - Correct Water deflection Tube Installation for Closed Shank Electrode

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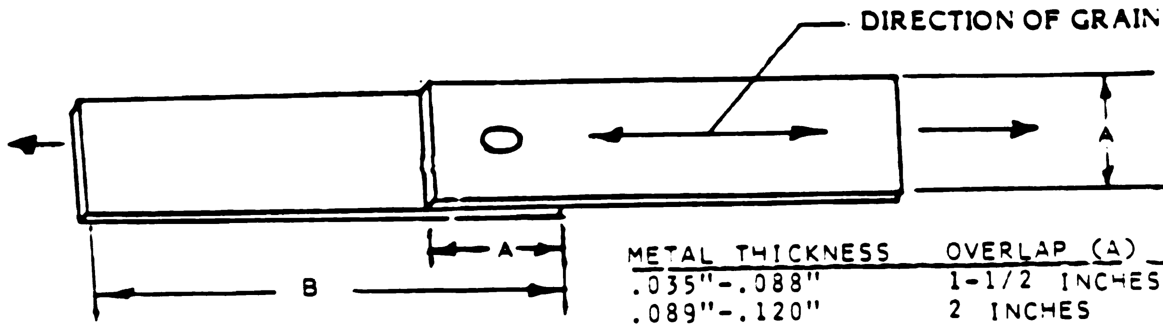
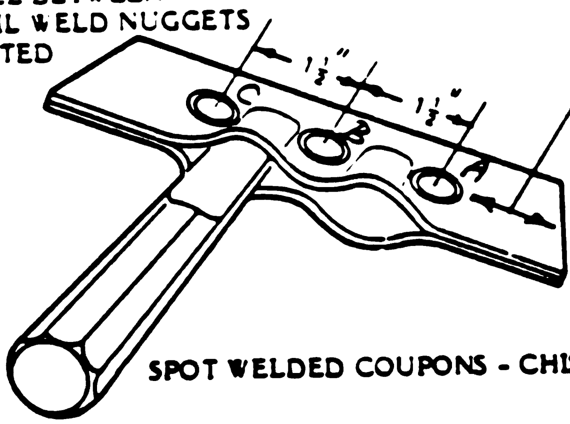


METAL THICKNESS	OVERLAP (A)	LENGTH (B)
.035"-.088"	1-1/2 INCHES	5 INCHES
.089"-.120"	2 INCHES	6 INCHES

SPOT WELDED COUPONS FOR TENSILE TEST

FIGURE 2



SPOT WELDED COUPONS - CHISEL TESTED

FIGURE 3

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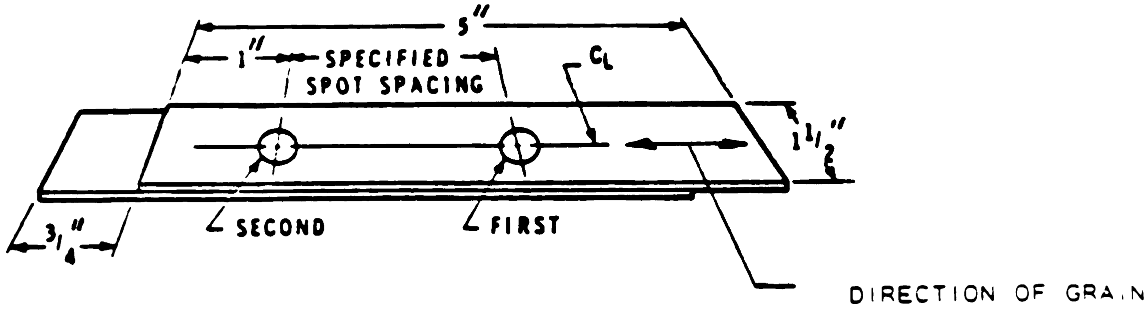
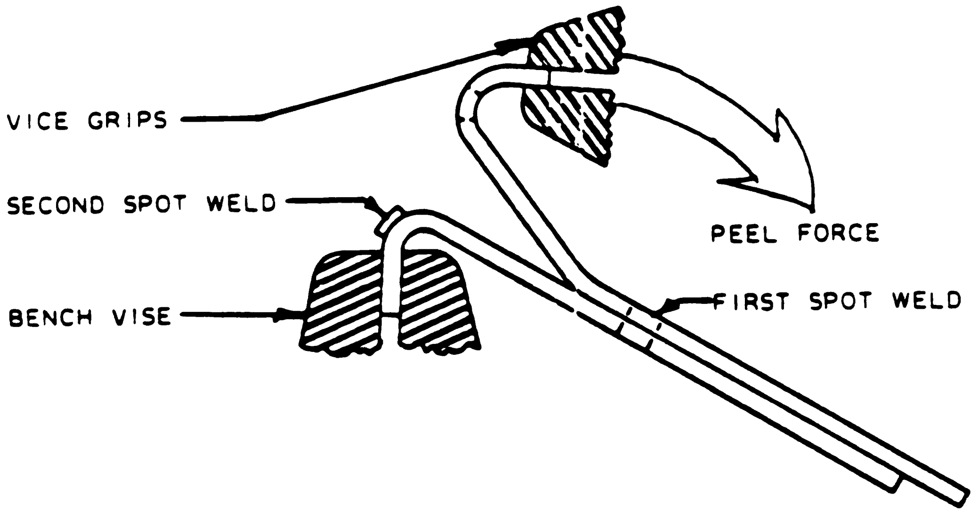


SPOT WELDED COUPONS FOR PEEL TEST

FIGURE 4A



SPOT WELDED COUPONS - PEEL TESTED

FIGURE 4B

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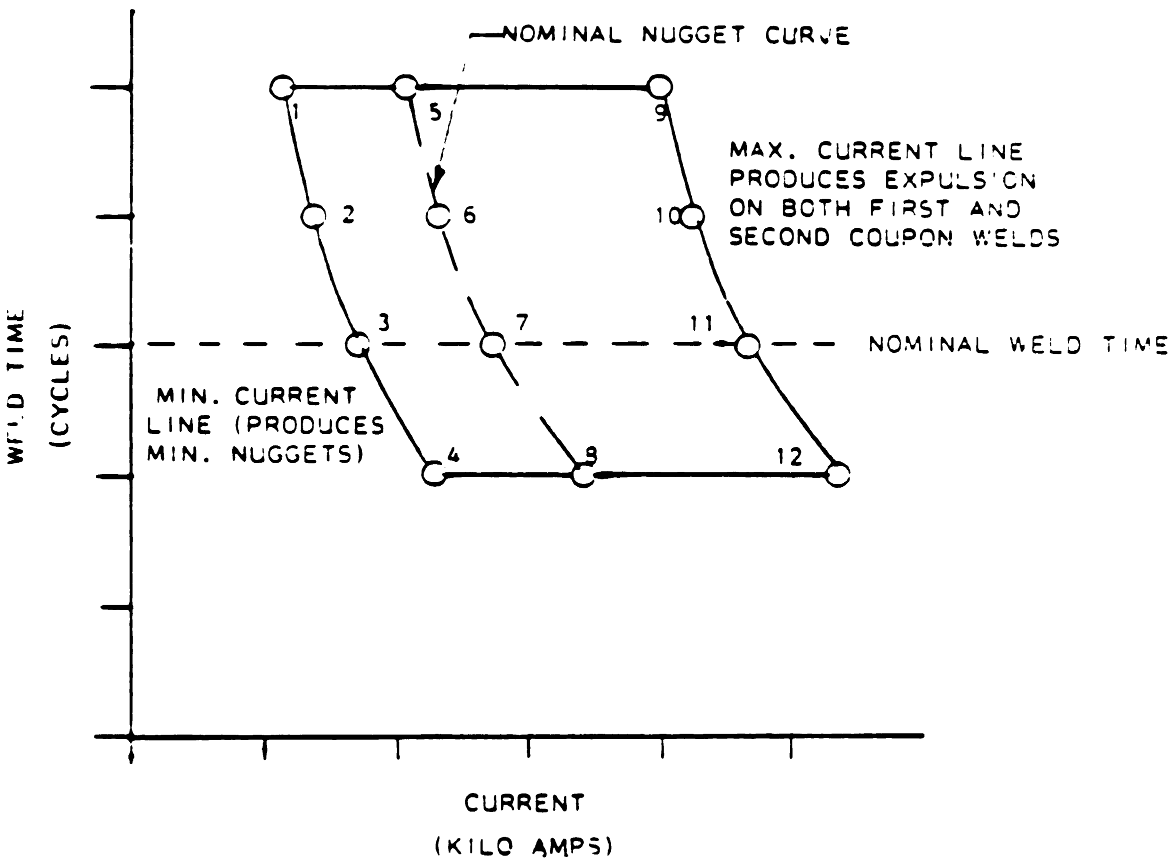
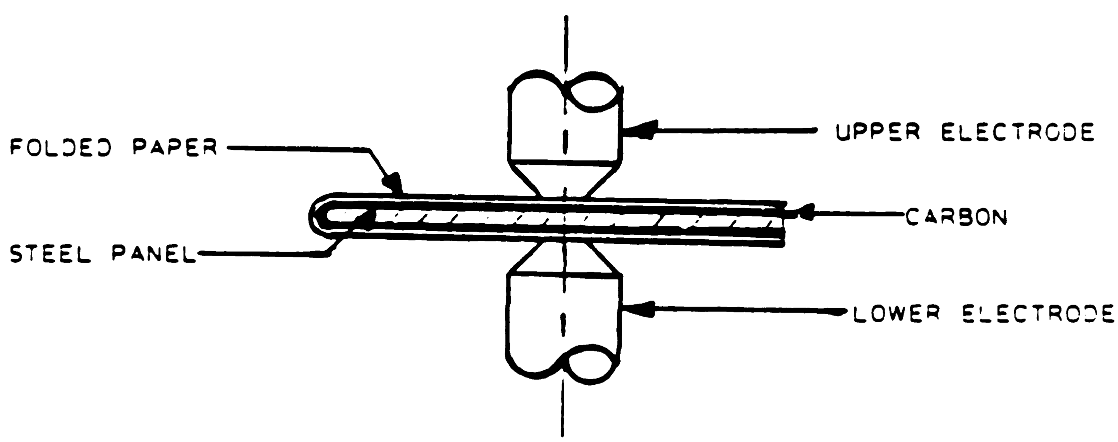


TYPICAL WELD LOBE

FIGURE 5



ELECTRODE CARBON IMPRINT

FIGURE 6

APPENDIX B

Mathematical Solution to the Common Area of Winking Circles

APPENDIX B - 1

Mathematical Solution to the Common Area of Winking Circles

The contact area of misaligned spot weld electrodes can be represented by "winking" circles, as shown in Figure B.1. The common shaded area A(m), is of interest in determining current density and pressure density in spot welding. The assumptions of this area approximation are:

1) Aligned electrodes are co-axial, flat and perpendicularly faced.

2) Misaligned electrodes are only misaligned in a radial direction, as in Figure B.2. Therefore the electrodes axes are still parallel, although they are no longer co-axial.

3) Misalignment, m, is defined as the distance between the axes.

4) Radius, R, is defined as 1/2 the face diameter of one of the electrodes.

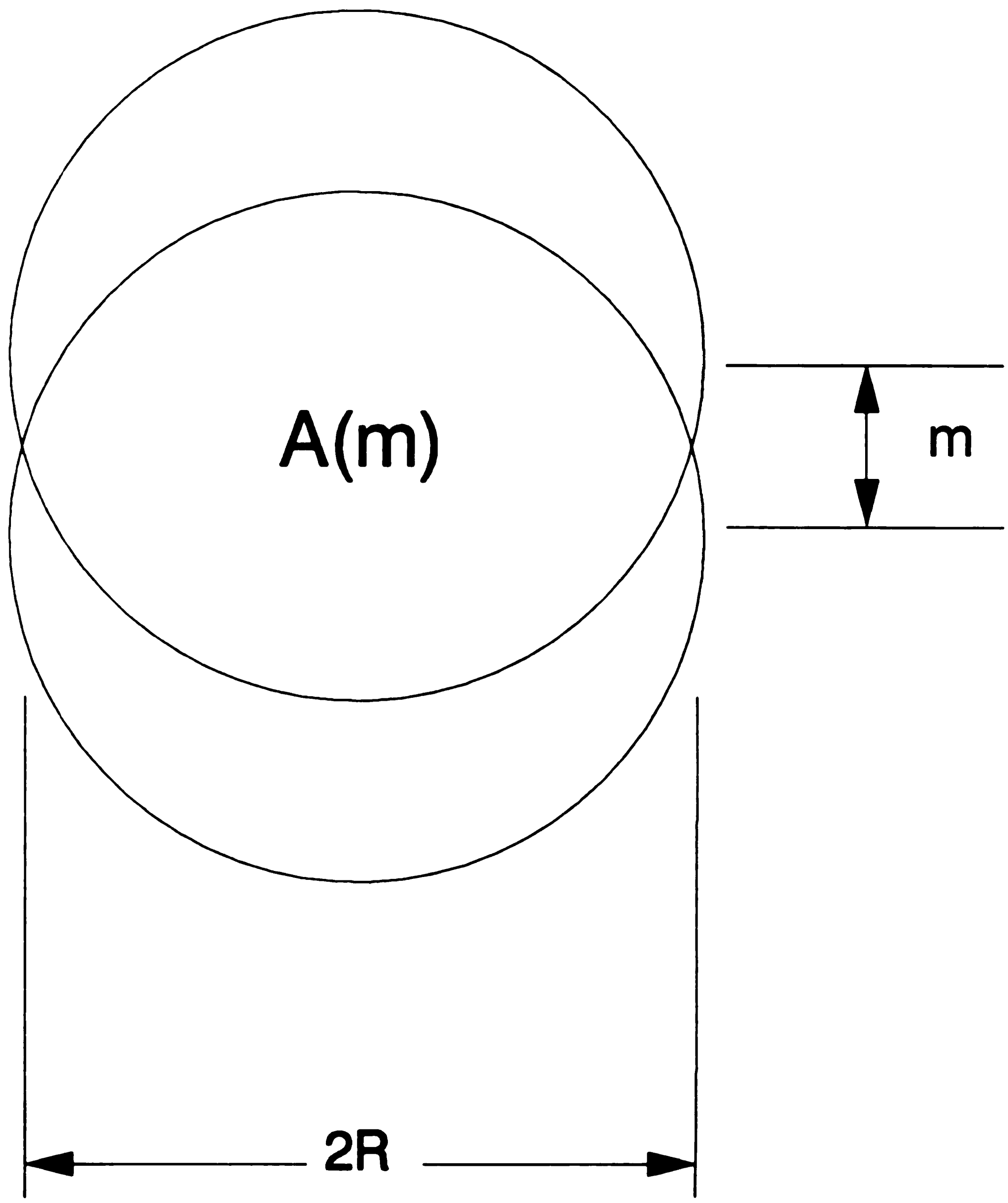
5) A(m) is the contact area A, at misalignment m.

6) $\bar{A}(\bar{m})$ is the fractional area $\bar{A}$, at fractional misalignment $\bar{m}$ (the fractional terms are dimensionless).

Consider the quadrant area A(m)/4, as in Figure B.3. The area of the quadrant at misalignment m, may be determined using rectangular elements as shown in Figure B.4. The solution follows as shown in Equations B.1 through B.13.

A plot of Equation B.13 is shown in Figure B.5. From the graph we see that the percent lost area due to misalignment is always greater than the percent

APPENDIX B - 2



R = radius of (flat-faced) electrode
m = displacement of electrode centers
A(m) = common electrode area of misaligned electrodes

Figure B.1 Model of "winking" circles.

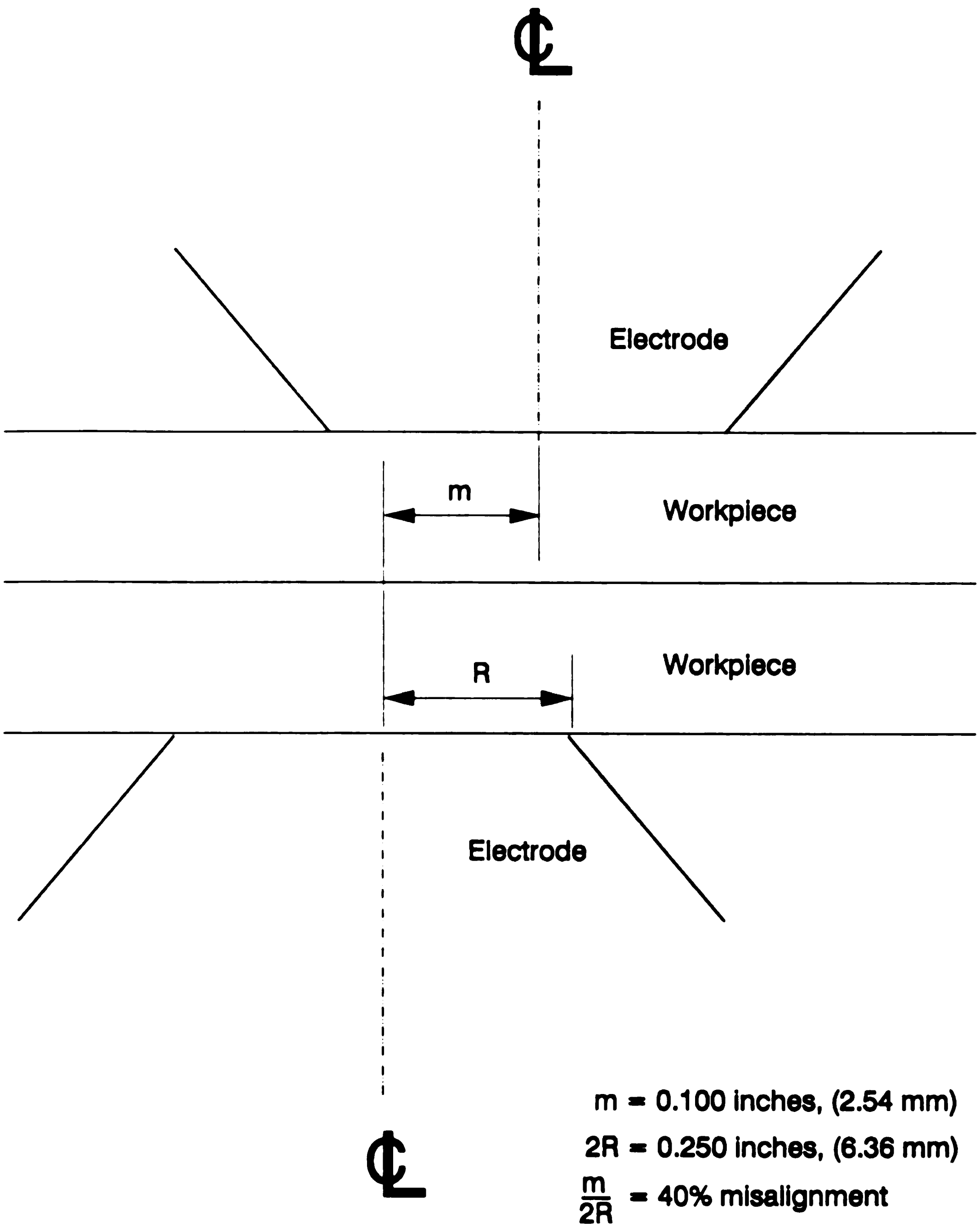


Figure B.2 In the "winking" model of electrode misalignment, the electrodes are allowed to shift out of alignment by distance m, while the axes remain parallel.

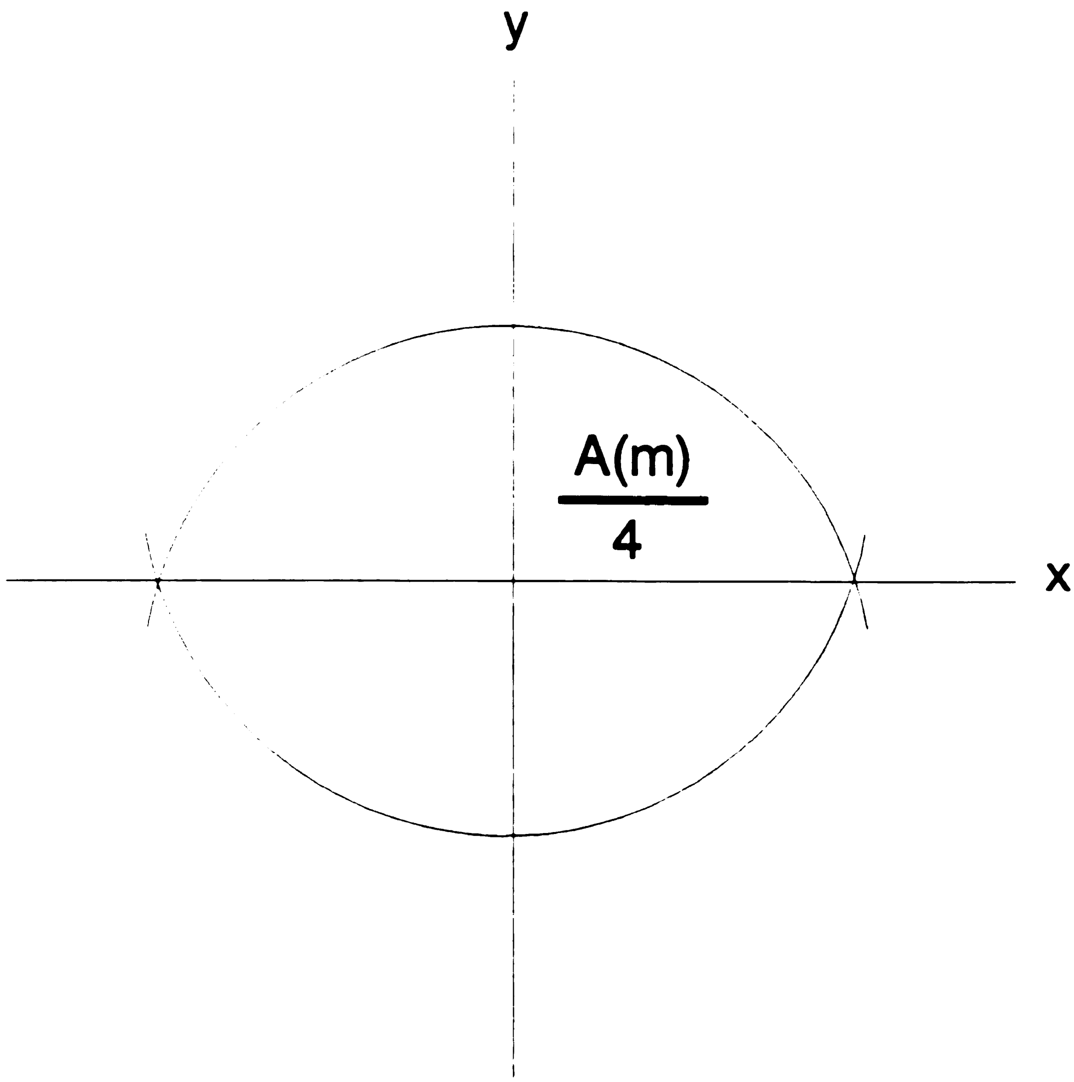


Figure B.3 The quarter area A(m)/4 is 1/4 of A(m), the contact area at misalignment m.

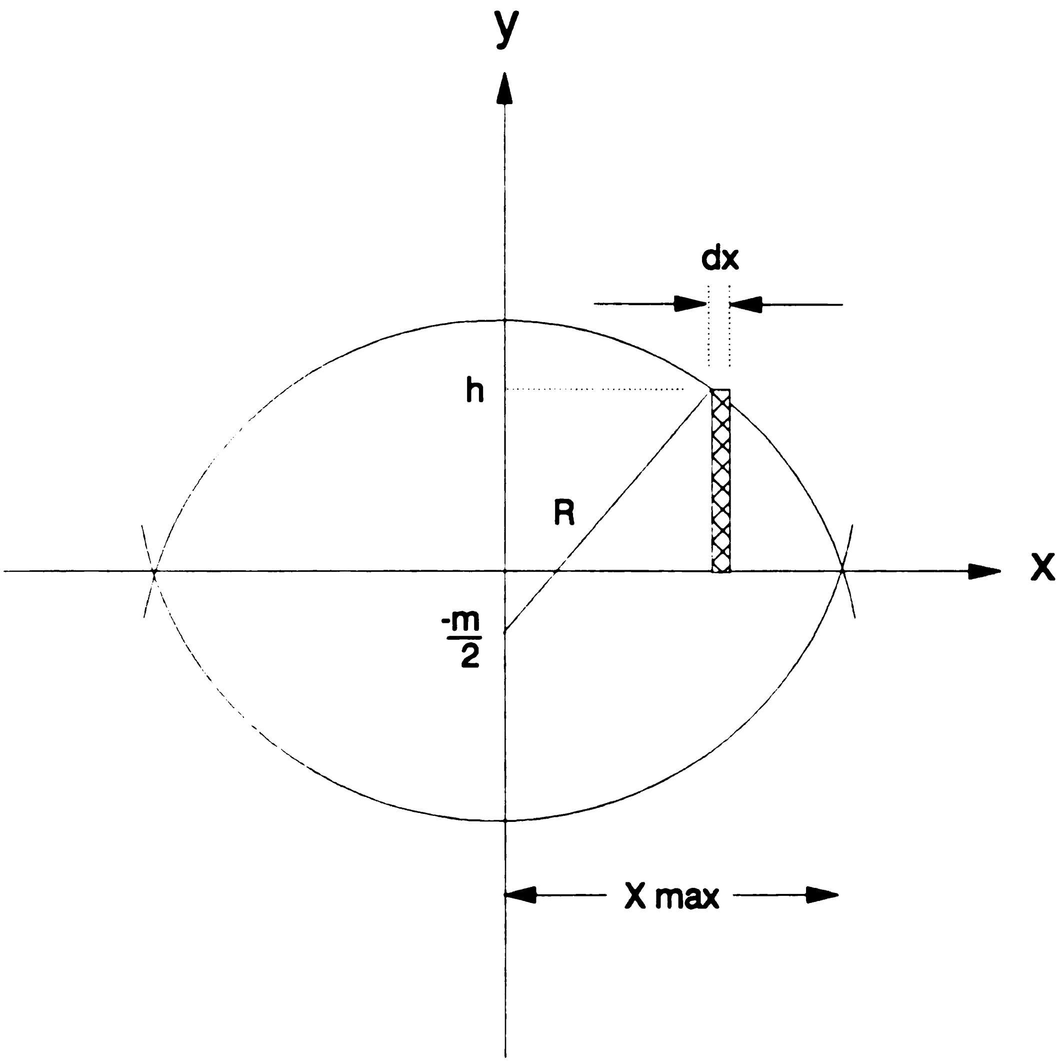


Figure B.4 The summation of rectangular elements by calculus.

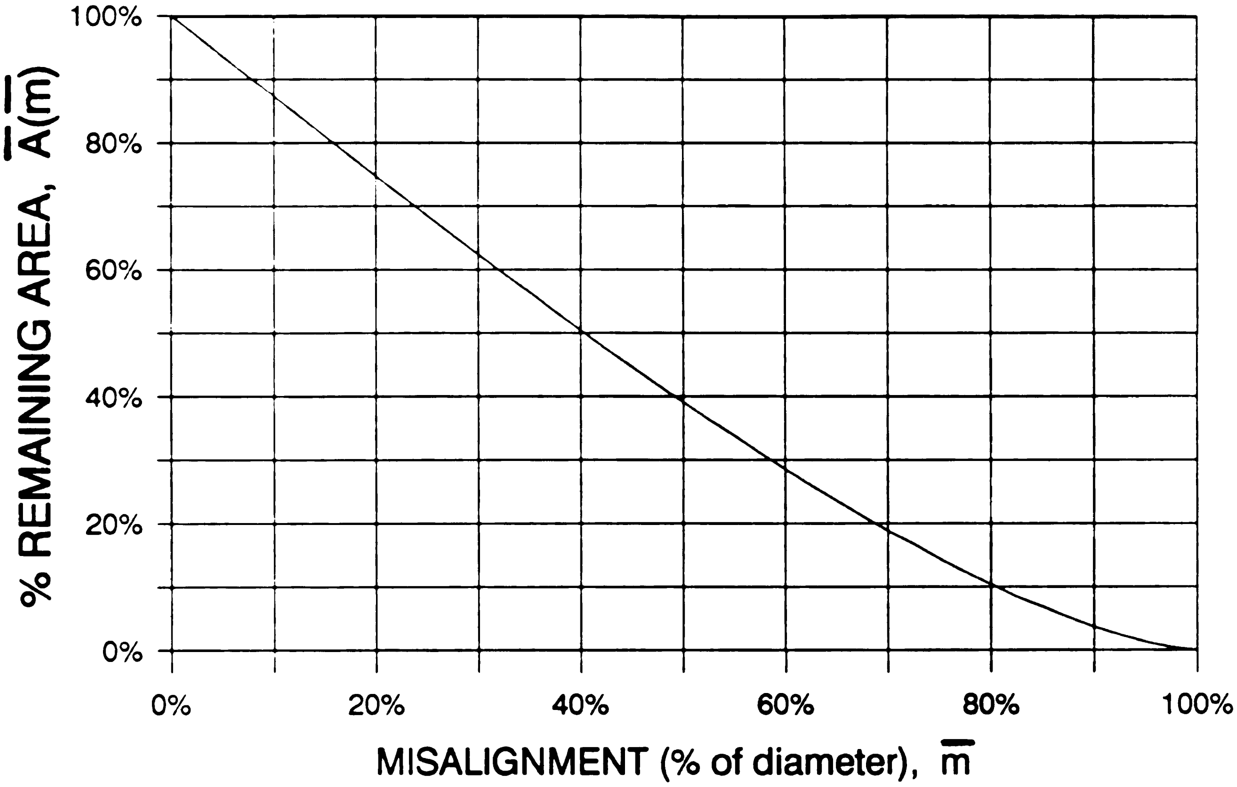


Figure B.5 The remaining contact area of misaligned electrodes.

misalignment, (% Lost Area = 100 - % Remaining Area). For example, at 40% misalignment the lost contact area is 50%. For electrodes 0.25 inches (6.35 mm) in diameter, this represents a misalignment of 0.10 inches (2.5 mm). This scenario is used in Section 4-4 of the main report.

APPENDIX B - 8

$$\frac{A}{4} = \int_0^{x(max)} h(x)\ dx \qquad [\ B.1\ ]$$

$$A = 4 \cdot \int_0^{x(max)} h(x)\ dx \qquad [\ B.2\ ]$$

where

$$h = \sqrt{R^2 - x^2} - \frac{m}{2} \qquad [\ B.3\ ]$$

and

$$x(max) = \sqrt{R^2 - \left[\frac{m}{2}\right]^2} \qquad [\ B.4\ ]$$

$$Am = 2 \cdot x \cdot \int_0^{x(max)} \sqrt{R^2 - x^2}\ dx - 2 \cdot m \cdot \int_0^{x(max)} dx$$

[B.5]

$$Am = 2 \cdot x \cdot \sqrt{R^2 - x^2} + 2 \cdot R^2 \cdot \operatorname{asin}\left[\frac{x}{R}\right] - 2 \cdot m \cdot x \Bigg|_0^{x(max)} \qquad [\ B.6\ ]$$

APPENDIX B - 9

$$Am = 2\cdot\sqrt{R^2 - \left[\frac{m}{2}\right]^2}\cdot\sqrt{R^2 - R^2 + \left[\frac{m}{2}\right]^2} +$$

$$+ 2\cdot R^2\cdot \operatorname{asin}\left[\frac{\sqrt{R^2 - \left[\frac{m}{2}\right]^2}}{R}\right] - 2\cdot m\cdot\sqrt{R^2 - \left[\frac{m}{2}\right]^2} \qquad [\ B.7\ ]$$

$$Am = m\cdot\sqrt{R^2 - \left[\frac{m}{2}\right]^2} + 2\cdot R^2\cdot \operatorname{asin}\left[\frac{\sqrt{R^2 - \left[\frac{m}{2}\right]^2}}{R}\right] - 2\cdot m\cdot\sqrt{R^2 - \left[\frac{m}{2}\right]^2}$$

[B.8]

$$Am = 2\cdot R^2\cdot \operatorname{asin}\left[\frac{\sqrt{R^2 - \left[\frac{m}{2}\right]^2}}{R}\right] - m\cdot\sqrt{R^2 - \left[\frac{m}{2}\right]^2} \qquad [\ B.9\ ]$$

The partial misalignment, $\bar{m}$, is defined:

$$\bar{m} \equiv \frac{m}{2 \cdot R} \quad , \quad m = 2 \cdot R \cdot \bar{m} \qquad [\text{ B.10 }]$$

And the remaining area in dimensionless terms, is defined:

$$\bar{A}(\bar{m}) = \frac{A(\bar{m})}{A(0)} \qquad [\text{ B.11 }]$$

Substituting,

$$\bar{A}(\bar{m}) = 2 \cdot R^2 \cdot \left[\frac{\operatorname{asin}\left[\frac{\sqrt{R^2 - (R \cdot \bar{m})^2}}{R} \right]}{\pi \cdot R^2} \right] - 2 \cdot R \cdot \bar{m} \cdot \frac{\sqrt{R^2 - (R \cdot \bar{m})^2}}{\pi \cdot R^2} \qquad [\text{ B.12 }]$$

which simplifies to:

$$\bar{A}(\bar{m}) = \frac{2}{\pi} \cdot \left[\operatorname{asin}\sqrt{1 - \bar{m}^2} - \bar{m} \cdot \sqrt{1 - \bar{m}^2} \right] \qquad [\text{ B.13 }]$$

APPENDIX C

Rewards and Benefits from Implementation of Findings in General Motors Plants

APPENDIX C - 1

Rewards and Benefits from Implementation of Findings in General Motors Plants

The following pages contain letters, reports, and excepts from meeting minutes regarding the implementation of weld process control that followed from this research. The program was implemented in three phases at the BOC Lansing Fabrication Plant of General Motors. The three phases were:

PHASE I	- Get Documents in Order
	- Get Inspection in Order
	- Get Repair Operations in Order
PHASE II	- Fix Processes
PHASE III	- Keep them Fixed

Although these phases were identified specifically for this implementation program, they were intentionally labeled generically, so as to encourage their use in process areas other than welding.

The Lansing Fab
Feature Line
Sept./Oct. 1990 Buy American

Weld Verification takes on an increasingly important role

Article inside page 7

To our brave service personnel serving in the Middle-East, our hearts and thoughts are with you

APPENDIX C - 3

Weld Verification Update

Information provided by Dave Kelly

In Sept of 1989 the weld verification team started to verify approximately 1503 weld guns at Plant 1,2 and 3. This was done with the cooperation of our production, trades, engineers and management working together to meet GM corporate standard that are required.

Weld verification and welder maintenance are on going jobs. From the time that a welder is verified, it needs to be monitored to be sure that all of the weld parameters are maintained. The welder maintenance personnel go through the welder and check the air pressure so that each weld gun has 600 lb of force. They take current readings so that they can set proper starting weld schedules. All other aspects of the welding process are checked out to be sure that they are operating properly. (water flow, gun operation, weld up alignment, etc)

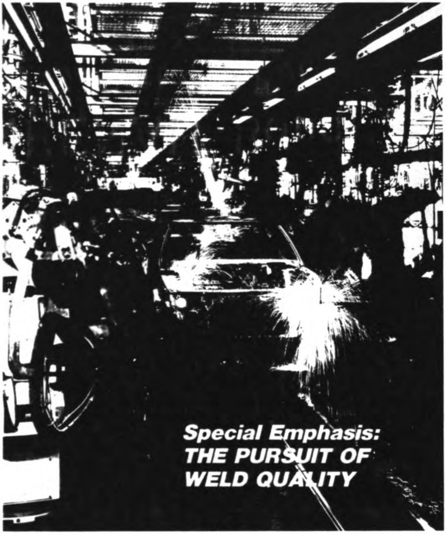
After all of the thing above are accomplished each variable needs to be monitored to make sure they are maintained at the proper setting.

Process monitoring is currently visually monitoring all the welders in Lansing through check sheets. The check sheets carry all the weld schedules and air pressure. The monitor will go to a welder and visually check the water flow indicators, they will check the weld controllers to make sure that that proper weld and stepper schedules are being maintained. We check with QC to see if all welds are acceptable and check air pressure gages for proper PSI. If during any of the checks, the monitor finds that any variable has been changed they document the findings on the maintenance log. The log is than given to the floor supervisor to report to area maintenance so that they can correct the situation or find out the reason for the change. Each week the maintenance log is reviewed. All documentation from the monitor is kept on file for one year.

On the cover Katherine Miller, C/H Rail Offline #3 welder operator talks with Skip Collins and Sheri Dubber, Process Monitoring. Other key figures that deal with the C/H line maintenance are Mike Miller, setup-man, Lynn Marier, jobsetter, Dale Napier and Jim Sonday, die tryout and Jim Stewart, supervisor.

MARCH 1991

AWS



How Cadillac Won the Malcolm Baldrige Quality Award 57

WELDING JOURNAL

PUBLISHED BY THE AMERICAN WELDING SOCIETY TO ADVANCE
THE SCIENCE, TECHNOLOGY AND APPLICATION OF WELDING

Fig. 1 — John O. Grettenberger (left), General Motors vice president and general manager of the Cadillac Motor Car Division, is greeted by Secretary of Commerce Robert A. Mosbacher at the 1990 Malcolm Baldrige National Quality Awards ceremony

PRACTICAL WELDER

Weld Quality Helps Cadillac Win the Malcolm Baldrige Award

BY BOB IRVING

Resistance spot welding played a key role in the recent Malcolm Baldrige National Quality Award competition for manufacturing won by the Cadillac Motor Car Division of General Motors Corp., Detroit — Fig. 1. For the 1990 award, more than 167,000 companies requested applications, but only 97 completed the rigorous procedure established by the U.S. Department of Commerce. Of the 97, only six made it to the finals. Four winners were chosen, but Cadillac was the only manufacturer engaged in welding production. The other manufacturer to win a 1990 Baldrige Award was the Rochester Division, IBM Corp. — see Table.

William Sarwas, a manufacturing engineer at Cadillac, said more than one-million resistance spot welds are made every day in the Detroit-Hamtramck Assembly Center. Each vehicle receives about 2700 resistance spot welds and 1900 of them are applied robotically. The balance, for the most part, are applied using hard automation.

Phillip Borowski, weld verification coordinator, said the mean average of good welds increased one whole percentage point, from 96.8% in December 1988 to 97.8% during the summer of 1990.

BOB IRVING is Features Editor of the Welding Journal.

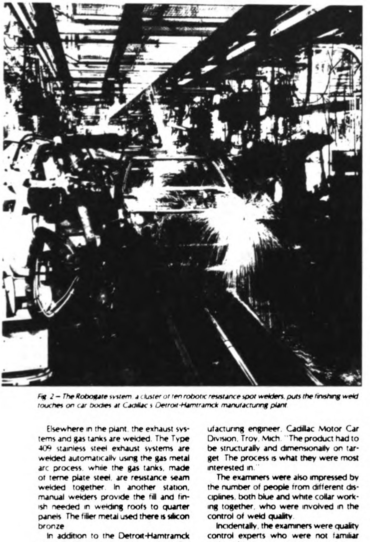


Fig. 2 – The Robogate system, a cluster of ten robotic resistance spot welders, puts the finishing weld touches on car bodies at Cadillac's Detroit-Hamtramck manufacturing plant.

Elsewhere in the plant, the exhaust systems and gas tanks are welded. The Type 409 stainless steel exhaust systems are welded automatically using the gas metal arc process, while the gas tanks, made of terne plate steel, are resistance seam welded together. In another station, manual welders provide the fill and finish needed in welding roofs to quarter panels. The filler metal used there is silicon bronze.

In addition to the Detroit-Hamtramck plant, the Baldrige examiners visited Cadillac's stamping and metal fabricating plant in Grand Blanc, Mich., as well as the Buick Reatta plant in Lansing, Mich. (Cadillac is responsible for manufacturing the Reatta.) The Baldrige examiners also visited the divisional engineering offices in Detroit and in Troy, Mich.

Phillip D. Jones, superintendent of manufacturing engineering at the Detroit-Hamtramck plant, said, "The examiners were interested in our preventative maintenance and in our weld verification areas. They were particularly interested in our use of statistical process control in resistance spot welding."

"The examiners wanted to make sure that our statistical checks were stable and capable," added Al Turley, advanced manufacturing engineer, Cadillac Motor Car Division, Troy, Mich. "The product had to be structurally and dimensionally on target. The process is what they were most interested in."

The examiners were also impressed by the number of people from different disciplines, both blue and white collar working together, who were involved in the control of weld quality.

Incidentally, the examiners were quality control experts who were not familiar with welding.

The body steels of the automobiles assembled at the Detroit-Hamtramck Assembly Center are, in many areas, two-side hot-dipped and electrogalvanized steel. The steels are generally SAE 1008 and 1010 mild steel. Of course, it is more difficult to weld these types of galvanized steel than it is to weld bare steel of the same composition. To aid in the welding of these coated steels, Cupal caps are snug fitted onto resistance welding electrode shanks. Cupal is an acronym for a dispersion-strengthened copper and aluminum oxide powder metal alloy. The caps are expensive, but Cadillac production people believe they are worth it in terms of reliability.

Of the 190 resistance spot welding robots in use at the Detroit-Hamtramck plant, 188 of them are robots from GM-Fanuc Robotics Corp., Auburn Hills, Mich. These units are 6-axis articulated coordinate, electromechanically operated robots. Their repeatability is rated at ±0.02 in.

On the welding line, there are two Robogates (Fig. 2) which initially weld the automobile frames. Each Robogate contains ten robotically controlled resistance spot welding guns.

In terms of welding equipment, another prominent investment at the Detroit-Hamtramck plant is numerous robot-mounted high-frequency DC transformers from Square D Co., Chatsworth, Calif. An advantage of these transformers is that they are about 60% lighter than conventional AC integral gun transformers. These units are also helping to improve weld quality on the Cadillac auto bodies.

With its ability to localize high energy, the DC permits the elimination of "kickless" weld cables, thereby reducing the maintenance cost of this installation. Cadillac likes the fact that the trans-gun or high-frequency DC gun permits it to program weld schedules in amperes without going through all the time-consuming steps required to do the same using conventional controls.

"Our statistics are based on destructive testing," said Borowski. "That is the most reliable way to check whether you have good or bad welds."

In terms of resistance spot welding, the destructive test plays a critically important role in quality control at Cadillac. It is the results from these tests that provide the data for statistical process control within the Detroit-Hamtramck plant. Chisel tests are frequently performed to ascertain whether fusion is taking place. The chisel test is also a good means of checking for broken or stuck welds, one of six categories of "discrepant welds." Four other categories, off-location welds, omitted welds, edge welds and burn-throughs, can be detected visually. An undersized weld, the sixth category of discrepant welds, can only be detected during "tear-down." There are between 35 and 40 tear-downs per year. For that type of work, the Jaws of Life, a rescue tool manufactured by the Hale Fire Pump Co., Conshohocken, Pa., and often used by firemen, is used to rip the spot-welded auto frames apart – Fig. 3.

The information gleaned from tear-downs is applied to the SPC chart. Supervisors can then determine whether the spot welding operations are still within their limits whether they are trending up or down

Each year, the Detroit-Hamtramck plant spends 30,000 man-hours in chisel checks, tear-downs, current analyses and preventative maintenance on its welding operations. The 30,000 man-hours only represent the time spent in the one plant by the hourly work force. It does not include the enormous amount of time consumed in designing and building new equipment for welding or in modifying existing equipment for new model runs.

A great deal of money for welding at Cadillac is spent on the mechanics of the assembly line, for tooling and fixturing and clamping.

"A lot of plant input goes into constantly updating tool design standards," said Turley. "One of the very key things is a formal weld tool verification procedure. At the construction phase, tooling goes through a formal checkout to see if it does indeed represent design intent. That process will catch design errors and construction errors before they ever reach the plant."

Cadillac made it to the finals for the 1989 Baldrige award.

To apply for the award, companies must submit a 75-page application which is actually a detailed examination of what the companies are all about. The seven sections in the application include leadership, information/analysis, planning, human resources, quality assurance, results and customer satisfaction.

The overseer of the award is the National Institute of Standards and Technology, Gaithersburg, Md. An administrator of the 1990 award was the American Society for Quality Control, Milwaukee. The 1990 board of examiners consisted of nine judges and 169 examiners.

Quality improvements at Cadillac have led to a 30% reduction in warranty costs over the last four years. Six years ago, the GM division became heavily involved in simultaneous engineering, and that has had significant impact on its quality improvement program.

The Cadillac Detroit-Hamtramck Assembly Center is one of the plant tours scheduled during next month's AWS Welding Convention and Exposition in Detroit, Mich. Plans call for three tours, one on Wednesday, April 17, and two on Thursday, April 18. Each tour will be limited to 45 people. For tour information, call (800) 443-9353. ♦

Malcolm Baldrige National Quality Award Winners

Year	Winner	
1988	Motorola Inc.	Manufacturing
	Westinghouse Electric Corp. Commercial Nuclear Fuel Division	Manufacturing
	Globe Metallurgical Inc.	Small Business
1989	Xerox Corp. Business Products and Systems	Manufacturing
	Milliken & Co.	Manufacturing
1990	Cadillac Motor Car Division, General Motors Corp.	Manufacturing
	IBM Corp. Rochester Division	Manufacturing
	Wallace Co. Inc.	Small Business
	Federal Express Corp.	Service

Fig. 3 — In the tear-down tests at Cadillac, special tooling is used to evaluate the integrity of the resistance spot welds.

APPENDIX C - 8

WELD TOOL VERIFICATION
GUN PREPARATION STEPS

1. GOOD COPPER (BIDDLE)
2. MACHINE LABELED
3. HANG STATION/GUN/HIT/SCR CHARTS
4. AIR GAGES ALL IN GOOD SHAPE
5. GUNS ALL IN ACCEPTABLE CONDITION
6. GUNS ALIGNED, WELD LOCATIONS CORRECT
7. COOLING WATER ACCEPTABLE (INFRARED)
8. ITEM NUMBERS OF CAPS, SHANKS, ADAPTERS, SHUNTS
9. WTIS - RECORD ALL WELD SCHEDULES/SCR'S BY GUN NUMBER

GUN QUALIFICATION STEPS

1. TEST CURRENT BALANCE BETWEEN SIMULTANEOUS WELDS. (GOAL: ALL WELDS WITHIN 10% OF EACH OTHER)
2. TEST FOR MAXIMUM OUTPUT AT 81% HEAT FOR (5) CYCLES ON TOP OF A PREVIOUS WELD. IF MAX CURRENT COMPARES WELL WITH DESIGNED MAX. CURRENT (OR RED BOOK CURRENT RECOMMENDATION), THEN SET-UP WELD SCHEDULE ACCORDING TO RED BOOK RECOMMENDATIONS AT 20% LESS CURRENT. IF CURRENT OUTPUT IS LESS THAN DESIGNED (OR RED BOOK) THEN USE PULSATION (2-3 PULSES). SET WELD FORCE: 600# FOR LIGHT GAGE METAL; 900# IF GMT GREATER THAN .055".
3. WHEN FINISHED - GET FINAL PART OK FROM WELD INSPECTION. NUGGET SIZES RECORDED AND SIGNED STATEMENT THAT ALL WELDS MEET SPECIFICATIONS.
4. CLEAN UP WTIS AND <u>POST</u>

PREVENTIVE MAINTENANCE

1. SET-UP PREVENTIVE MAINTENANCE SCHEDULE AND GET SHEETS MADE UP.
2. SET-UP PROCESS MONITORING WITH PRODUCTION APPROVAL.

Subject: GM Weld Information Group
(GM-WIG) January Mtg

January 23, 1989

From: M. L. Brinkmann

To: See Attached Distribution

The January meeting took place at Medar, Inc in Farmington Hills, MI on Thursday, January 18, 1989. Attendance indicated on the attached sign-in sheet.

Following are the dates and locations of future meetings:

February 15, 1990 - 8:30 AM
Kirkhof-Flex-Cable
Troy Hilton
Contact: Jack Goodrich (313)689-4666

March 15, 1990 - 8:30 AM
? - Need a volunteer

April 19, 1990 - 8:30 AM
? - Need a volunteer

Highlights of the January Meeting as follows:

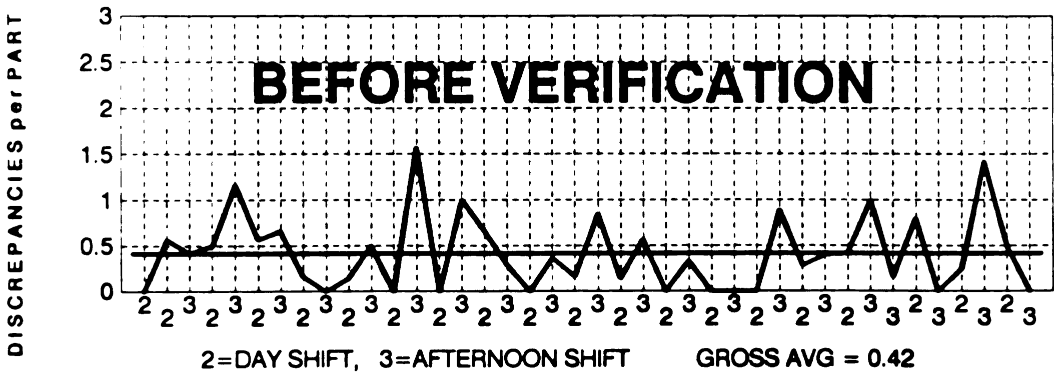
LANSING (BOC) FAB WELD VERIFICATION

Mike Karagoulis of BOC Lansing explained their weld tool verification, gun qualification, and preventive maintenance plans. The capability of the process to reduce discrepancies was demonstrated with a "before and after" story for an actual part. A nifty part of Mike's presentation was a parameter chart of "Recommended Values for Phase II Weld Tool Verification". This chart may provide the "operational" parameters mentioned earlier in these minutes. A neat feature is to show the reduction in required current for different tip combinations; for example two ball nose caps take approximately .5 X the current shown on the chart; one ball nose and one flat cap take approximately .75 X the current shown; etc..

There was so much good stuff in Mike's presentation that it was agreed to attach his presentation material - including the aforementioned chart - to these minutes.

WELD QUALITY: 25541582

C/H SHOCK TOWER - RH (from 09/01 - 09/30)



WELD INTEGRITY HISTORY REPORT -- DAILY FLOOR DATA from LANSING FAB

PART: C/H SHOCK TOWER - RH period: 09/01/89 - 09/30/89

CAR SERIES: C/H GROSS AVG = 0.42 DISCREPANCIES PER PANEL
HIGH AVG = 1.57 LOW AVG = 0.00

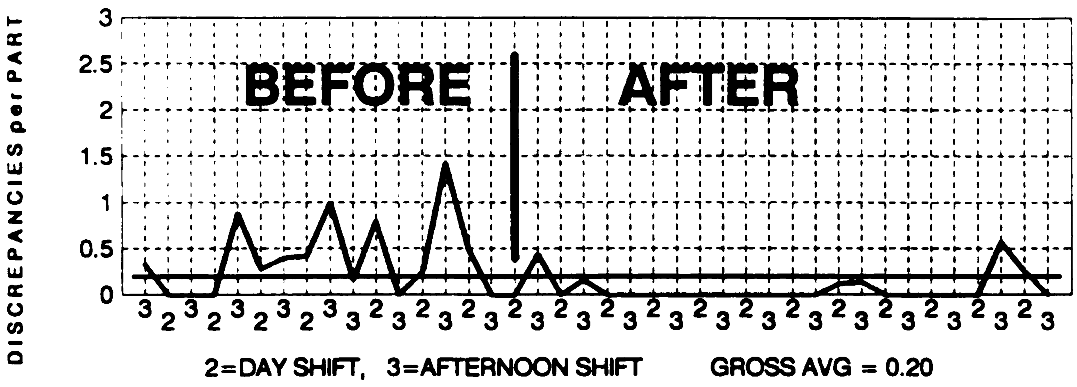
BUILDING/AREA: 207

NUMBER of SHIFTS REPORTED = 40

Date	PART	NAME	Sft	Pnls Chkd	DISC /pnl	DEM /pnl
09/01/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	8	0.00	0.00
09/05/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	7	0.57	2.57
09/05/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	7	0.42	2.85
09/06/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	4	0.50	3.50
09/06/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	6	1.16	5.66
09/07/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	7	0.57	4.28
09/07/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	6	0.66	1.66
09/08/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	6	0.16	1.66
09/08/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	5	0.00	0.00
09/11/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	7	0.14	1.42
09/11/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	6	0.50	4.00
09/12/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	3	0.00	0.00
09/12/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	7	1.57	6.28
09/13/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	6	0.00	0.00
09/13/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	4	1.00	2.50
09/14/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	6	0.66	2.33
09/14/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	7	0.28	1.42
09/15/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	4	0.00	0.00
09/15/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	8	0.37	3.00
09/18/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	6	0.16	0.66
09/18/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	7	0.85	2.57
09/19/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	7	0.14	0.57
09/19/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	7	0.57	2.57
09/20/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	8	0.00	0.00
09/20/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	6	0.33	1.66
09/21/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	6	0.00	0.00
09/21/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	8	0.00	0.00
09/22/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	5	0.00	0.00
09/22/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	9	0.88	3.55
09/25/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	7	0.28	2.00
09/25/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	5	0.40	2.00
09/26/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	7	0.42	2.85
09/26/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	7	1.00	2.85
09/27/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	6	0.16	1.66
09/28/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	5	0.80	5.60
09/28/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	8	0.00	0.00
09/29/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	4	0.25	1.00
09/29/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	7	1.42	5.71
09/30/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	6	0.50	0.66
09/30/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	8	0.00	0.00

WELD QUALITY: 25541582

C/H SHOCK TOWER - RH (from 09/20 - 10/25)



WELD INTEGRITY HISTORY REPORT -- DAILY FLOOR DATA from LANSING FAB

PART: C/H SHOCK TOWER - RH period: 09/20/89 - 10/25/89

CAR SERIES: C/H GROSS AVG = 0.20 DISCREPANCIES PER PANEL
HIGH AVG = 1.42 LOW AVG = 0.00

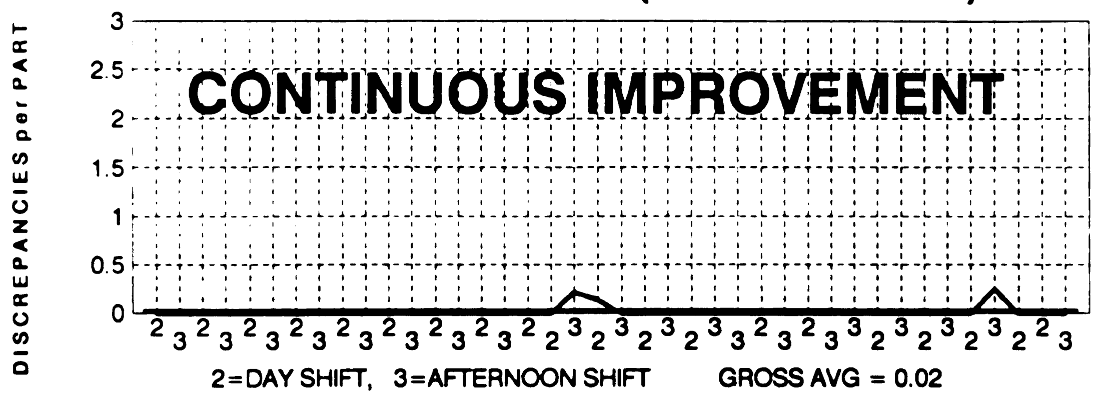
BUILDING/AREA: 207

NUMBER of SHIFTS REPORTED = 40

Date	PART	NAME	Sft	Pnls Chkd	DISC /pnl	DEM /pnl
09/20/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	6	0.33	1.66
09/21/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	6	0.00	0.00
09/21/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	8	0.00	0.00
09/22/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	5	0.00	0.00
09/22/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	9	0.88	3.55
09/25/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	7	0.28	2.00
09/25/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	5	0.40	2.00
09/26/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	7	0.42	2.85
09/26/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	7	1.00	2.85
09/27/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	6	0.16	1.66
09/28/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	5	0.80	5.60
09/28/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	8	0.00	0.00
09/29/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	4	0.25	1.00
09/29/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	7	1.42	5.71
09/30/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	6	0.50	0.66
09/30/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	8	0.00	0.00
10/10/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	7	0.00	0.00
10/10/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	9	0.44	1.11
10/11/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	4	0.00	0.00
10/11/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	6	0.16	0.66
10/12/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	7	0.00	0.00
10/12/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	8	0.00	0.00
10/13/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	7	0.00	0.00
10/13/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	5	0.00	0.00
10/16/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	6	0.00	0.00
10/16/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	5	0.00	0.00
10/17/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	8	0.00	0.00
10/17/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	8	0.00	0.00
10/18/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	8	0.00	0.00
10/18/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	7	0.00	0.00
10/19/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	8	0.12	1.25
10/19/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	7	0.14	1.42
10/20/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	8	0.00	0.00
10/20/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	8	0.00	0.00
10/23/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	8	0.00	0.00
10/23/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	8	0.00	0.00
10/24/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	7	0.00	0.00
10/24/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	7	0.57	2.85
10/25/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	8	0.25	1.75
10/25/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	7	0.00	0.00

WELD QUALITY: 25541582

C/H SHOCK TOWER - RH (from 10/30 - 12/05)



WELD INTEGRITY HISTORY REPORT -- DAILY FLOOR DATA from LANSING FAB

PART: C/H SHOCK TOWER - RH period: 10/30/89 - 12/05/89

CAR SERIES: C/H GROSS AVG = 0.02 DISCREPANCIES PER PANEL
HIGH AVG = 0.25 LOW AVG = 0.00

BUILDING/AREA: 207

NUMBER of SHIFTS REPORTED = 40

Date	PART	NAME	Sft	Pnls Chkd	DISC /pnl	DEM /pnl
10/30/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	7	0.00	0.00
10/30/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	7	0.00	0.00
10/31/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	7	0.00	0.00
10/31/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	7	0.00	0.00
11/01/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	5	0.00	0.00
11/01/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	1	0.00	0.00
11/02/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	7	0.00	0.00
11/02/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	6	0.00	0.00
11/03/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	8	0.00	0.00
11/03/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	7	0.00	0.00
11/06/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	7	0.00	0.00
11/06/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	5	0.00	0.00
11/07/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	7	0.00	0.00
11/07/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	5	0.00	0.00
11/08/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	3	0.00	0.00
11/08/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	10	0.00	0.00
11/09/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	12	0.00	0.00
11/10/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	7	0.00	0.00
11/10/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	9	0.22	0.44
11/13/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	7	0.14	0.57
11/13/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	8	0.00	0.00
11/14/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	9	0.00	0.00
11/14/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	7	0.00	0.00
11/15/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	7	0.00	0.00
11/15/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	6	0.00	0.00
11/21/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	8	0.00	0.00
11/22/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	5	0.00	0.00
11/22/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	8	0.00	0.00
11/27/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	1	0.00	0.00
11/27/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	9	0.00	0.00
11/28/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	10	0.00	0.00
11/29/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	5	0.00	0.00
11/29/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	5	0.00	0.00
11/30/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	5	0.00	0.00
11/30/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	7	0.00	0.00
12/01/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	3	0.00	0.00
12/04/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	8	0.25	0.50
12/05/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	8	0.00	0.00
12/05/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	9	0.00	0.00
12/05/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	2	0.00	0.00

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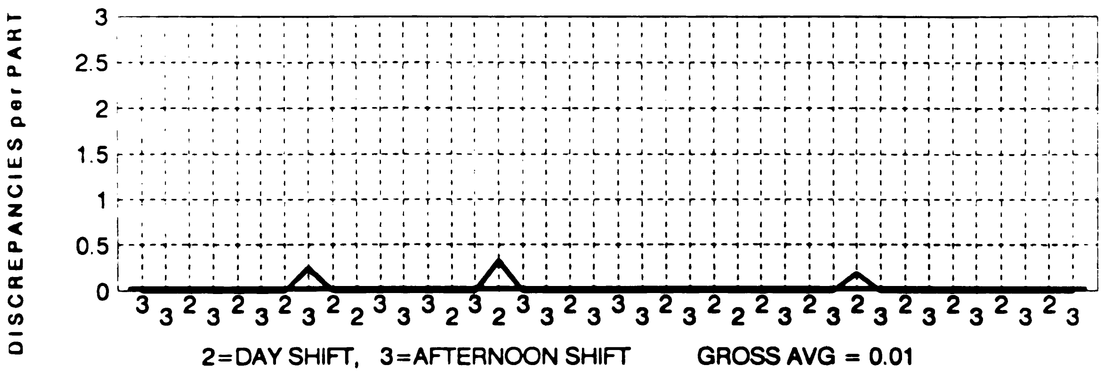
WELD QUALITY: 25541582

C/H SHOCK TOWER - RH (from 11/27 - 01/24)



2=DAY SHIFT, 3=AFTERNOON SHIFT GROSS AVG = 0.01

WELD INTEGRITY HISTORY REPORT -- DAILY FLOOR DATA from LANSING FAB

PART: C/H SHOCK TOWER - RH period: 11/27/89 - 01/24/90

CAR SERIES: C/H GROSS AVG = 0.01 DISCREPANCIES PER PANEL
HIGH AVG = 0.33 LOW AVG = 0.00

BUILDING/AREA: 207

NUMBER of SHIFTS REPORTED = 40

Date	PART	NAME	Sft	Pnls Chkd	DISC /pnl	DEM /pnl
11/27/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	9	0.00	0.00
11/28/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	10	0.00	0.00
11/29/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	5	0.00	0.00
11/29/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	5	0.00	0.00
11/30/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	5	0.00	0.00
11/30/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	7	0.00	0.00
12/01/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	3	0.00	0.00
12/04/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	8	0.25	0.50
12/05/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	8	0.00	0.00
12/05/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	9	0.00	0.00
12/05/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	2	0.00	0.00
12/06/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	9	0.00	0.00
12/07/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	7	0.00	0.00
12/08/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	5	0.00	0.00
12/08/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	9	0.00	0.00
12/11/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	3	0.33	1.33
12/11/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	8	0.00	0.00
12/12/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	8	0.00	0.00
12/13/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	4	0.00	0.00
12/13/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	7	0.00	0.00
12/14/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	8	0.00	0.00
12/15/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	7	0.00	0.00
12/18/89	25541582	PANEL ASM-MTR COMP SI & WH RH	2	7	0.00	0.00
12/18/89	25541582	PANEL ASM-MTR COMP SI & WH RH	3	9	0.00	0.00
01/08/90	25541582	PANEL ASM-MTR COMP SI & WH RH	2	11	0.00	0.00
01/09/90	25541582	PANEL ASM-MTR COMP SI & WH RH	2	8	0.00	0.00
01/16/90	25541582	PANEL ASM-MTR COMP SI & WH RH	2	7	0.00	0.00
01/16/90	25541582	PANEL ASM-MTR COMP SI & WH RH	3	5	0.00	0.00
01/17/90	25541582	PANEL ASM-MTR COMP SI & WH RH	2	4	0.00	0.00
01/17/90	25541582	PANEL ASM-MTR COMP SI & WH RH	3	9	0.00	0.00
01/18/90	25541582	PANEL ASM-MTR COMP SI & WH RH	2	5	0.20	0.80
01/18/90	25541582	PANEL ASM-MTR COMP SI & WH RH	3	7	0.00	0.00
01/19/90	25541582	PANEL ASM-MTR COMP SI & WH RH	2	4	0.00	0.00
01/19/90	25541582	PANEL ASM-MTR COMP SI & WH RH	3	9	0.00	0.00
01/22/90	25541582	PANEL ASM-MTR COMP SI & WH RH	2	6	0.00	0.00
01/22/90	25541582	PANEL ASM-MTR COMP SI & WH RH	3	7	0.00	0.00
01/23/90	25541582	PANEL ASM-MTR COMP SI & WH RH	2	3	0.00	0.00
01/23/90	25541582	PANEL ASM-MTR COMP SI & WH RH	3	8	0.00	0.00
01/24/90	25541582	PANEL ASM-MTR COMP SI & WH RH	2	7	0.00	0.00
01/24/90	25541582	PANEL ASM-MTR COMP SI & WH RH	3	8	0.00	0.00

LEADING CAUSES OF SPOT WELD PROBLEMS

1) EXCESSIVE OPEN-CIRCUIT RESISTANCE IN SECONDARY LOOP

- WORN CABLES
- LOOSE, PITTED CONNECTIONS

2) COOLING WATER INSUFFICIENT

- BLOCKED FLOW
- INADEQUATE PRESSURE DROP ACROSS WATER MANIFOLDS

3) GUN CONDITION MECHANICALLY SUBSTANDARD

- CYLINDER LEAKING, WORN OUT
- BUSHING WEAR
- SPOT LOCATION

4) CURRENT NOT SET PROPERLY

- TRANSFORMER SIZE INAPPROPRIATE
- CABLE ROUTINGS CAUSE EXECESSIVE IMPEDANCE LOSSES
- CURRENT BALANCE OF SIMULTANEOUS WELDS
- IRON IN THE LOOP

CONTROL METHODS FOR MAIN VARIABLES

1) OPEN-CIRCUIT RESISTANCE

- MONITOR USING "BIDDLE" METER OR THROUGH WELD CONTROL

- SERVICE LOOPS AS NEEDED TO KEEP RESISTANCE GENERALLY < 150 u-ohm

2) COOLING WATER

- MONITOR USING:
  - FLOW INDICATORS
  - PRESSURE GAUGES
  - INFRA-RED SCANNER

- SERVICE COOLING AS NEEDED TO ELIMINATE HOT SPOTS IN TOOLS

3) GUN CONDITION

- MONITOR USING FREQUENT VISUAL CHECKS FOR:
  - AIR PRESSURE
  - GUN ACTION (STICKING)
  - BLOW BY (HISSING)
  - SPOT LOCATION
  - ALIGNMENT
- MONITOR USING FORCE GAUGE

- SERVICE AS NEEDED TO MAINTAIN POSTED SETUP

4) CURRENT MONITORING

- RUN PROCESS NEAR EXPULSION POINT
- PROGRAM WELD CONTROL IN CURRENT (AMPS), RATHER THAN %H OR %I
- MONITOR WELD SCHEDULES FREQUENTLY AGAINST POSTED VALUES
- WATCH PARTS FOR A FEW LARGE WELDS LATE IN THE STEPPER SEQUENCE
- MEASURE CURRENT BALANCE USING WCS-515 PHASE II TECHNIQUE

- SERVICE AS NEEDED TO MAINTAIN POSTED CURRENTS FOR EACH WELD

SPOT WELD PROCESS MONITORING GUIDE

	KEY PROCESS VARIABLES			
CHECK METHODS	1 LOOP RESISTANCE	2 COOLING WATER	3 GUN CONDITION	4 WELD CURRENT
WITHOUT TOOLS:	■ THROUGH WELD CONTROL	■ FLOW INDICATORS ■ PRESSURE GAUGES	■ AIR PRESSURE ■ GUN ACTION (sticking) ■ BLOW-BY (hissing) ■ SPOT LOCATION ■ PART DISTORTION ■ MISALIGNMENT ■ LEAKS	■ SETUP AT EXPULSION POINT (visual) ■ WELD SCHEDULE CHANGES ■ LARGE WELDS (visual) ■ THROUGH WELD CONTROL
WITH TOOLS:	■ "BIDDLE" METER	■ INFRA-RED SCANNER	■ FORCE GAUGE	■ CURRENT METER(s)

APPENDIX C - 17

November 1, 1989

To: Distribution

From: Jim Rypkema

Subject: Measured Improvements Weld-Fab Shocktower Lines
09-01-89 to 09-30-89 / 10-01-89 to 10-31-89

As a result of weld verification process and ongoing scheduled maintenance for both North & South Shocktower Lines we have achieved the following results in the last 60 days:

QUALITY:

Based on documentation from destruct tests for failed welds on a daily shift basis:

	September 1989 Total Failed Welds-All Samples	October 1989 Total Failed Welds-All Samples
R/H Shocktower	81	29
L/H Shocktower	68	48

Analysis: **R/H Side saw a reduction in failed welds of -52.**
L/H Side saw a reduction in failed welds of -20.

This represents a 64% improvement in the R/H Side, and a 29% improvement in the L/H Side.

UPTIME:

The actual increase in parts run as a result of this maintenance and weld verification is as follows:

	September 1989 Parts Per Hour	October 1989 Parts Per Hour	+/- %
R/H Side	207.7	221.8	+14.1 +6.7%
L/H Side	204.9	222.7	+17.8 +8.7%

The actual increase in capacity was 4,512 more R/H parts, and 5,696 L/H parts. By producing more parts per hour in same allotted time, we are decreasing the cost per part and increasing the net profit for Weld-Fab!!

As weld verification continues, and scheduled maintenance continues to accomplish their work, this major gain in performance will continue. Congratulations to both maintenance (skilled trades) and operations for a job well done!

Jim Rypkema
Operations Supervisor

APPENDIX C - 18

Inter Organization

Chevrolet-Pontiac Canada Group

Date January 22, 1990

Subject Weld Tool Verification and Process Monitoring at Lansing Fab

To C-P-C Quality Directors - Asm & Fab
C-P-C Weld Coordinators - Asm & Fab

I would like to share with you and your plant some excellent work done on the above subject by Lansing Fab of B-O-C. Mike Karagoulis, Welding Engineer, presented this information at the GM Weld Information Group (W.I.G.) meeting on 1/18/90. The 9 page report is attached.

This work is significant because it shows what can be done and typical quality gains that can be achieved by identifying and controlling the main process variables in welding. This report is based on the Lansing Fab's analysis of 1,100 weld guns. It may very well reflect those key process variables at your plant.

The second and third graphs of discrepancies illustrate the typical quality improvement achieved by controlling the 4 main variables based upon deformation testing. Mike commented that the only areas which didn't have comparable improvements were those where short-cuts were made in the process.

This process doesn't require a large expenditure for equipment, but it does require a commitment of people. At Lansing Fab it took some reassignment of people and an overtime commitment to get the job done.

The payoff seems to be in long term benefits; quality improvement, less scrap/repairs and less productive down time. It looks like a worthwhile investment.

Richard J. Lipinski

Richard J. Lipinski
C-P-C Operations Quality

cc: Mike Karagoulis
R. Heithaus
S. Wechsler

APPENDIX D

A Technical Summary of the Resistance Spot Welding Process

APPENDIX D - 1

A Technical Summary of the Resistance Spot Welding Process

Production resistance spot welding involves simultaneously:

1) a physical process,
2) an electrical process
3) a metallurgical process
4) a cultural manufacturing environment.

D.1) The Physical Process

In the spot weld process, two or more pieces of sheet metal are clamped together by copper electrodes as in Figure D.1. The working contact diameter of the electrodes is often 0.25 inches (6.35 mm) for thin-sheet automotive steel (0.024-0.120 inches [0.6-3.0 mm] thick). Clamping force is generally 400-1300 pounds (174-565 kg). Electrical current, of the order of $2x10^5$ amps/in^2 is passed between the electrodes. The current causes intense heat build-up inside the clamped volume of metal. The heat produced results from Joulean (resistance) heating. In a short time (.1 - 1.0 seconds), melting occurs at the weld interface and the current may be stopped. After the current is stopped, solidification occurs very rapidly because the sheets are relatively thin, the electrode force is high enough to provide good thermal coupling, and the copper electrodes are water cooled. If the surface temperature of the weld is

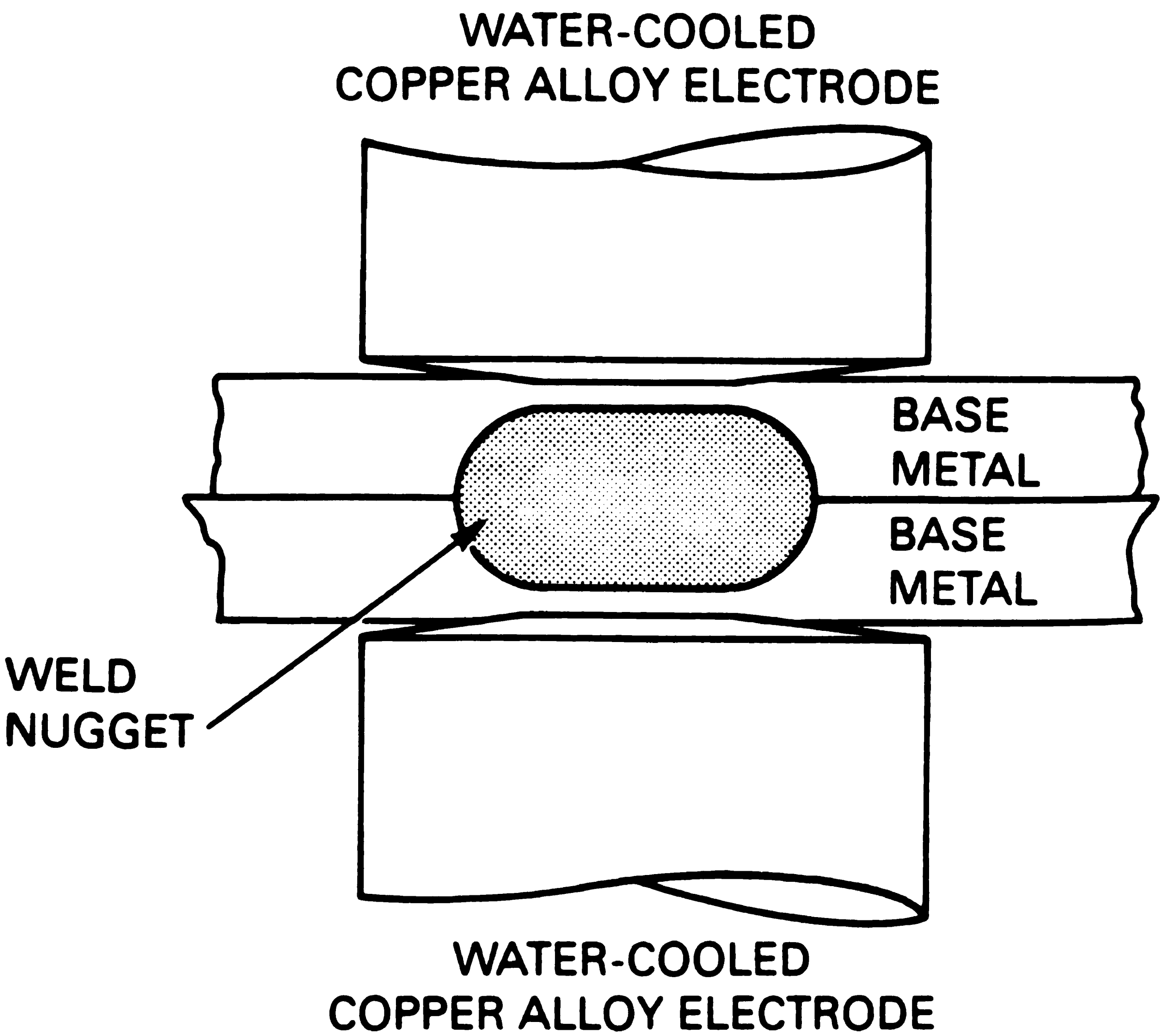


Figure D.1 Schematic of resistance spot welding (Ref 62).

maintained below a critical "sticking" temperature, then electrode sticking will not occur and the welded metal may be easily unclamped. The electrodes are then re-useable for thousands of welds before being replaced or re-dressed. Surface temperature is mainly controlled by cooling water, force, current, and weld time. The main wear mechanisms for the electrodes are: mushrooming (a gradual increase in the tip area due to either warm or cold plastic flow of the copper), alloying, and contamination by oil or paint residue.

D.2) The Electrical Process

The governing equation for joulean heat release in a spot weld is Joule's Law:

$$H = I^2 \cdot R \qquad [\ D.1\ ]$$

H = heat [watts]
I = current [amps]
R = resistance [ohms]

The resistance of a spot weld is within the range of 50 - 200 micro ohms. As far as electrical power loads are concerned, a spot weld is considered a low resistance load. According to the joulean equation above, this condition necessitates high current for adequate resistance heating. A typical setup for 1mm sheet steel might be 10,000 amps and

1 volt at the weld. It is necessary in the design and maintenance of the welding circuit to keep the open-circuit resistance low, so as not to cause heat build-up in the hardware. Large cables with silver plated connections are recommended for stable, low resistance circuits operating under high current.

The waveform used for resistance heating is generally not critical, so AC power is most often used for economic reasons. Low voltage, high amperage power is delivered to the weld through a step-down transformer. Typical turns-ratios for welding transformers are in the range of 20:1 through 200:1. A constant-current circuit is becoming increasingly desired in industry, rather than constant-voltage or constant-wattage circuits, so that the energy lost due to circuit variation such as cable wear will not alter the current or resulting voltage drop across the weld.

The root mean square (RMS) of the current waveform is the most measurable heat input parameter. RMS current is adequately controlled during welding by precisely timing a point during each half-cycle of power when current is allowed to begin flowing. Thus, in resistance welding there is a brief period of off-time at the beginning of each half-cycle. Therefore although the line power is nominally sinusoidal, the weld does not receive a sinusoidal waveform (see Figure D.2). The off-time is proportional to the

APPENDIX D - 5

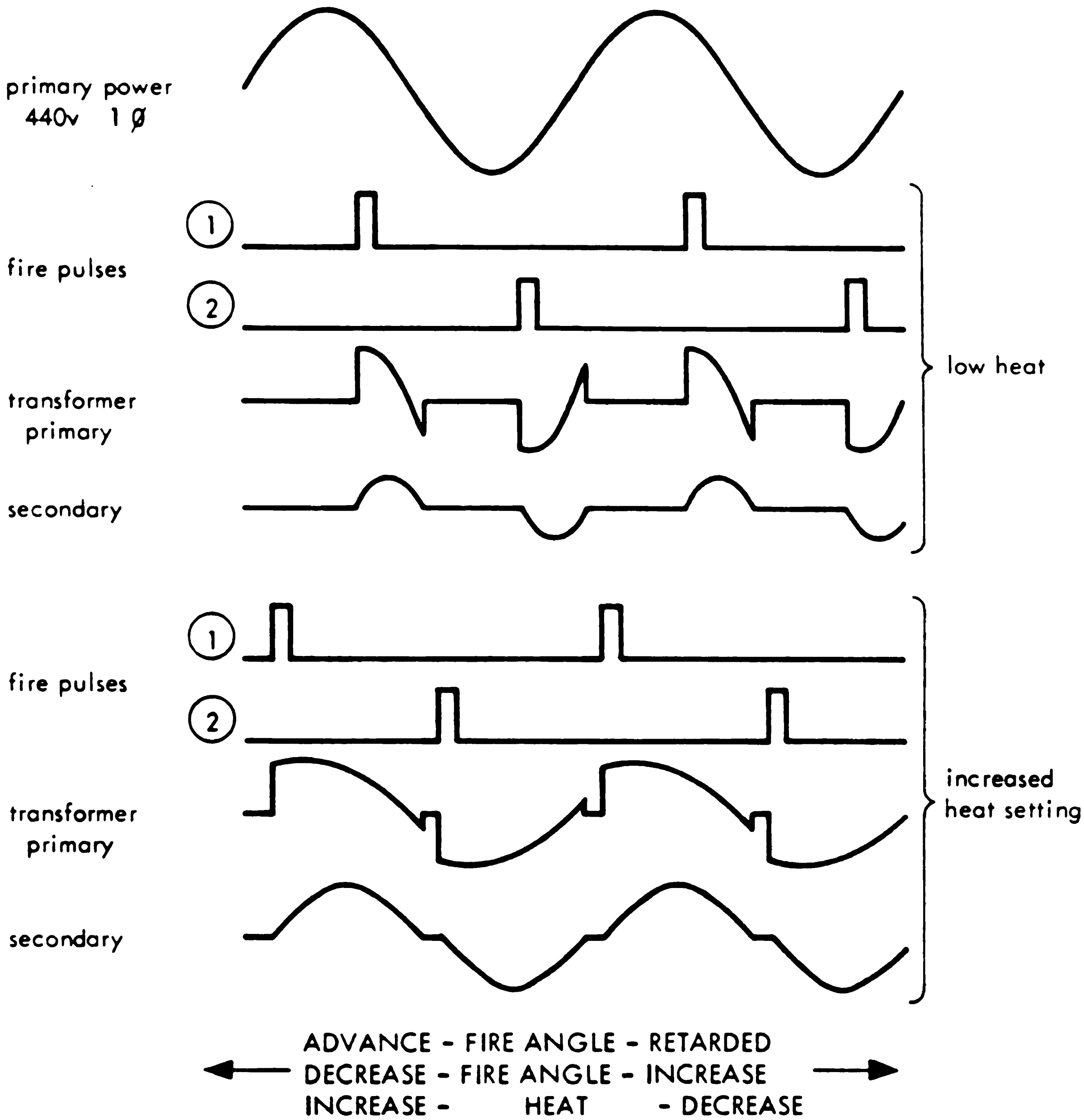


Figure D.2 Waveforms in resistance welding (Ref 63).

timing of the firing circuit. The off-time throttles back the system to a desired RMS current. Maximum RMS current occurs with no off-time; this condition of full power is referred to as 99% current or 99% heat (depending on which current programming convention is used).

Pulsing signals control RMS current in modern welding equipment by switching on silicon controlled rectifiers (SCR's). The SCR's operate in pairs on the primary (input) side of the transformer. Upon receiving a pulse the SCR is "gated" (turned on) for whatever time remains in the half-cycle. Current automatically stops when the power alternates to the opposite polarity. A second SCR is then similarly gated to pass current in the next (opposite) half-cycle (see Figure D.3).

The SCR's receive their timing pulses from a microprocessor-based weld control called a weld timer. The primary function of the weld timer is to fire weld schedules to the SCRs. A weld schedule is essentially a set of pulses which will cause the SCRs to fire for a programmed length of time at a programmed level of RMS current.

Weld time is programmed in cycles of the standard 60 Hz waveform (.0166 seconds), or the standard 50 Hz waveform (.0200 seconds). Current may be programmed in either percent heat, percent current, or in secondary amps. Therefore, typical weld schedules might read:

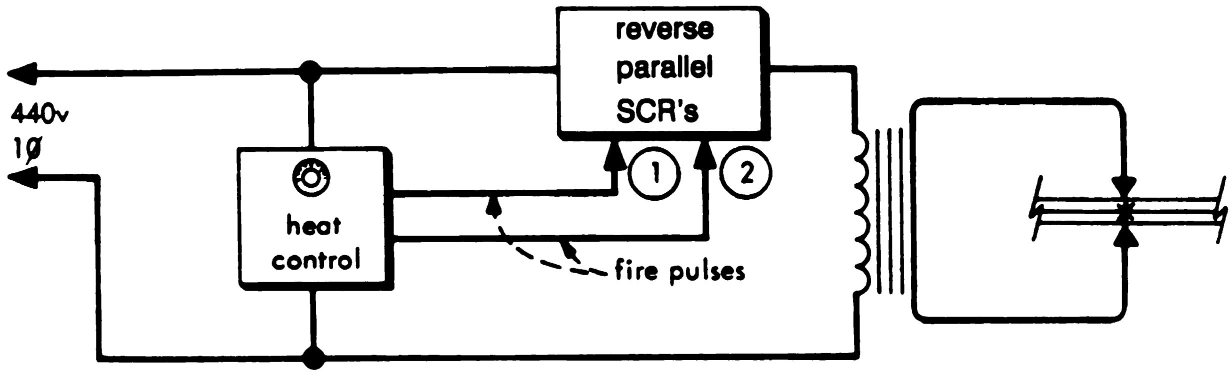


Figure D.3 Typical single phase SCR wiring diagram for resistance welding (Ref 63).

WELD 15 CYCLES at 50% HEAT

or,

WELD 15 CYCLES at 71% CURRENT

or,

WELD 15 CYCLES at 9000 AMPS

% HEAT and % CURRENT are related by the equation:

$$\%H = \%I^2 \qquad [\ D.2\ ]$$

% CURRENT and CURRENT are related by the equation:

$$\%I = \frac{I}{I(max)} \qquad [\ D.3\ ]$$

where Imax is the current at full power.

Over a number of welds the required current for welding increases because of tip mushrooming. This swelling of the electrode face actually causes the weld diameter to decrease, since current density decreases. Therefore, in order to maintain a certain weld diameter, the control must be programmed to compensate by stepping up the current after a predetermined number of welds. By increasing the current, current density remains nearly constant throughout the life of the electrodes.

Electrode wear is by far the main source of variation in the entire spot weld process. However, once good weld schedules and stepper schedules are developed, there is no longer any loss of process efficiency due to electrode wear since no discrepant welds are produced. The electrodes are simply replaced at the required interval and the stepper counter reset to zero welds. A negative aspect of using a current stepper is that power consumption increases as the current is raised. Even so, the energy required to produce a spot weld is relatively small, roughly only .0005 kw-hr, according to the calculation:

$$E = I \cdot V \cdot t \quad [\text{ D.4 }]$$

$$E = 10 \cdot 1 \cdot 0.00005 \quad \text{(kilo-amp volt hr)} \quad [\text{ D.5 }]$$

$$E = 0.0005 \text{ kw-hr} \quad [\text{ D.6 }]$$

The next major source of process variation is in the resistance of the welding cables and the inductive losses of the secondary loop. Wear in the cables or electrical connections of the secondary loop causes a direct loss in weld current, which in turn will reduce weld size from the initial setup. This resistance may be measured with a sensitive ohmmeter (in micro-ohms) as a preventive maintenance practice, or monitored through the weld control during normal production welding.

Variation in inductive loss is due to a change in secondary loop area or the amount of magnetic material in the loop.

Induction and resistance losses may together impede current flow to the point that the system output is inadequate for welding. In such a case, the required current may be attainable by either: an increase in transformer size, a decrease in loop area, a decrease in loop magnetism, or a decrease in loop resistance. A remedy specifically for excessive inductive losses is the use of direct current rather than alternating current.

D.3) The Metallurgical Process

There is a wealth of interesting metallurgical phenomena associated with resistance spot welding. According to basic principles in materials science, welding may be defined as a metallurgical joining of metals in intimate contact. It is common knowledge among materials scientists that atomistically clean metallic surfaces bond to one another readily upon contact in order to reduce surface energy. Using this as a first principle the in analysis of welding, every metallic welding process may be rationalized fundamentally as a two step process, where:

1) the surfaces are cleaned, and
2) brought into intimate contact.

In the case of spot welding these two steps are fulfilled by resistance heating to the point of melting. Some of the events known to occur are (in relative chronological order):

1) Cold plastic flow of surface asperities during initial clamping.
2) Surface cleaning by electrical heating and pressure extrusion.
3) Warm plastic flow of contacting surface asperities.

4) Phase transformations in the bulk volume upon rapid heating.

5) Dissolution and stirring of remaining surface impurities upon fusion (melting) at the weld interface.

6) Intense heat flow towards copper electrodes.

7) Phase transformations upon rapid cooling of the melt.

D.4) The Impact of the Cultural Manufacturing Environment

Operating a controlled process gives predictable results. Given that one of the goals of manufacturing is return on investment, then process control is important because it contributes to controlled, predictable profits. Predictability is crucial whenever competitiveness and market share are at stake. Let us first establish this discussion within a framework of basic definitions.

Process:

A process is a series of manufacturing operations which result in a definable, useful product.

Product:

The product may either be a saleable end product or an intermediate product used in a downstream process. All useful products contribute eventually to a final marketable product. It is the sale to a customer of the final product which generates business resources and profits.

Customer:

A customer is any downstream user of the product.

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Customer Requirements:

The customer's specifications and expectations make up the "customer requirements".

Key Variable:

An input variable which affects the output to a significant degree.

Minor Variable:

An input variable which does not affect the output to a significant degree.

Remote Variable:

A variable which is outside the span of control of the employees at the process.

Process Control:

A devised method of keeping output characteristics of a process within desired limits, achieved by maintaining key inputs within a set of limits. In a controlled process the outputs are nearly predicted by the key inputs. However, a margin of uncertainty still exists due to the impact of minor variables which are not controlled, and due to statistical variation.

The level of understanding necessary for process control must include both technical and human variables. A manufacturing process cannot be singularly controlled from either the technical or the human point of view. If so, the technical "laboratory" approach may neglect true plant conditions and the human "plant" approach may be seriously lacking in technical integrity. Because true processes are often socio-technical, both factors must be understood in order to be controlled. A controlled laboratory environment may provide the technical facts about materials processing interactions, but the laboratory must at some point include the plant environment in order to comprehend the "real world". Key variables in a laboratory environment are not necessarily key variables in the plant. In addition, an important advantage of extending the laboratory into the plant environment is the possibility of further developing the process. The goal is to alter the set of key variables to a configuration that is socially practical and economically controllable.

Some of the symptoms of a manufacturing process out of control are: product rework, sorting of incoming and outgoing stock, and excessive reliance upon product inspection to ensure quality. It is vital to competitive manufacturing that all critical processes are controlled, in order that costly practices may be minimized or eliminated. The purpose of describing the cultural manufacturing environment is to underscore that for a process to be controlled it must be sufficiently understood. The problem for many manufacturing processes is that there exist both technical and social variables.

The feasibility of process control in any manufacturing process necessitates the following nine requirements:

1) To control a process, all key variables must be known, readily measurable, and controllable. The process should be developed to the point of having as few key variables as possible, since each key variable is to be monitored and controlled.

2) The process must be simply understood in terms of basic concepts by those who are given the job of monitoring and controlling it.

3) The process must be properly defined to include both human and technical key variables.

4) The setup should be developed and refined to desensitize any remote variables. Examples of remote variables in spot welding might be material, metal fit, coatings, and line voltage.

5) It is not feasible to completely control a process having key variables which are remote.

6) An remote key variable can only be tolerated if its variation has been minimized. However, once a key variable has insignificant variation it is arguably no longer a key variable. A key variable under control might be re-classified as a minor variable, once a reliable trend has been thoroughly established.

7) Preventive maintenance items are the best kind of key variables. This is because they may be adequately controlled during periods of scheduled downtime, using a planned inventory of spare parts. Variation in preventive maintenance may be minimized through procedures, training, supervision, and management support.

8) The process manager must execute a plan to monitor and control each key variable at its optimum value. The healthiest mode of operation (both technically and socially) is to continually minimize variation at every step in the process.

9) After periods of continuous improvement, it may be possible to demote more key variables to minor variable status. Having fewer key variables simplifies process monitoring requirements.

APPENDIX E

Elements of Process Control in Manufacturing

APPENDIX E - 1

Elements of Process Control in Manufacturing

The major goal of this study was to understand the resistance spot welding process well enough to control it in the socio-technical environment of the automotive factory. It was necessary to consider in some detail all perceived sources of significant variation in order to distill reality from the sea of perceptions. Having done this, the results help justify the technical validity of the findings. All of the academic questions have not been answered on the subject, but the level of understanding has been sufficiently raised for good, economical process control. From a business standpoint the project has been a success in that the problem was properly defined and solved, the results implemented, and the benefits realized and measured. Therefore since the welding problems which triggered and sustained this study have been solved, it is not economically necessary at this time to pursue more in-depth academic knowledge of this process. Rather, it will probably take a few years' time to allow the implementation to catch up with the level of knowledge currently available.

To list the generic elements that have made this process control plan a success, an effective plan must have:

1) Simplicity. Can the plan be understood by the users? A technically accurate approach will fail if the key employees cannot understand it in their own terms. For example, in this plan the employees were taught to

expect some visible weld expulsion, and to question whenever there wasn't any.

2) Technical Integrity. Is the understanding accurate? It really doesn't matter how practical conclusions are if they are technically unsound. A house built on sand will not stand (64).

3) Cultural Appropriateness. Can people really perform as required? In this plan the key variables were all shown to be maintainable process parameters. In support of the journeyman labor establishment present in our plant, the extra maintenance required to support this plan was divided equitably between the various trades. For example, the electricians were given responsibility for cable and current maintenance, the pipefitters were given cooling water maintenance, and machine repairmen were given the gun cylinders etc. In addition, preventive maintenance groups were established in order to proactively keep equipment running properly. Consequently, the social needs of the key employees were met (eg. ownership, pride and teamwork), while the technical needs of the process were also well maintained.

4) Economic Feasibility. What is the cost of not controlling the process? In this project there were clear economic incentives to support process control. Some incentives were: downtime, quality and rework, not to mention the public liability of poor welds on automobiles. See Appendix C for a presentation of economic benefit from this program.

APPENDIX F

Conclusion About Applied Research Strategies

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Conclusion About Applied Research Strategies

In this study, it was crucial to invest the proper amount of time and effort working directly with those who stood to benefit from the work. When doing applied research, frequent personal contact is always recommended for at least two reasons:

1) It is normally advisable to get a good first-hand look at an open-form problem before attempting to solve it. This helps ensure that the problem has been properly defined. Whenever there are layers of people between the problem and the problem solver, there are significant opportunities for critical information to become overlooked, misinterpreted or misrepresented. Once the facts and assumptions about a problem are misunderstood the risk level for the researcher rises rapidly. Few things are more aggravating in the business of applied research than solving the wrong problem!

2) When conducting research in the plant environment, keep the information flowing both ways. Teamwork and teambuilding are essential in the midst of a vast manufacturing complex, since the researcher cannot possibly be personally present all of the time.

VITA

Michael John Karagoulis was born in Detroit, Michigan in 1957. Attending the University of Michigan, he graduated as Bachelor of Science in Materials and Metallurgical Engineering in 1979, and Master of Science in Metallurgical Engineering in 1980. Since 1981 he has worked at the Buick-Oldsmobile- Cadillac Group of General Motors Corporation, in a variety of materials-related engineering areas, notably eight years in the field of resistance welding.

He is known in the welding community for his research and development in the resistance seam welding of polymer-coated terne plate for automotive fuel tanks, having been credited for pioneering this process, which has been widely used throughout General Motors since 1984. He has written two major papers on this subject and presented them at the American Welding Society. He has presented work on non-destructive testing of spot welds, using both ultrasonic and the resistivity methods. He is also credited within General Motors with a highly successful application of molybdenum alloy inserts for projection welding electrodes, which gave a 50-fold increase in electrode life over conventional copper electrodes.

To date, his most personally rewarding contribution to the welding field is this present work on spot welding process control. The results summarized in this dissertation have contributed significantly to General Motors through the elimination of reworked welds and redundant waste. This work has shown that discrepant weld rates of 0.00% to 0.02% are economically achievable and controllable under production conditions. This quality level is more than 2 orders of magnitude better than previously considered possible. Consequently, engineers are now driven to design comparable vehicles using fewer welds and more reliable welding processes. By taking extra care to monitor and control the four key variables revealed by this study, General Motors is becoming more competitive in its core automotive business. To date, portions of this present study have been presented at the TMS fall meeting, the American Welding Society, and within General Motors.