AN INVESTIGATION OF RESISTANCE SPOT WELDING CURRENT AND TIME PARAMETERS FOR DIFFERENT THICKNESSES OF SAE CR 1010 STEEL

by

Joan Chiung-Tzu Jung

Thesis to be Submitted to the Graduate Faculty of the
Virginia Polytechnic Institute
in candidacy for the degree of

MASTER OF SCIENCE
in
INDUSTRIAL ENGINEERING

August 21, 1964
Blacksburg, Virginia

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENT

The author wishes to express her sincere appreciation to Professor Marvin H. Agee for his guidance, constructive criticism, encouragement and patience which helped in the preparation of this thesis.

The author expresses her gratitude to Dr. R. H. Myers of the Statistics Department for his guidance in the statistical design of this investigation.

Appreciation is expressed to Dr. Roger L. Smith and Professor Herbert L. Manning of Industrial Engineering Department for their encouragement and sincere consideration towards the author during the entire college curriculum.

Acknowledgement is given to Mr. R. E. Dillon of Industrial Engineering for his guidance and assistance during running this thesis investigation.

Finally, the author is greatly indebted to Mr. S. C. Wang, whose unfailing confidence, help, and encouragement have aided in the writing of this thesis.

CHAPTER I

INTRODUCTION

As a result of the rapid growth of resistance welding as a joining process for sheet metal, a lot of research work has been done during the past thirty years in the fabricating industry. In 1856 A. D., the British physicist, James Joule, is credited with accomplishing the first authentic resistance weld by electrically heating two wires; then forging them together. The American inventor, Elihu Thomson, in 1877 was the first to use contact resistance as a heat source for welding[1].

Partially due to increasing demands on the quality of the weld and partially due to new apparatus becoming available for controlling the variables involved, the development of resistance welding is still in progress. A knowledge of the relation of mechanical properties of a weld, strength for example, to the welding time, welding current, and pressure for the different gauges and kinds of material available is an important key to the future development of the welding industry.

Although resistance welding machine manufacturers recommended machine settings for various base metals and related thicknesses, the maxima and minima conditions normally are not specified. Furthermore, the available manufacturer's machine specifications are either incomplete and/or non-existent with respect to results as a function of input variables.

The stringent demands on the quality of weldments, the increasing number of weldable materials being developed each year and the improvements continually being made in welding machinery require additional research and development in the field of resistance-welding. The characteristics of any spot weldment are based on fundamental principles of metallurgy, electricity, thermodynamics, and force mechanics. In order to obtain meaningful information from scientific research into basic phenomenon, it is first necessary to obtain or engineer the capabilities and limits of the experimental equipment. The experimental equipment in this investigation is the resistance spot welder.

Therefore, the primary purposes of this thesis investigation are:

1. To establish the maxima and minima values, within limits, of the welding machine parameters: current and time, for 28 gauge, 24 gauge, 20 gauge, 18 gauge, and 16 gauge of SAE CR 1010 steel.

2. To implement and calibrate the instrumentation necessary to determine accurate values, within limits, of the variables under investigation. Also, to devise suitable controls for those fixed variables not investigated.

3. To correlate values of welding current and welding time with resulting tensile-shear strengths of the lapped weld joints.

4. To establish the combination of welding current and weld time which gives a maximum value of tensile-shear strength for the metal gauges under investigation.

There are a multiplicity of factors which may affect the tensile-shear strength of a lapped resistance spot-welded joint. This author investigated only those factors considered major; namely, welding time, welding current, and metal thickness.

The thesis investigation was generally performed in the following manner:

For each gauge of metal under investigation, the maximum machine settings for both current and time were used initially. In this region of machine settings the resulting maximum tensile-shear strengths of welded specimens were found. Then by changing the machine settings on a decreasing scale, a series of welds were made until no weld occurred. When this range was found, additional specimens were welded to prove the validity of this "minimum" range.

Each welded specimen prepared under all conditions of current, time, and base metal thickness was given a tensile-shear test to destruction. The results of these tests are summarized as:

1. Generally speaking, the tensile-shear strength of a weld increases with an increase in weld time for all sheet thicknesses and all levels of heat settings except the 100% and the 80% heat settings for the 28 gauge sheet.

2. Generally speaking, the tensile-shear strength of a weld increases with an increase in welding current for all sheet thicknesses and all levels of weld time.

3. At constant electrode force, the maximum tensile-shear strengths occur at the maximum current setting of 100% in all cases.

4. Assuming constant electrode force, a certain combination of variables can produce a weld having a particular tensile-shear value. A different combination of variables can produce a weld having an equal tensile-shear value.

5. The maximum tensile-shear value for all conditions investigated was for 18 gauge steel with a 100% heat setting and 28 cycles of weld time.

CHAPTER II

REVIEW OF LITERATURE

A. INTRODUCTION:

There is considerable literature available relative to the spot welding of ferrous metals, non-ferrous metals, and non-metallic materials. Only a cursory discussion of major fundamentals pertaining to the resistance spot welding of metals is herein presented. Much of the literature is devoted to general discussions of resistance welding techniques and the more technical reports deal mainly with the relation of welding variables to joint strengths. However, little information is available whereby welding variables are optimized with respect to maximum joint strengths. Such reports, of necessity, optimize conditions for specific welding machines used in testing.

The purpose of this review is to summarize the literature available on the major variables which affect the strength of the spot weld in carbon steel and some general aspects of resistance spot welding.

B. PRINCIPLE OF RESISTANCE WELDING:

Spot, roll-spot, seam, upset, and projection welding comprise the group of resistance welding processes. The required heat at the joints to be welded is generated by the resistance offered by the workpieces and the interface to the relatively short time flow of low voltage, high-density electric current. Force is always applied before, during and after the application of current to assure a continuous electrical circuit and to forge the heated parts together[1]. The heat required for the resistance process is generated by the resistance to an electric current[2]. Although there are many resistances in the electrical circuit, the resistance of primary concern is at the weld joint interface. Here, contact resistance due to the constriction of current as it passes through metal bridges[3], initiates the heat generation necessary for the resistance weld.

The Generation of Heat:

Funk[3] has developed heat generation formulae for any resistance welding process as follows:

$$Q = \int_0^t i^2 (t)\ R\ (t)\ dt \qquad Q = \int_0^t i\ (t)\ V\ (t)\ dt$$

where, Q = heat generation in Joules

i = Current flow in rms amperes

R = resistance of the work in ohms

t = time of current flow in seconds

v = voltage across the circuit in volts

The current, voltage, and resistance all vary with time. Although the current flowing through a circuit is the same at any point in that circuit[4], the current densities may vary at different locations. Such is true at the base metal interfaces and therefore the applied electrode bearing pressure affects the interface metallic contact area, the resistance, the current densities, and the heat generated.

Only a fraction of the total heat generated at the interface is utilized for accomplishing the weld. The remainder of the generated heat leaks into the surrounding work, electrodes, and atmosphere by radiation and conduction.

Funk[3] stated that the rate at which heat transfers away from the weld is a maximum at the beginning of the weld period but that the amount of heat loss is proportional to the square root of the weld time. Thus, it is evident that, for a given quantity of heat generated, the longer the time of generation, the larger the fraction of heat loss. This is one of the reasons why a long weld cycle time is undesirable.

C. EFFECT OF MACHINE SETTING ON STRENGTH PROPERTIES

Simplifying, the quantity of heat generated at the base metal interface may also be expressed as, $H = (I)^2 R T K$, where the heat generated is the product of the current, resistance, weld time, and a correction factor for heat losses[1, 2, 4, 5]. The resultant interface weld is a manifestation of this heat and therefore the joint strength is a function of these primary variables: current, resistance, weld time, and pressure.

1. Current:

Many investigations have generalized that increasing the current magnitude increases the tensile-shear strength of a lapped weld joint. That is, up to some critical value where, under a given applied force, molten metal expulsion occurs at the joint.

Unger[6] illustrated the current vs. tensile-shear strength relationship for spot welds in several gauges of mild steel, a low-alloy steel, and 18-8 stainless steel. The results show that the thicker sheet requires higher current than that of thinner sheet for equivalent strengths.

Hess and Ringer[7] investigated the effects of current on the tensile-shear strengths of 0.029 in. thick hot-rolled, annealed and pickled mild steel specimens. They found that increasing the current magnitude increased the tensile-shear strengths. This is apparently explained by the fact that increasing current increases the volumetric size of the resistance weldment. The larger the cross-sectional area of the weldment opposing shear, the higher the tensile-shear value. This reasoning of course neglects the many metallurgical factors, such as grain growth, precipitation, aging of non-ferrous metals, etc., which must be considered before a true analysis could be made. A discussion of these is outside this review and the reader is referenced to metallurgical texts, such as "Metallurgy for Engineering" by Wulff[28].

Hess[7] advises that: "it is difficult to prevent the variation in the line voltage from affecting the tensile-shear strength of the spot welds." This author encountered the same problem during the preliminary phase of this thesis investigation. Hess[7] has suggested that a compensator may be used to correct these fluctuations.

2. Weld Time:

Weld time is one of the three major variables in resistance spot welding. A weld time of too long a duration in regard to heat generation results in excessive heat losses. This exemplifies power inefficiency. On the other hand, insufficient weld time of course may result in no weld being formed. If a weld is formed, insufficient time may produce a weld that is less than maximum tensile shear value. The results of this thesis investigation show that for a given machine setting of current and electrode bearing pressure there is, in most cases, an optimum weld cycle time.

Funk[8] states that there are two critical periods of time during welding; namely, the first couple of milliseconds of heating when expulsion may take place due to very rapid heat generation; and the fraction of a second after the current has been terminated, but pressure is still applied, when cracking may occur.

3. Electrode Force:

Funk[9] states that the most important function of electrode force is to confine the weld metal so that the metal vapor generated during welding does not expel the molten metal in small globules and leave a porous weld.

According to Stanley[10] and Johnson[11], insufficient force will result in weak welds, expulsion, surface burning, and other defects, while too much force applied will result in indentation and insufficient welding heat for the work to reach fusion temperature because of lower contact resistance.

Fitzgerald[12] found, that for a given machine setting of current and weld time, increasing the electrode force decreased tensile-shear strength values and decreased spot-weld penetration.

D. CONTACT RESISTANCE

Funk[23] and his co-workers state: "contact resistance is due entirely to the fact that the current flow is constricted as it approaches the metallic bridges."

According to the Welding Handbook[1] and Jennings[14], contact resistance depends on:

"(1) The surface condition of the work to be welded. A smooth, clean surface has a lower contact resistance than a dirty, rough one.

(2) The specific electrical resistance of the material being welded.

(3) Electrode variables, including size, shape, surface condition and electrical conductivity.

(4) The amount of the pressure being exerted. The greater the pressure, the less the contact resistance."

Van Thijn and Tylecote[15] have commented that interface resistance in spot welding does not depend on the gauge of the metal.

In other words, contact resistance is unaffected by the thickness of a given metal-composition sheet.

Cramptom and Vreeland[16] investigated the spot welding of copper alloys and concluded that contact resistance measured at room temperature decreased greatly as the electrode pressure is increased and contact resistance has little relation to the strength of the spot welds. In agreement with Cramptom and Vreeland[16], Tylecote[15] has made a test on 24 welds incorporating the measurement of initial contact resistance. The test was carried out under 'constant' conditions as regarded to current and pressure. He illustrated that there is no relationship between initial resistance and strength of the spot welds. In other words, the interfacial contact resistance has little connection with the strength of the weld. Therefore, it is not necessary to have a consistent interfacial contact resistance. However, if Funk's[3] definition of contact resistance is true; then the reasoning above by Cramptom, Vreeland, and Tylecote is incorrect.

E. ELECTRODE TIP

Johnson[11], Vecchio[2] and The Welding Handbook[1] give the following two general formulae in determining the electrode tip diameter required for a given sheet thickness for carbon steel (0.05 - 0.15% C.)

$$d = (0.1 + 2t) \text{ in.} \qquad (1)$$

$$d = t \text{ in.} \qquad (2)$$

Where d is the tip diameter, t is the thickness in inches of one thickness of the material to be welded. Equation (1) has been found more applicable for thinner material, while equation (2) is for thicker material.

F. ELECTRODE SHAPE AND MATERIAL

The type of electrode and the chemical composition affects the heat generated.

The dome and radius contours are most commonly used for all material because it concentrates the welding current and increases the current density[2, 4, 5]. The flat type is used where surface marking must be minimized.

Electrode material has to be of high electrical conductivity and possess wear resistance. This is explained by the fact that material of lower conductivity will alloy with the work and if relatively soft, will deform quickly under applied pressure.

G. SURFACE CONDITION OF THE SHEETS

The surface preparation of the work prior to welding is important and requires consideration because cold-rolled steel, as-received, normally has a coating of lubricant which serves as a media for holding dirt particles.

The Welding Handbook[1] and A. W. S. consider it very poor practice to weld through grease, paint or steel scale and rust. Jeffs[18] indicated that the surfaces of the material to be welded should be clean if quality results are desired. He pointed out that grease and scale will lower the melting point of the steel to be welded. Grease and oxide scale may prevent the passage of the welding current. Hess and Wyant[19] found very little difference (2 - 3%) in the strength of welds made without removing the protective oil film of cold rolled steel. Johnson[11] states that oil, in itself, will not affect the weld quality; however, an oily surface will cause dirt particles to cling to the work and these particles will cause erratic results even to the point of burning through the entire thickness of the work. "Oil in contact with the electrode will cause carbonization of electrode tip and thus lower the life of the electrodes." The Welding Handbook[1] recommends pickling as the best method of cleaning steel prior to spot welding.

H. COATING ON STEEL

The primary reasons for coating metals are for (1) surface protection, (2) to alter surface properties such as electrical, thermal, and wear characteristics, (3) to alter surface metallurgical properties such as creating diffusion barriers; provide bonding aids, etc., and (4) for decorative purposes[20].

Considering that coatings may be metallic, inorganic, vitreous, or organic and that within each general class of coatings there are many individual treatments, the effect of different treatments on the "weldability" of different base metals comprises an extensive study. Therefore, for the purposes of this Literature

Review, let it suffice to say that the type and amount of coating does influence the "weldability".

According to Johnson[11], thicker coatings require higher current levels for comparable strength. This is due to coatings, such as nickel plated steel, offering considerable resistance to the flow of current with the possible result that the electrodes are welded to the base metal.

The ideal result would be for the coating material to be melted and squeezed out of the joint, then become cooled by the surrounding metal and form a ring around the weld steel nugget[21]. This condition is illustrated in Fig. 1.

I. JOINING OF DISSIMILAR METALS AND UNEQUAL THICKNESSES

In spot welding, if two sheets of similar chemical composition and equal thicknesses are spot-welded together with electrodes of the same shape, similar chemical composition (hence similar conductivities), and equal bearing areas, the heat generated and heat dissipated in each base metal will theoretically be uniform. The weld nugget, therefore, will be symmetrical about the base metal interface[22].

However, if the sheets to be welded are dissimilar metals and/or unequal thickness, the resultant weld nugget will be asymmetrical about the interface. In order to obtain a symmetrical nugget, heat balance is an important consideration, i. e., heat generated in and heat transferred out of the weldment zone.

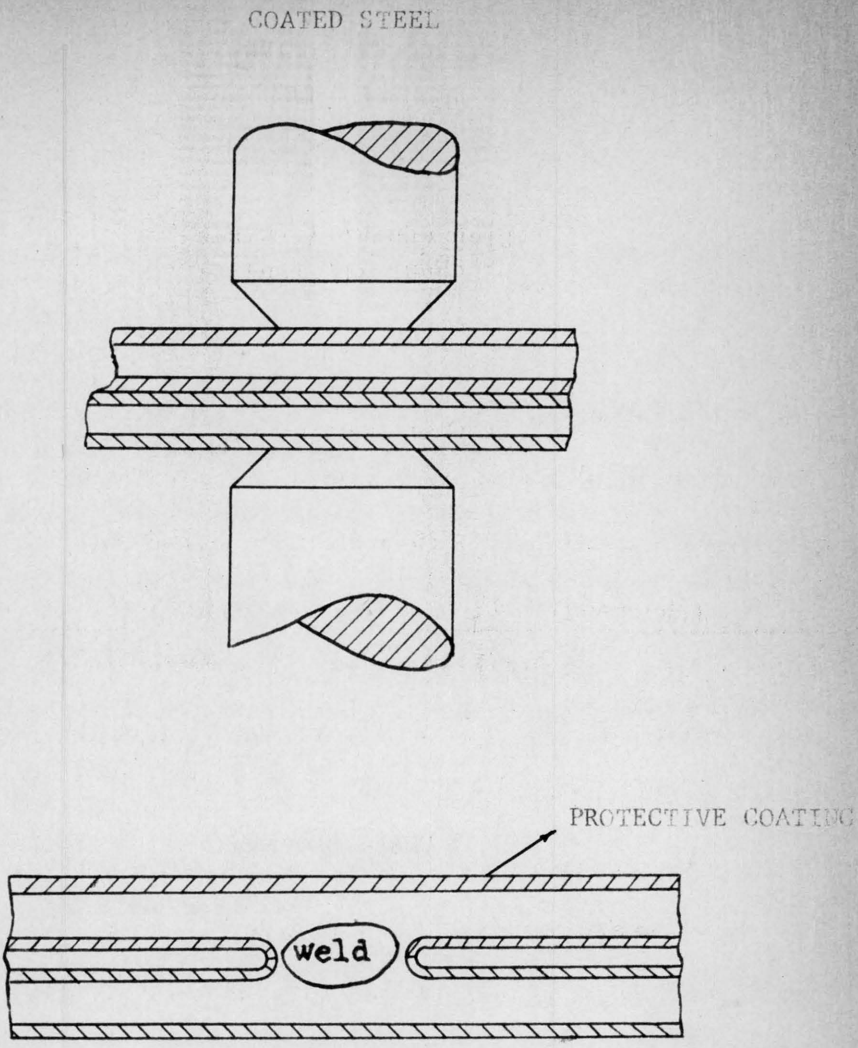


FIG. 1 - Ideal Spot Weld in Coated Steel, Having Nugget Entirely Surrounded by Protective Coating.

As previously discussed, heat is a function, in part, of the electrical resistance. For a symmetrical weld nugget, the electrical conductances of the two sheets should be equivalent. These relationships may be expressed as follows:[22]

$$G = (g/L)\ A \qquad K = (k/L)\ A$$

Where L = the electrical or thermal path length or sheet thickness.

A = electrode bearing area.

G = electrical conductance.

g = electrical conductivity.

K and k are the corresponding thermal units.

These general formulations may be applied to the additional situations[22] as follows:

1). Same metal composition vs. sheets of different thicknesses

$$L_1 / L_2 = A_1 / A_2$$

2). Different metal composition (hence different conductivities) vs. sheets of equal thicknesses.

$$g_1 / g_2 = A_2 / A_1$$

3). Different metal compositions vs. sheets of unequal thicknesses.

$$\frac{g_1/L_1}{g_2/L_2} = \frac{A_1}{A_2}$$

Consideration should be given to the above formulations especially when dissimilar metals are welded. It is difficult to produce a satisfactory weld between dissimilar metals which will not alloy.

J. DIMENSIONS OF JOINT

The width of the base metal specimen has an influence on the form of failure, especially in thin sheets. The greater widths of the strip provide greater stiffness to resist bending and tearing. On the other hand, the length of the strip affects the breaking load. If the strip is too short (2 in., for instance), the specimen would be torn but not sheared on a standard testing machine[23]. Experimental results regarding the effect of width of specimens on the tensile-shear strengths of single spot welds have been provided by Dearden and O'Neil[23]. The minimum length required for a sheet of 0.10 in. or more in thickness is 6 in. for the process qualification tensile-shear test.

For a lapped spot-welding joint, The Welding Handbook[1] recommends the amount of lap to be equal to the width of the specimens.

K. THE EFFECT OF THICKNESS

The effect of sheet thickness is illustrated in the experimental results reported by Taylor[24]. The results show that as sheet gauge increased from 22 to 10 (0.031 to 0.125 in.), shear strength increased from 1100 to 5500 lbs. per spot. (No welding conditions were detailed.) This might be explained by the fact that the heavier gauge could be welded to a deeper penetration if more heat was generated in performing the weld. This can be done by increasing the diameter of electrodes, the current, and the weld time and decreasing pressure in proportion to thickness. Thus, higher tensile-shear strengths of the weld will result.

L. TESTING METHODS

The methods of testing weldments for ductility, toughness, mechanical strengths, etc. which predict behavior under loading are normally standard destructive tests. Those tests for weldment porosity, micro fractures, incomplete penetration, etc. are general non-destructive tests of radiography, ultrasonics, visual analysis, etc.

The Welding Handbook[1], Vecchio[2], and Blumenstein[25] have described the methods of testing resistance spot welds. Badlaney[26] has also presented a review of the testing procedures. The tensile-shear test for lapped joints is perhaps the most commonly used static test for spot-welds. A specimen tested to failure is schematically shown in Fig. 2.

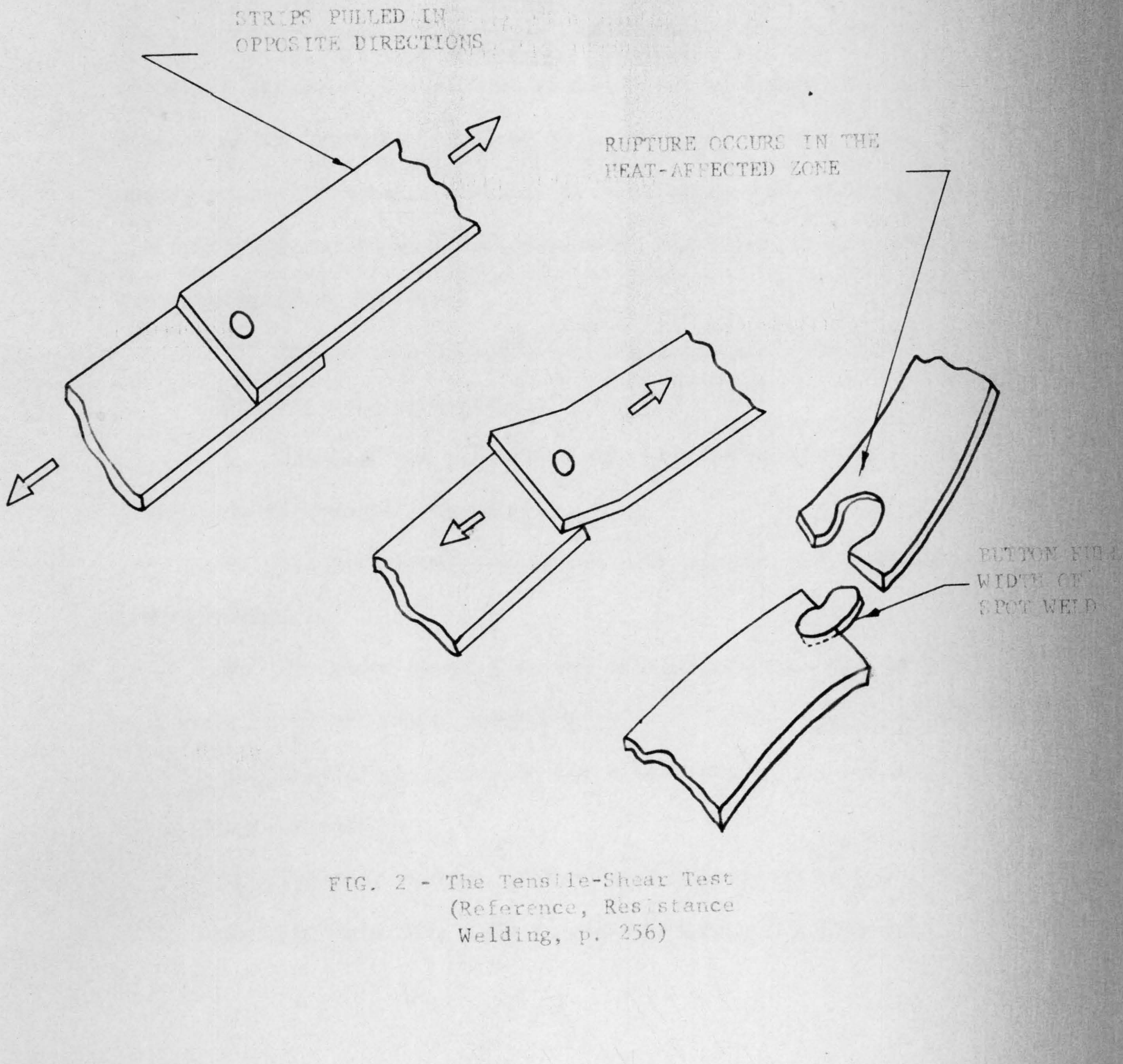


FIG. 2 - The Tensile-Shear Test
(Reference, Resistance
Welding, p. 256)

CHAPTER III

DISCUSSION OF VARIABLES

As previously stated, this thesis investigation is concerned with the A. C. resistance spot welding of SAE CR 1010 steel specimens. The test results are expressed as tensile-shear values, called the dependent variable, for various combinations of independent variables such as metal thickness, current magnitude, and welding time. A survey of the literature about A. C. resistance spot welding reveals the following enumeration of independent variables which may affect the tensile-shear results:

1. The welding current; its magnitude and wave form.
2. The welding voltage.
3. Broadly, the resistance in the welding circuit — a function of several factors.
4. The heat generated in the weld nugget — a function of several factors.
5. The force applied to the electrodes prior to and after the application of welding current.
6. The force applied to the electrodes during the application of welding current.
7. The squeeze time (before welding current is applied.)
8. The hold time (after welding current has ceased.)

9. The weld time (interval of current flow.)
10. The electrode composition, shape, and size.
11. The surface condition of the electrode bearing areas.
12. The test specimen.
    (a) Composition.
    (b) Thickness.
    (c) Surface condition.
13. The temperature of the electrode cooling system.
14. The human element, i. e., the experimenter.

The above enumeration, like virtually any other, is not necessarily complete nor finitely phrased. However, the items included are commonly mentioned in the literature and perhaps can be considered the general majority of influencing factors.

For the purpose of this thesis investigation, the composition of the test specimen and its thickness, the welding current, the welding time, and the weld joint resistance are considered major factors. This may be substantiated by the following logic. Since the tensile-shear strength of two lapped metal specimens is a function of the spot weld "nugget" volume, the heat generated in the weld zone is of paramount significance. According to most researchers[1, 2, 3], the heat generated, H, at the interface of two bearing surfaces, across which current flows, is equal to the product of I^2RTK - the welding current, resistance, the weld time, and heat-loss factor. These major factors will be subsequently discussed in some detail whereas the other factors are presented briefly. The reader of this thesis is referred to Badlaney[26] and Fitzgerald[12] for additional discussion on the above list of independent variables.

Although in the following discussion an attempt has been made to isolate the individual effect on tensile-shear values of a particular variable, this is erroneous in most cases. That is, it is virtually impossible to exclude (or control) all other factors and investigate a single variable. Further, there is known interaction[12] between some variables and suspected interaction between all others. The approach to solving this overall problem is a voluminous series of experimentations to determine the statistical significance of individual variables as well as the statistical significance of interactions between variables. If interaction is statistically significant, it can be ascertained whether the effect is of a linear or polynomial relationship, if such information is desired.

A. TEST SPECIMEN COMPOSITION AND THICKNESS

It is perhaps inane to state that weld-joint strength is a function of the base metal type and thickness; yet it is of paramount significance and therefore is mentioned in this discussion.

Obviously, for a given interface "weld-nugget" cross-section and thickness, the tensile-shear strength of a high-carbon steel weldment would be greater than that of a non-heat-treatable aluminum weldment. However, for a given welding current, welding time, welding pressure, base metal thickness, etc., the resultant "nugget" size will be different for the high-carbon steel specimen than the aluminum specimen. The explanation for this involves the effect of several factors. Generally speaking, one can say that the electrical resistance of the joint is different.

Since the average total heat generated in the joint is equal to (I^2RTK) and the "nugget" volume is a function of the heat generated, one can readily appreciate the effect that resistance has on tensile-shear values. The resistance to current flow is a direct function of the resistivity of the base material, a direct function of the length of current flow, and the inverse function of the cross-sectional area over which the current flows (i. e., $R = \rho \frac{L}{A}$).

Therefore, the thickness of the base metal (for given other conditions) influences the resistance, which influences the heat generated in the weld zone, which influences the size of the nugget, and consequently, the tensile-shear value.

For a given type of base metal, say SAE CR 1010 steel, the variabilities of carbon, manganese, silicon, sulfur, and phosphorous content from test specimen to test specimen may influence the resultant tensile-shear values. Absolute control over these metallurgical percentages is impossible and the degree of control is a matter of economics. Commercial grades of materials, such as SAE CR 1010 steel, are manufactured within compositional limits and therefore test results are within certain limits. Such was the case in this thesis investigation and the effect of the inaccuracies introduced into the test results are contained by the experimental error term in the statistical model used.

In any event, one can intuitively reason that to obtain a particular range of tensile-shear values for varying base material characteristics, it would be necessary to compensate by varying welding factors such as current, time, electrode pressure, etc.

This thesis investigation considers only a certain portion of the overall problem and has delved into welding current and welding time versus different sheet thickness of SAE CR 1010 steel. A conscientious attempt has been made to exclude the effect of other independent variables.

B. WELDING CURRENT

Recall from the previous section that the average total heat generation in the spot weld nugget is:

$H = I^2RTK$[1, 2, 10]

H = Heat generation in Joules.

I = Current flow in rms amperes.

R = Resistance to current flow in ohms.

T = Time of current flow in seconds.

K = A correction factor for heat losses by conduction, convection, and radiation.

Those comments made previously about heat affecting the weld nugget size and consequently the tensile-shear results are equally applicable here. From the equation above, the reader can readily appreciate that the heat generated is a function of the current.

A significant problem in an experimental investigation of this nature is the determination of the actual current passing through the joint during the weld cycle. The instrumentation necessary to determine this is discussed fully in Section B, Experimental Procedure, Chapter IV, Instrumentation.

For the resistance spot welder used in this investigation, the welding current was varied by a machine setting dial in terms of % heat. That is, rheostat adjustments drew varying amounts of current from the line power supply. The actual welding current (secondary) and the input current to the machine (primary) were monitored and recorded during each weld cycle. It was necessary to do this because of: (1) the possibility of fluctuating power supply, and (2) a lack of calibration between % heat setting and the secondary current.

Roberts[27] has stated that the greater the magnitude of the welding current flowing through a workpiece held by two electrodes, the smaller will be the instantaneous resistance between electrodes. The logic is better understood by stating this inversely. The smaller the resistance, the larger the current that will transfer. The subject of heat generation in the spot-weld zone and the cause of the resistance in the circuit is somewhat involved and difficult to interpret quantitatively. The reader is therefore referred to some excellent references[2, 3, 4, 5] on this subject.

Let it suffice to comment that the resistance is composed of "contact" resistance between upper electrode and base metal, contact resistance at the base metal's interface, contact resistance between lower electrode and base metal, and the electronic resistance of the base metal. The electronic resistance of the base metal is a function $(f(R) = \rho \frac{L}{A})$, where ρ is the resistivity of the metal at a given temperature of the base metal, L is the length of current flow (thickness of base), and A is the cross-sectional area perpendicular to the path of current flow (electrode bearing area.) This electronic resistance increases as the temperature of the base metal increases and conversely.

According to Funk[3], contact resistance is that resistance due to constricted current flow as it passes through small metallic bridges at an interface. An increase in metallic contact area reduces the contact resistance and thereby allows a current of less density to pass through a given metallic bridge. Thus, it is well known that current and resistance have significant interaction and virtually any factor affecting resistance will also affect the current actually passing through the weld joint. Welding current as a variable in this thesis investigation means the % heat settings on the spot welder although the actual secondary (welding) current was recorded for every test situation.

C. WELDING TIME

Again referring to the fundamental equation for heat generation in the spot-weld zone, $H = I^2RTK$, the time of current flow is a major variable. An increase in welding time, if the other variables could be maintained constant, increases the amount of heat generated. The increase in heat increases the size of "nugget" produced and thereby increases the tensile-shear strength of lapped specimens. That is, up to some maximum point. This maximum point has been previously defined as that set of welding conditions which produce a molten spot and metal expulsion at the interface. Convection waves then cause a joint of lower tensile-shear strength.

An increase in welding time does not necessarily cause a proportional increase in heat. There are interactions between current, resistance, time, and the thermal losses (K). Extensive information about these interactions is not known, although excellent articles on this have been written[1, 2, 3].

Introductory comments on these interactions are as follows: the longer the time of current flow, the more heat and consequently the more resistance. As resistance increases, the current flow becomes less (for constant voltage.) The more heat that is generated, the larger the heat losses.

The meaning of the variable, time, as used in this thesis investigation is the number of cycles set on the spot welder's automatic timer control. The maximum time that was possible on this spot-welding machine was 30 cycles. Since the alternating current frequency was 60 cps, then 1/2 seconds was the maximum duration of current flow.

The above three items: (1) Test specimen composition and thickness, (2) Welding current, and (3) Welding time were those investigated in this thesis. The succeeding topic of Other Variables includes those either considered minor in importance or those controlled.

D. OTHER VARIABLES

The following variables have been discussed in Section II, The Review of Literature, and therefore only brief summarizing statements are made here.

1. Electrode Material, Shape, and Size

The electrode material, shape, and size was that recommended by the AWS Handbook for thin sheet steel. The electrode material and shape for this thesis investigation was constant within manufacturer's specifications. The electrode tip size was maintained within .187"± .002" diameter by machining.

2. Electrode Force

For a given machine setting of current and weld time, increasing the electrode force decreases spot-weld penetration[12].

The electrode force was monitored during all test welds and was between the limits of 21.8 psi ± 5%.

3. The Squeeze Time and Hold Time

Squeeze time is the time interval from the instant that the electrodes close and begin to apply pressure on the work until the welding current starts to flow.

Hold time is the time interval from the instant welding current ceases to flow and electrode pressure is released. The purpose is to cool the weld.

These times were set on the welding machine's automatic controls and remained constant from test specimen to test specimen. Squeeze time was 120 cycles or 2 seconds and hold time was 60 cycles or 1 second. The effect on tensile-shear values by varying these times could not be found in the available literature nor was experimentation performed.

4. Surface Condition of Metal; Electrodes

Bearing surfaces (interfaces) that are unclean or coated usually give erratic tensile-shear values. Therefore, each test specimen in this investigation was cleaned with acetone solution and then dried. The electrode surfaces were cleaned by emery cloth after every third weld.

5. Temperature of the Electrode Cooling Water

The temperature of the cooling water can conceivably affect tensile-shear values although the relationship between these two is not well known. According to Thomson Electric Welding Company, the temperature of the cooling system should be kept less than 60° F. In order to control this variable, the rate of flow through the system was kept at 6 gallons per minute under an approximate 20 lb. gauge pressure. Random samples of the circulating water temperature were taken and found to be around 50° F.

6. Line Voltage Fluctuations

Current is the most important welding variable discussed previously. However, one of the most frequent causes of variation in welding current is a variation in the power supply voltage during welding. Since current flow is proportional to the line voltage and the line resistance to current flow is constant (i. e., $I = \frac{E}{R}$), then a change in line voltage affects the amount of current flow. Thus, any change in the line voltage will produce a proportional change in the welding current thereby affecting tensile-shear strength of weld joints. In order to identify the limits of line voltage fluctuation, a voltmeter was employed to record the line voltage. It was found that line voltage fluctuation was between the limits of 210 V $\pm$ 10 V.

Since current, time, and electrode force are three major variables of resistance spot welding, suitable controlling devices are necessary. Also implied is the necessity for accurately determining values for each variable. The following Section IV discusses the Instrumentation portion of this thesis.

CHAPTER IV

INSTRUMENTATION

The reader is again reminded of the heat generated formula, $H = I^2RTK$, and the concept of contact resistance. The variates of current, time, and resistance in the formula and electrode bearing pressure by implication, require rigorous control. Further, in order to correlate tensile-shear strength of test specimens with these variates, it is necessary to measure them within close tolerances. The following paragraphs discuss this instrumentation.

A. REVIEW OF PREVIOUS INVESTIGATIONS

Mr. Badlaney in 1963[26] and Mr. Fitzgerald in 1964[12] performed related investigations on the A. C. resistance spot-welder at McBryde Hall, V. P. I. Prior to the investigation by this author, Badlaney and Fitzgerald had developed measuring apparatus and calibration techniques. This author has improved upon their procedures and cites the following comparison.

Mr. Badlaney measured the current passing through the actual weld (secondary current); however, the secondary current magnitude was expressed as a function of the primary (input) current. That is, a value of, say 500 primary amperes, would be 500(K) secondary amperes. Although this was an adequate method of calibration with the facilities available to Mr. Badlaney, the actual values of secondary current were determined indirectly.

Mr. Fitzgerald obtained the secondary current, as a voltage, on an oscilloscope. A photograph of this voltage was made and through a calibration procedure, this voltage was interpreted as a secondary current. Mr. Fitzgerald's method was accurate but digital in nature and somewhat expensive.

In this thesis investigation the secondary current was recorded as a voltage on the continuously moving chart of the Sanborn Recorder. Since the velocity of the chart was constant, the time of current flow and also the current magnitude was found quite accurately. The major inaccuracies in these measurements are attributable to the response of the system lagging the actuating variable and minor calibration errors. The inertia of the response system was small, however, and the calibration procedure is subsequently described.

B. CALIBRATION PROCEDURE

In the calibration circuit for the secondary current it was necessary to change current to voltage by resistors. Chronologically then, it was first necessary to calibrate the resistors used in the circuit.

1. Calibration of Resistors

Two resistors were used in the current calibration circuits (one for the secondary current circuit and one for the primary current circuit.) The values of these resistors were 0.2515 ohms for the secondary current and 0.2545 ohms for the primary circuit.

The ohmic values of the resistors were determined by the use of a Wheatstone Bridge as shown in the following schematic, Fig. 3.

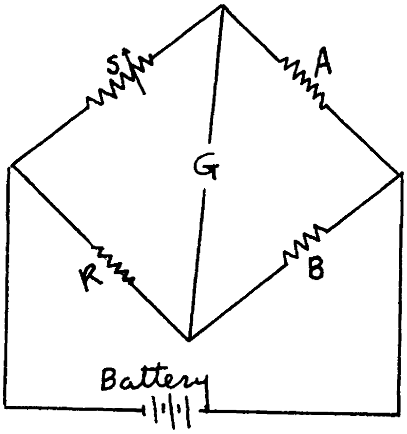


FIG. 3 - Wheatstone Bridge.

Fig. 3 shows the bridge circuit where:

A, B = fixed equal resistance, or resistors.

S = an adjustable resistance.

R = an unknown resistance, or resistor.

The theory of the Wheatstone bridge states: If the voltage potential across the branch containing A and B is the same as the potential across the branch containing S and R, then no current will "flow" through G, the galvanometer. That is, if S/R = A/B, then the galvanometer will indicate zero or the "null" position. Therefore, if A and B are fixed equal resistors and S an adjustable resistance, then an unknown resistor, R, can be found by adjusting S to give a "null" reading on the galvanometer. The value of S is read and this is the value of R.

$$R = A/B\ (S)$$

In this fashion, the resistors were calibrated to give 0.2515 ohms of the resistor used in the secondary current circuit and 0.2545 ohms for the primary current circuit resistor.

2. Calibration of the Secondary Current and Primary Current

The secondary current could not be measured directly with an ammeter because of the large values of current during the welding cycle. It was therefore necessary to place a current transformer on the secondary side of the welding machine during the actual weld cycle. Equipment set up for calibrating current is shown in Fig. 4.

The circuitry for calibrating both secondary current and primary current is schematically shown in Fig. 5. In this schematic, the signal generator is the source voltage of 60 cycles/sec. This output goes into a vacuum tube voltmeter and also into a recording channel on the Sanborn recorder. That is, the voltage transmitted to the Sanborn recorder is reflected by a mm. deflection on the strip. The magnitude of the voltage necessary to calibrate ranged from 0.3 volts to 3.9 volts and it was therefore necessary to calibrate in smaller ranges by suppressing voltages (by a dial on the Sanborn unit) for the higher ranges. The result of these calibrations are shown in Fig. 6, Fig. 7, and Fig. 8.

The calibration circuit for the primary current was the same as that for the secondary current. Voltage suppression was not necessary

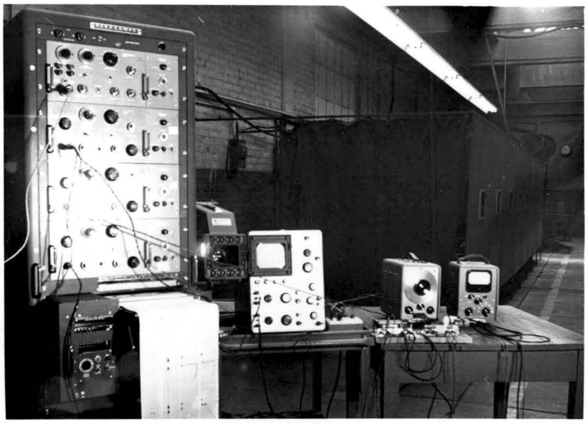


FIG. 4 - Equipment Set Up For Calibrating Current.

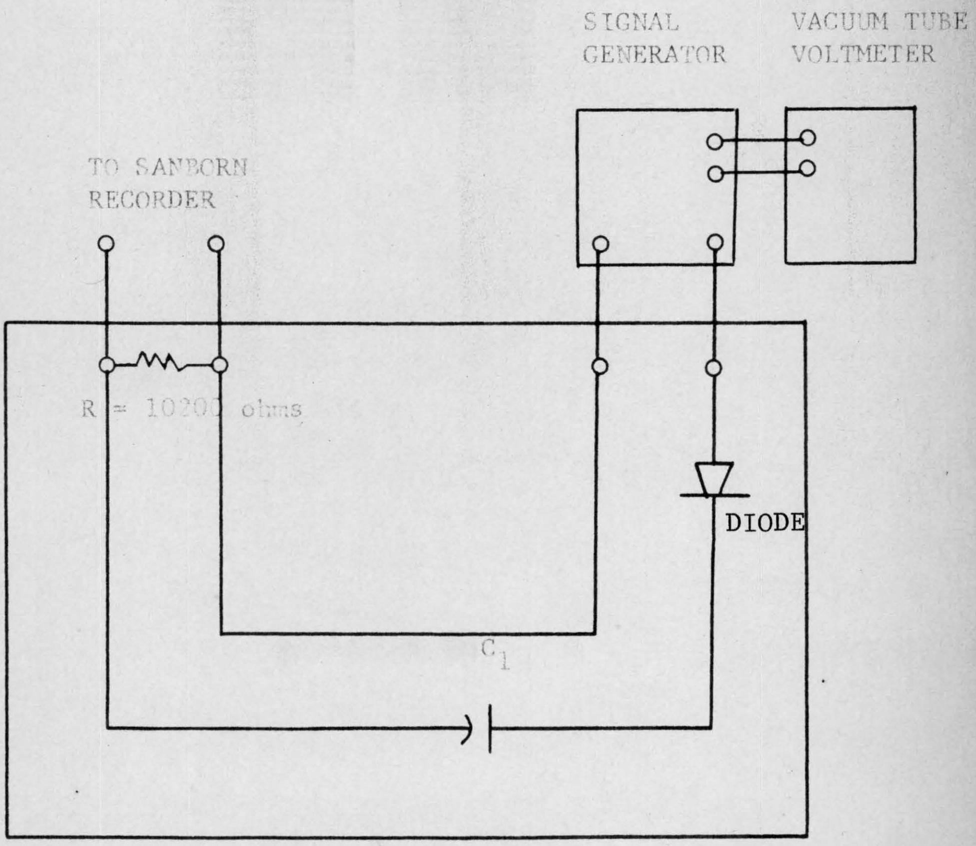
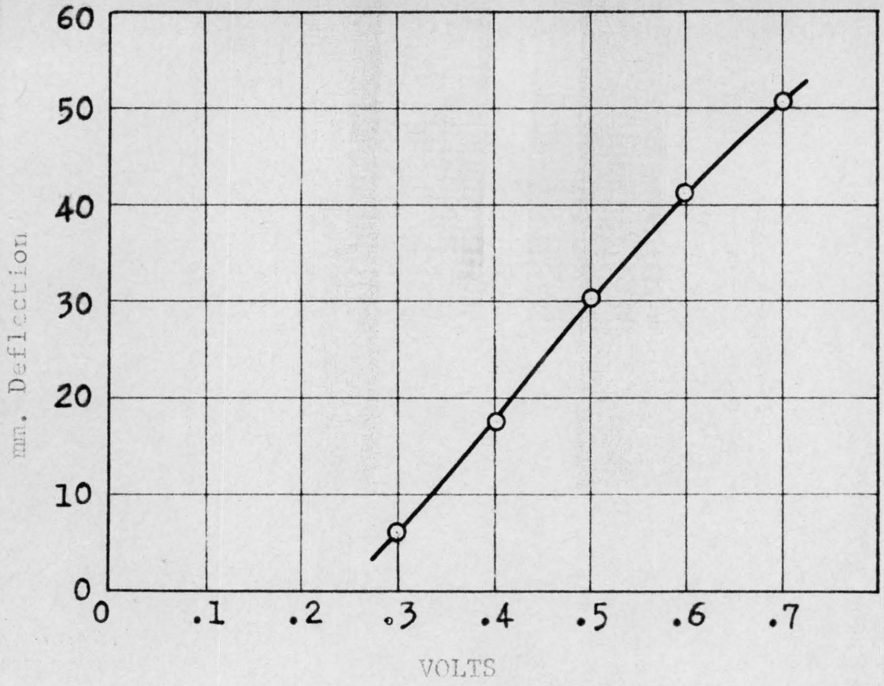
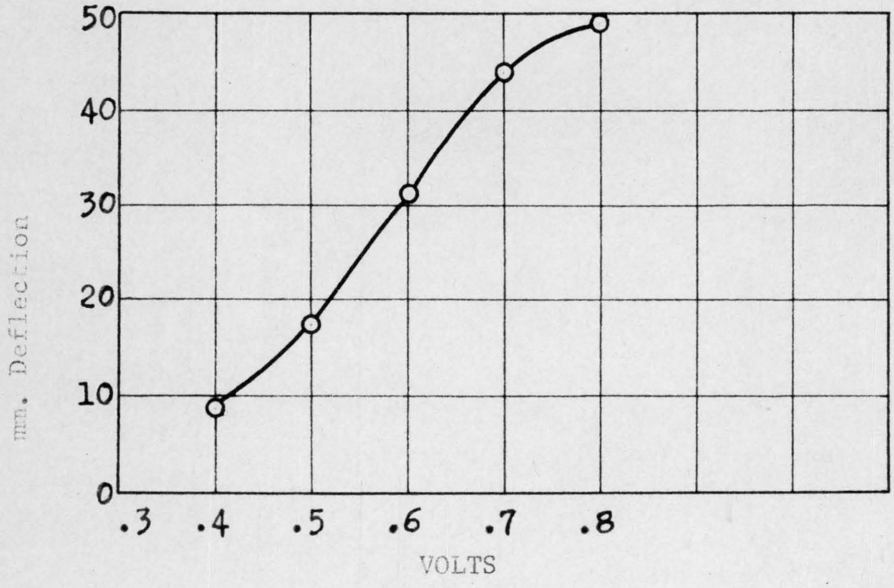


FIG. 5 - Calibration Circuit for both Primary Current and Secondary Current.

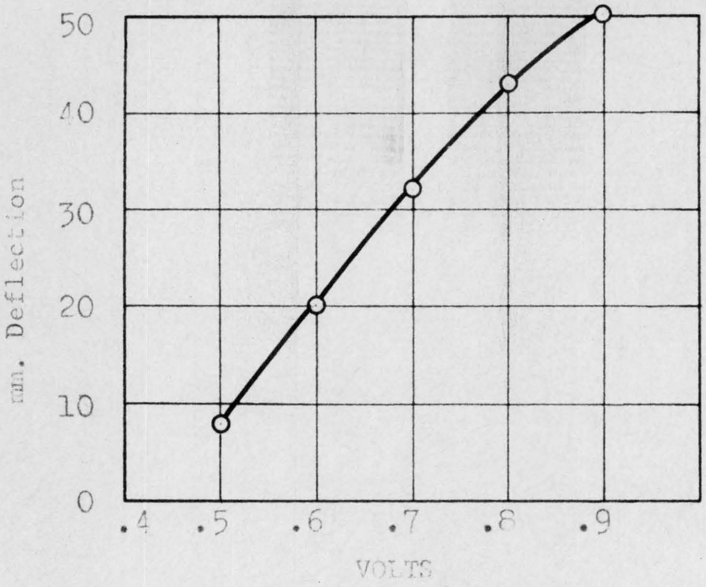


Note: 0 Volt Suppression

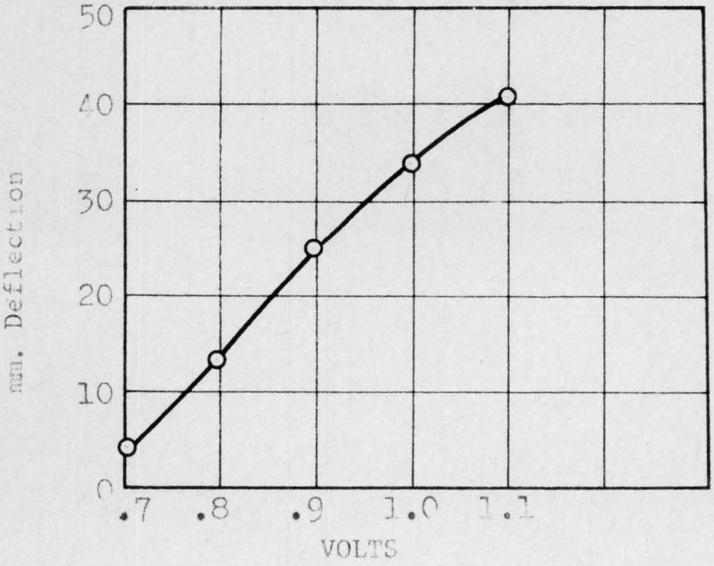


Note: 0.2 Volts Suppression

FIG. 6 - Calibration Curves for
Secondary Current.

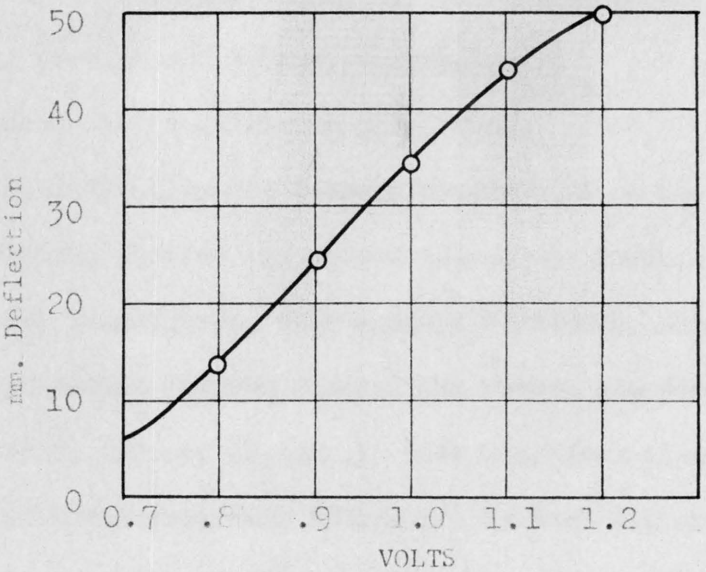


Note: 0.4 Volts Suppression

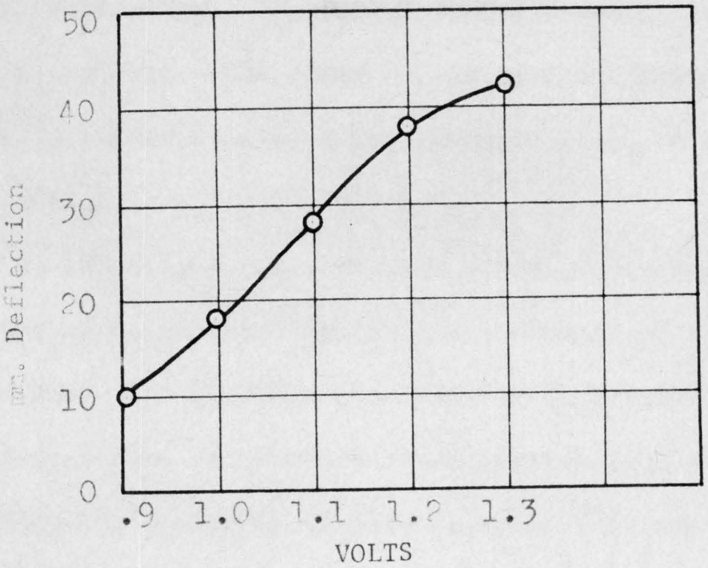


Note: 0.8 Volts Suppression

FIG. 7 - Calibration Curves
for Secondary
Current.



Note: 1.0 Volts Suppression.



Note: 1.4 Volts Suppression.

FIG. 8 - Calibration Curve
for Secondary
Current.

for the primary current calibration. The result is shown in Fig. 9.

As stated above, the mm. deflection on Sanborn recorder Vs. voltage was calibrated. Thus, the necessary circuits for measuring secondary current and primary current could be set up. This will be discussed in the following paragraphs.

Specifically, the current transformer on the secondary side of the welding machine was placed around the lower rocker arm. The current transformer, with a ratio of 2400:5, transmitted the secondary current flowing through the rocker arm (say 2400 amps) to the measuring circuit (5 amps.) This step-down transformer thus allowed standard recording devices to be used during the weld tests.

3. The Circuit for Measuring Secondary Current

The circuit for measuring secondary current is shown in Fig. 10. In this schematic, the input A. C. current is from the 2400:5 step-down transformer. The 0.2515 ohmic resistor changes the current to an A. C. voltage. The diode of the circuit dampens out one-half of the A. C. characteristic (sine wave) to give, in effect, a D. C. characteristic.

The 100 microfarad capacitor stores, then releases, to give a pulsating D. C. characteristic to one channel of the Sanborn amplifier Recorder. The 10,200 ohmic resistor (R_2) across the measuring circuit output into the Sanborn input terminals is to "bleed" residual voltage from the measuring circuit prior to the next test weld.

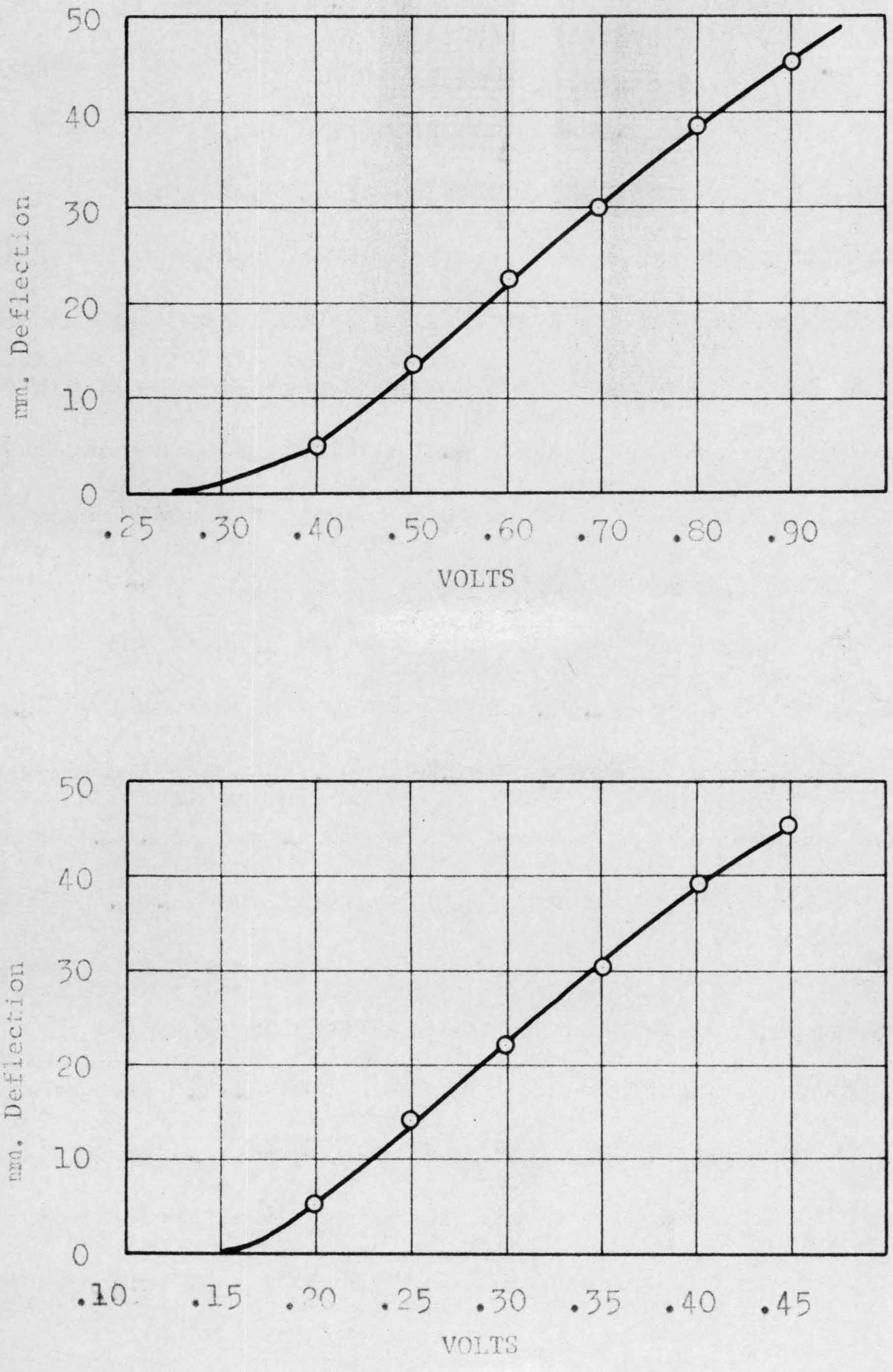


FIG. 9 - Calibration Curves for
Primary Current.

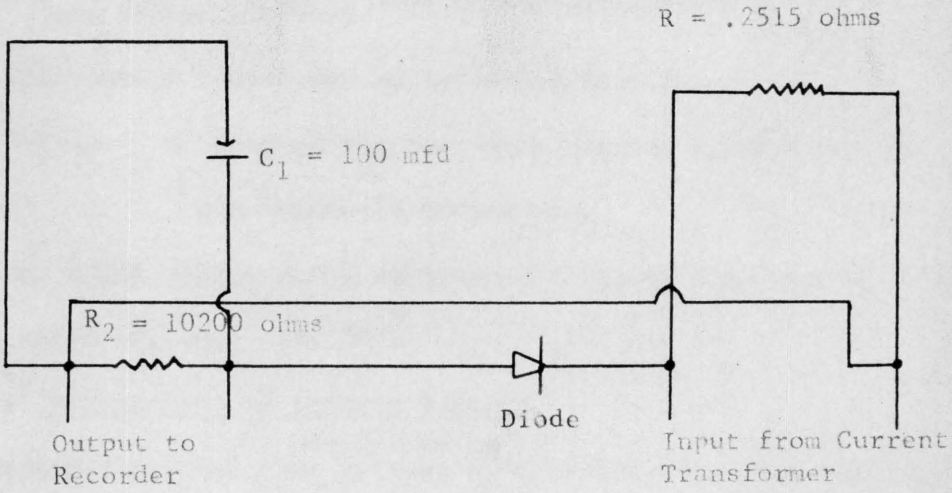


FIG. 10 - Schematic Circuit for Measuring Secondary (Welding) Current.

The voltage thus transmitted to the Sanborn Recorder is reflected by a mm. deflection on the strip chart. Therefore, it was necessary to find out the amount of mm. deflections for given voltage inputs. Once this was known (from previous calibration circuit), the secondary current was calculated from

$$I = \frac{E}{0.2515 \text{ ohms}} (2400:5)$$

$$E = \frac{1}{\text{mm. deflection/volt}} (\text{No. of mm. deflection})$$

.2515 ohms = resistance of measuring circuit.

2400:5 = ratio of the step-down current transformer on the machine's rocker arm.

The actual values for E were taken directly from the calibration graphs on pages 37, 38, and 39 .

4. Measurement of Primary Current

Recognizing that line voltage fluctuations during a testing period could cause serious changes in the tensile-shear strengths, it was necessary to monitor the input current to the welding machine. Any variation in the line voltage could therefore be detected.

The circuit for measuring this primary current was similar to that for measuring the secondary current and is shown in Fig. 11.

The only differences in the circuit for measuring primary current and the secondary current is that the value of the resistor was different as shown in Fig. 11.

The voltage thus transmitted to the Sanborn Recorder is reflected by a mm. deflection on the strip chart. The computation

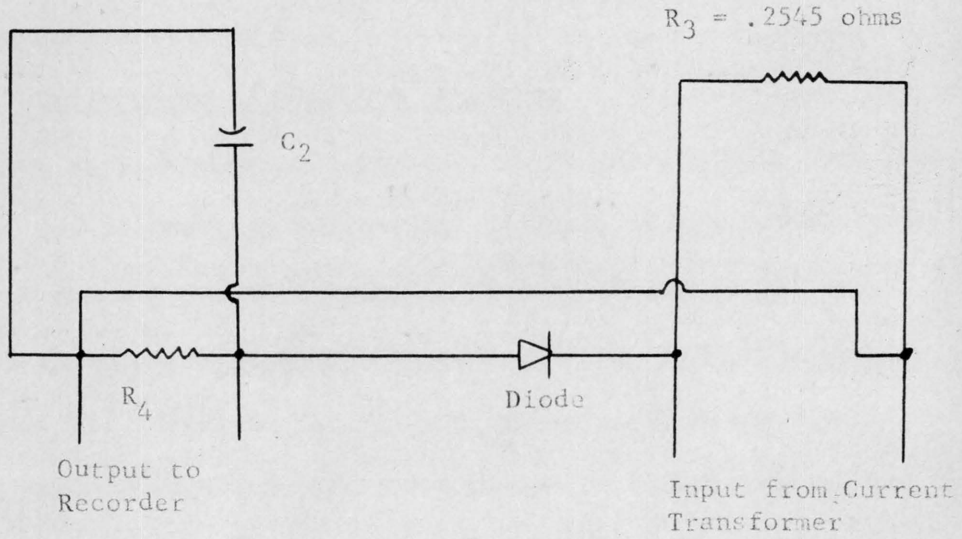


FIG. 11 - Schematic Circuit for Measuring Primary Current.

for the primary current was:

$$I = \frac{E}{0.2545 \text{ ohms}} (100:5)$$

$$E = \frac{1}{\text{mm. deflection/volt}} (\text{No. of mm. deflection})$$

.2545 ohms = resistance of measuring circuit.

100:5 = ratio of the step-down current transformer on the machine's upper rocker arm.

The actual values for E were taken directly from the calibration graphs on page 41.

5. Calibration of Electrode Pressure

Since varying electrode pressure on the base metals from test to test can cause erratic tensile-shear results, it was necessary to control this pressure to be a constant effect. Pressure was not a variable in this investigation. Pressure was set at 20 lbs. gauge pressure (for all tests) on the welding machine. By means of a monitoring transducer which was connected to the Sanborn unit, the actual pressure applied by the electrode was 21.8 ± 5% psi for all tests. The calibration curve for pressure is shown in Fig. 12.

In total, the Sanborn Recorder was used to record primary current, secondary current, secondary voltage, and electrode bearing pressure. The actual welding time could also be ascertained from the strip chart recordings.

C. MATERIALS AND EQUIPMENT USED

1. Materials: Commercial SAE CR 1010 steel; obtained in 8 feet lengths and 4 feet widths for 5 different gauges, i. e., 16 gauge, 18 gauge, 20 gauge, 24 gauge, and 28 gauge, from

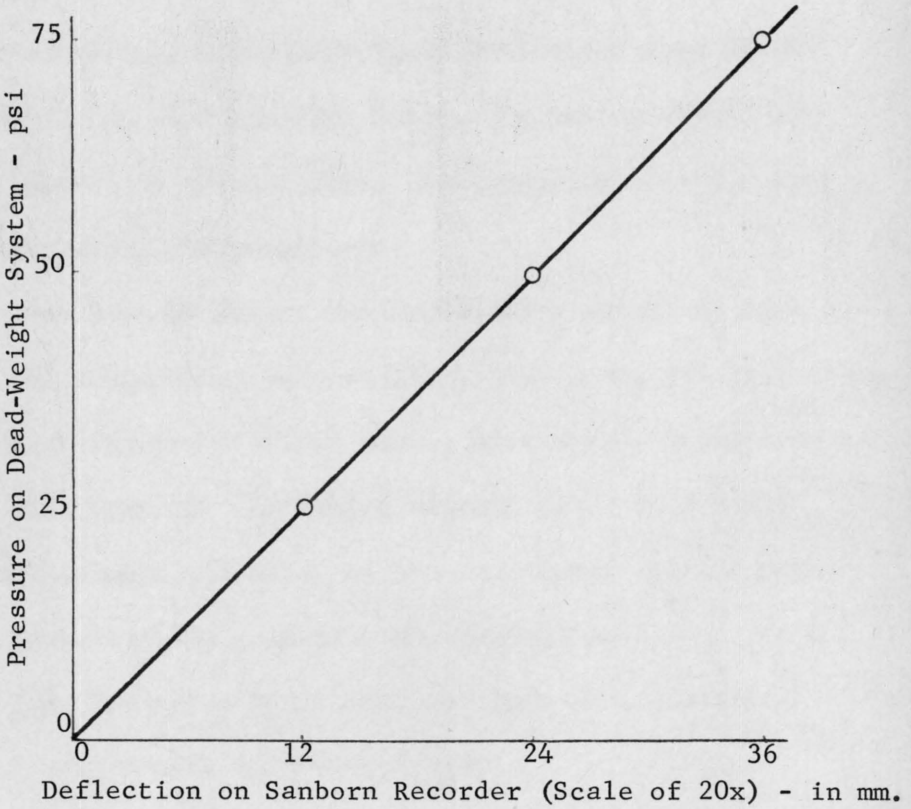


FIG. 12 - Calibration Curve
for Pressure.

(Reference: Fitzgerald M. S. Thesis, p. 39)

Edgecomb Steel Co., Greensboro, North Carolina.

2. Equipment

(a) A. C. Press Type Spot Welder: Transformer capacity about 5 KVA, 60 cps, Type 219, 200 volts, Serial Number 16329; obtained from Thomson Electric Welder Company, Lynn, Massachusetts.

(b) Control Equipment:

Weld-O-Trol Electronic Power Contactor: Type SW-600 with "B" size ignitron tubes. Switching device for control of current flow. Westinghouse Electric Corp., Pittsburgh, Pennsylvania.

Nema Type 3B Timer: Non-synchronous automatic timer for controlling squeeze time, weld time, and hold time; Westinghouse Electric Corp., Pittsburgh, Pennsylvania.

Heat Control: An analog current (therefore heat) adjustment expressed as per cent heat. Westinghouse Electric Corp., Pittsburgh, Pennsylvania.

(c) Dual-Beam Oscilloscope: Type 502; Tektronix Incorporated, Beaveton, Oregon.

(d) Camera: Type C-12 attachment for Oscilloscope which permits oscilloscope displays to be viewed and photographed simultaneously. Tektronix Incorporated, Beaveton, Oregon.

(e) Sanborn Amplifier with Recording Unit: Model 150-1100; obtained from Sanborn Company, Waltham, Massachusetts.

(f) Vacuum Type Voltmeter: Type 410 B, A. C.-D. C.; Hewlett Packard Company, Palo Alto, California.

(g) Tensile-shear Testing Machine: Used for tensile-shear test. Ranges: 60,000 pounds (100 pounds scale graduation); 12,000 pounds (20 pounds scale graduation); 1,200 pounds (2 pounds scale graduation.) Hydraulically operated; Tinnus Olsen, Willow Grove, Pennsylvania.

(h) Metal Shearing Machine: Wysong and Miles Company, Greensboro, North Carolina.

(i) Thermometer: Used for measuring the temperature of electrode cooling system.

(j) Micrometer Caliper: Used for measuring the thickness of test specimens.

D. EXPERIMENTAL SET-UP

The experimental set-up for the investigation is depicted by Fig. 13, Fig. 14, and Fig. 15.

a. Variables held constant.

1. Squeeze time at 120 cycles.
2. Hold time at 60 cycles.
3. Electrode force was monitored as 21.8 psi ± 5%.
4. Electrode Tip Diameter at .187" ± .002".
5. Material: SAE CR 1010 Steel.

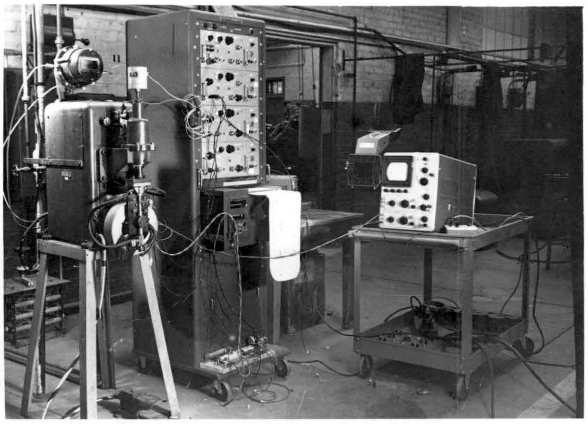


FIG. 13 - Equipment Set Up During the Investigation.

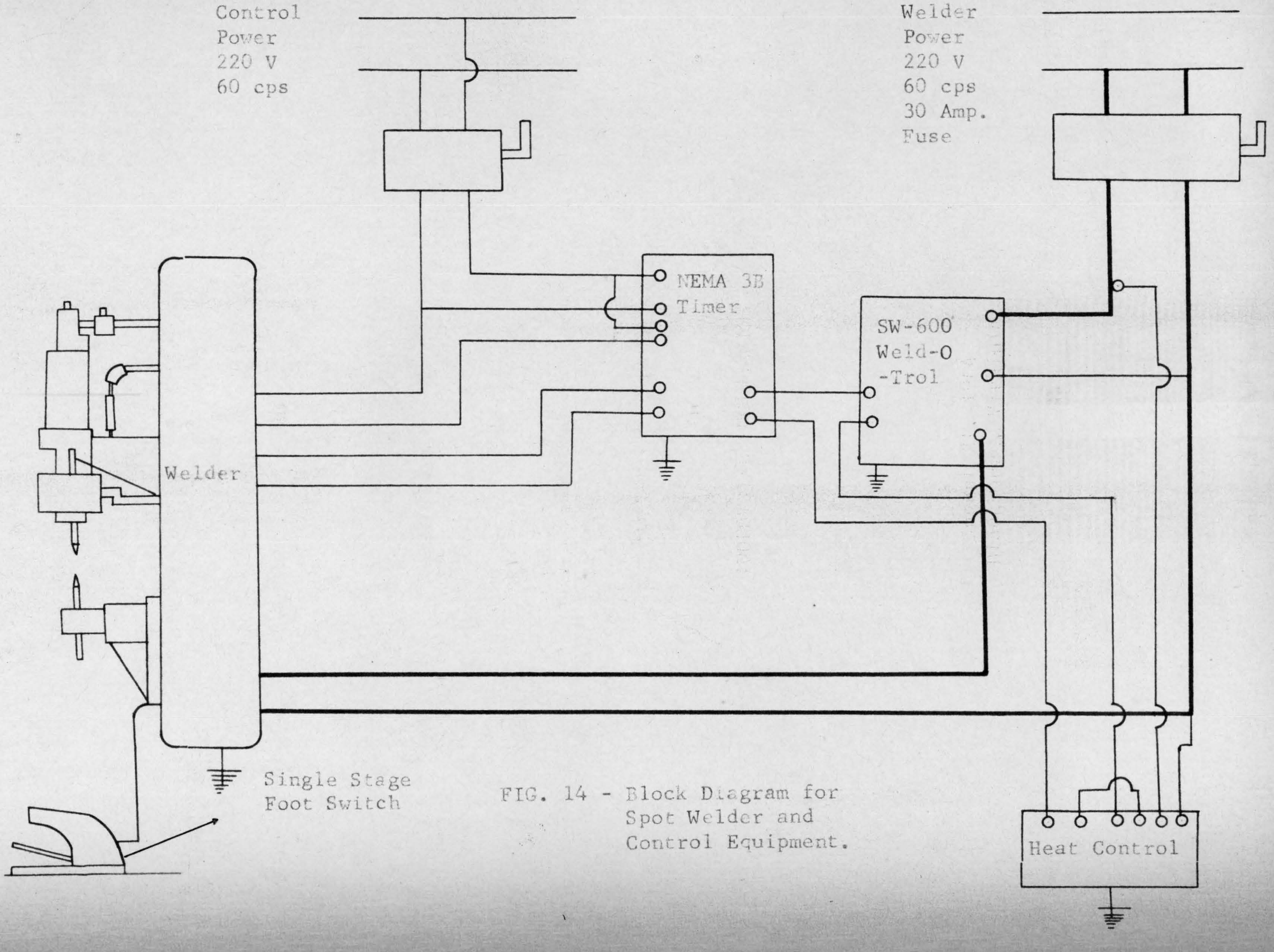


FIG. 14 - Block Diagram for Spot Welder and Control Equipment.

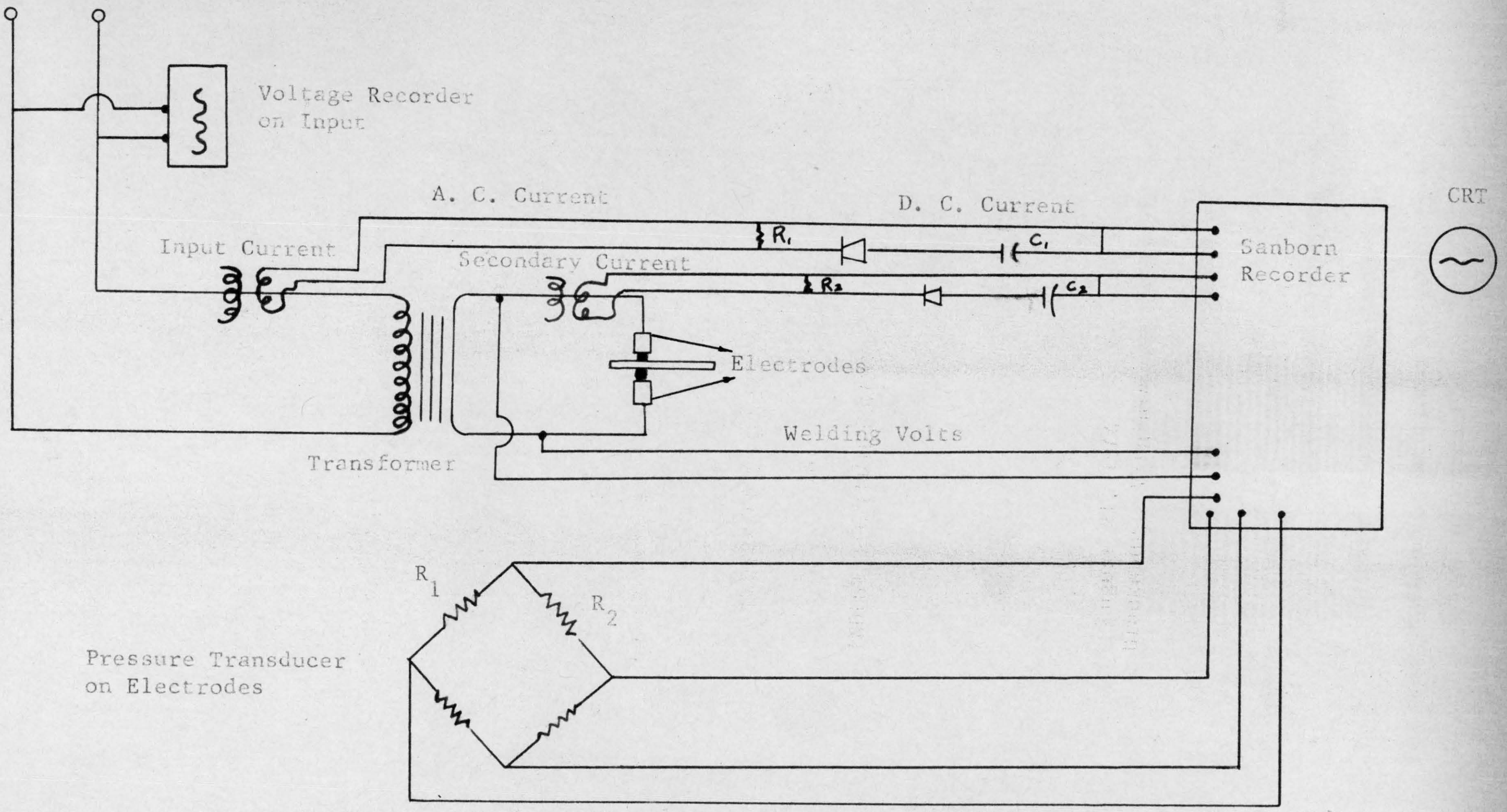


FIG. 15 - Welding Circuit.

6. Surface condition was assumed constant (cleaning treatment was given.)

b. Variables investigated.

   1. Weld time.
   2. Welding Current.
   3. Metal thickness.

CHAPTER V

THE INVESTIGATION

A. PRELIMINARY INVESTIGATION

(1) Preparation of Stock:

The stock specimens were cut in 1 in. wide by 6 in. long strips (see Fig. 17), a size that has been recommended as a standard for this material[23]. Prior to welding, all of the specimens were cleaned for welding by applying acetone solution and soft cotton swab. The specimens were overlapped 1 in. and with a single spot as shown in Fig. 18.

(2) Shape and Size of Electrode Tips

The electrodes were of the flat type with diameter .187" ± .002".

(3) Cleaning of Electrode Tips

The electrode tips were cleaned with fine emery cloth after every three welds. In order to minimize the rate of tip contamination, the diameter of the electrode was measured with a micrometer caliper after every third weld and was maintained within ± .002" tolerance. If the diameter was found larger than this tolerance, the tip was dressed on a lathe.

(4) Temperature of Electrode Cooling System

The water inlet temperature was maintained between 50° F. and 60° F. The water flow rate was approximately 6 gallons per minute.

WELDING SPECIMEN

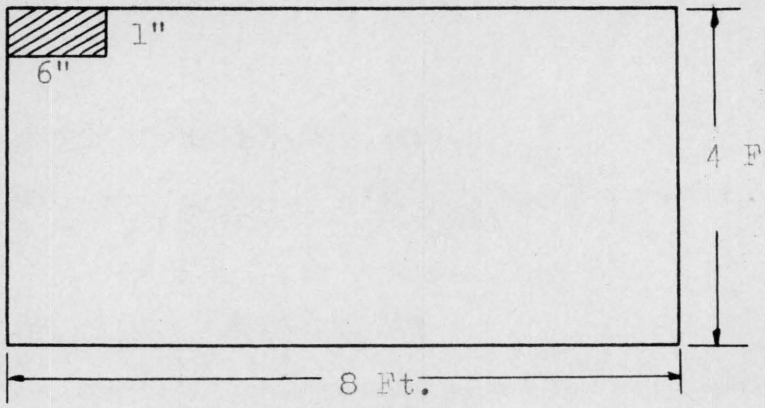


FIG. 16 - Method of Cutting
Specimen.

WELDING SPECIMEN

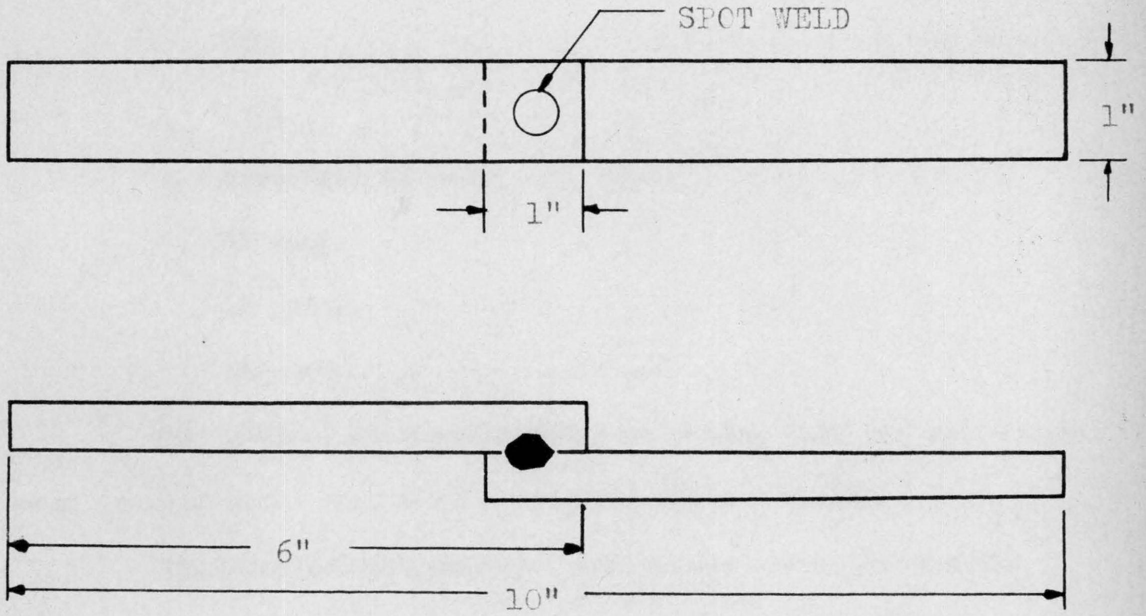


FIG. 17 - Dimensions of Spot Weld.

(5) Preliminary Experiment

The following combinations were used during the preliminary experiment:

a. Welding times:

30 cycles

20 cycles

10 cycles

b. Heat control settings:

100%

80%

60%

c. Sheet thicknesses:

28 gauge

20 gauge

16 gauge

One weld of each combination was made. All the spot-welds were tensile-shear tested on a standard testing machine.

This preliminary phase of the thesis investigation was mainly a familiarization period for the author and a planning stage for the Final Investigation. No real scientific information was collected in this phase.

B. FINAL INVESTIGATION

Although the Final Investigation was not carried out until consideration had been given to the methods for interpreting the data, the final investigation discussion is presented here for continuity.

In resistance spot welding, the variables involved are many and interdependent. It is evident that a weld produced by a certain combination of variables may present the same quality (tensile-shear strength) as a weld produced by another combination of variables. Since the material used in this thesis investigation was mild steel, the plastic range is so wide that many combinations of variables can produce the same tensile-shear strength. The prediction models developed in this thesis allow the various combinations tested to be found which will give a desired tensile-shear strength. In order that the objectives of this thesis investigation could be accomplished, the following combinations were used:

a. Heat control Settings:

100%
80%
60%
55%

b. Weld time in cycles:

30, 28, 25, 23, 20, 18, 15, 13, 10, 8, 5, 4, 3.

c. Sheet thicknesses:

28 gauge
24 gauge
20 gauge
18 gauge
16 gauge

In general, three welds were made for each possible combination above. As mentioned previously, one of the objectives of this investigation was to find the maxima and minima values of the parameters-weld time and welding current. Therefore, when the lower limits for each heat setting and weld time of each sheet thickness had been approximated, the "no-weld" zone had been located. When the minimum was reached, five welds were made at this setting and was considered as the minimum. Then, the weld time was reduced so that "no-weld" occurred and this weld time was tested for 5 specimens to prove the "no-weld" condition was apparently reached. The upper limit was found from experimental results that is discussed in Chapter VI, Discussion of Results and Conclusions.

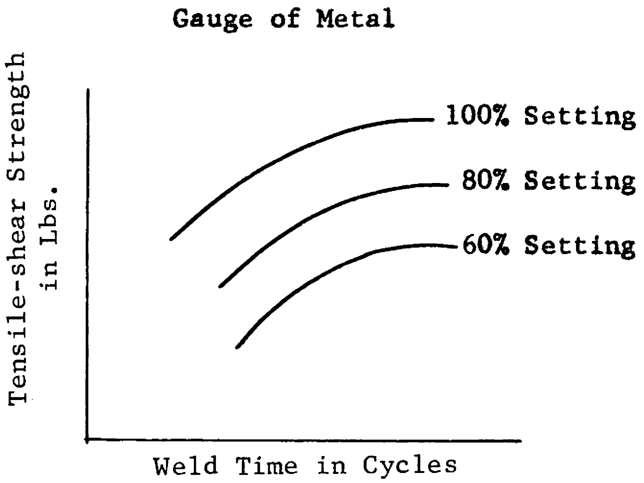
Welding pressure, welding current, welding voltage, and welding time were recorded by the Sanborn recorder. All specimens were tensile-shear strength tested on a standard testing machine. The data obtained from the experiment is shown in Appendix III.

It should be noted that complete randomization of the experiment was neither economically feasible nor necessary. However, the weld cycle times and the test specimens were randomized from test to test.

C. EXPLANATION OF DATA PROCESSING

As discussed in the Experimental Procedure Section of this thesis, once the test specimens were sheared from stock, the specimens were assigned numbers according to a random number table. The welds were made under pre-selected conditions of pressure, current settings, and weld cycle times for different gauges of CR 1010 steel. Each given set of weld conditions was replicated a minimum of three times in order to establish a better estimate of the result--tensile-shear strength of weld joint.

For each gauge of metal, graphical plots of tensile-shear strength vs. weld cycles for different levels of current settings were made.



Tensile-Shear Strength
Vs. Weld Time.

These plots were first made on Cartesian coordinates and the data array, with a few linear exceptions, indicated either a polynomial or logarithmic trend. Therefore, the next step in the analysis of data was to plot individual values on logarithm Vs. Cartesian coordinate and logarithm Vs. logarithm scale. It was concluded after a visual interpretation of these plots that

$$Y \neq \log x$$

and $Y \neq b\, x^{a}$

It was then necessary to determine whether the data were best approximated by linear lines or by quadratic curves. In the model:

$$Yi/x = A + B_1 X + B_2 X^2 + \mathcal{E} i, \quad (1)$$

the author used the following statistical method and assumptions to determine whether the data were best fit by quadratic curves or linear lines.

After finding those weld conditions best-fit by a quadratic and those weld conditions best-fit by linearity; then the equations for the best fitting lines or curves were found through programming of an IBM 1620 computer. From the polynomials and the use of calculus, the maximum tensile-shear strengths were computed.

1. MODEL

$$Yi/x = A + B_1X + B_2X^2 + \mathcal{E} i$$

where, Yi = observation under treatment i (tensile-strength in this investigation.)

X = independent variable (welding time in this investigation.)

$\mathcal{E}i$ = random error associated with the treatment i

A, B_1, B_2 are coefficients found by inverting a matrix.

2. ASSUMPTION FOR THE MODEL

1) Yi/x is a random variable, subject to random variation.

2) Assume $Yi \sim N(A + B_1x + B_2x^2, \sigma^2)$

The model can be rewritten as follows:

$$E(Yi/x) = A + B_1x + B_2x^2$$

The problem resolves itself into one of determining the value of A, B_1, and B_2 that will make the sum of squares of the errors associated with each data point a minimum. The expression to be minimized is

$$L = \Sigma(Yi - A - B_1xi - B_2x_i^2)^2$$

One can now differentiate L individually with respect to A, B_1, and B_2, then equate each expression to zero, and arrive at the following "normal equations" for estimating A, B_1, and B_2.

$$\Sigma Y = A N + B_1 (\Sigma X) + B_2 (\Sigma X^2)$$

$$\Sigma XY = A(\Sigma X) + B_1 (\Sigma X^2) + B_2 (\Sigma X^3)$$

$$\Sigma X^2Y = A(\Sigma X^2) + B_1 (\Sigma X^3) + B_2 (\Sigma X^4)$$

The coefficients of the polynomials are obtained from the equations above by the method of elimination and substitution or the Doolittle method.

The above equation could be written as:

$$\Sigma Yi = N A$$

$$S_{1y} = B_1S_{11} + B_2S_{12}$$

$$S_{2y} = B_1S_{21} + B_2S_{22}$$

where, S_{11} = Sum of squares of independent variable X.

S_{22} = Sum of squares of independent variable X^2.

$S_{12} = S_{21}$ = Sum of cross products of independent variables X and X^2.

S_{1y} = Sum of cross products of dependent variable Y and independent variable X.

S_{2y} = Sum of cross products of dependent variable Y and independent variable X^2.

3. STATISTICAL ANALYSIS

After obtaining the coefficients for the model, a valid test is required in order to insure whether or not there is a significant quadratic relationship between the independent variable and the dependent variable, i. e., to test for the quadratic relationship between Y and X.

In order to come to some conclusion based on statistical tests, a hypothesis should be established. A meaningful hypothesis here would be concerned with the parameter B_2 which is the coefficient for the quadratic term.

Therefore, the hypothesis used in this quadratic component test is as follows:

$$H_o \; : \; B_2 = 0$$

$$H_1 \; : \; B_2 \neq 0$$

Table 1

Analysis of Variance

Source	Sum of squares	D.F.	Mean squares
Regression	$B_1S_{1y} + B_2S_{2y} = SSR$	2	$\frac{SSR}{2} = MSR$
Error	$S_{yy} - SSR = SSE$	n-3	$\frac{SSE}{n-3} = MSE$
Total	$S_{yy} = \sum Y^2 - \frac{(\sum Y^2)}{n}$	n-1	

After running an overall analysis of variance (see Table 1), a t-test should be made to determine the significance of the quadratic term in (1), namely

$$t_o = \frac{B_2}{\sqrt{MSE\ C_{ii}}}$$

where the t-test is two-tailed with n-3 degree of freedom. n is the number of the data and C_{ii} is the ith diagonal element of S^{-1}, where S is the following matrix:

$$S = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix}$$

The value of t_o obtained was compared with the upper and low parental parameters of the t distribution with significant level of α, where α is the probability of rejecting H_o when H_o is true, i. e., probability of type I error. If $t_{\frac{1}{2}\alpha} < t_o < t_{1-\frac{1}{2}\alpha}$, accept the H_0, and conclude that one is unable to detect a significance that a quadratic relationship existed between Y and X. Otherwise, reject the H_0, and one may conclude that a quadratic relationship significantly existed between Y and X.

CHAPTER VI

DISCUSSION OF RESULTS AND CONCLUSIONS

The results of this investigation are discussed in two sections. The first section deals with the tensile-shear strengths of spot welds as affected by the variables of welding current and weld time (electrode force was held constant through entire investigation.) The second section deals with the determination of parameters (welding current and weld time) and the explanation thereof. The results of this investigation are based on visual inspection, mechanical testing, and statistical analyses of data.

I. Tensile-shear strengths of spot welds as affected by welding current and weld time. The effect of varying welding current and weld time on the tensile-shear strength of weld joints of a given sheet thickness was what one would expect, i. e., the value of tensile-shear strengths increase with welding current and with weld time on the condition that no expulsion of metal occurred. This is due to the fact that the more the heat that is generated, the larger the fusion zone will be. Neglecting chemical changes, the strength of welds in a given sheet thickness is proportional to the size and shape of the fused zone.

The reader should recall (welding current in Chapter III, Discussion of Variables) that the 100%, 90%, 80%, etc. heat control settings are an approximation of the current magnitude (proportionally) that is "passing" through the weld zone. It was found that for the

100%, the 80%, and the 60% heat control settings for 20 gauge, 18 gauge, and 16 gauge, and for the 60% heat control settings of 28 gauge and 24 gauge that weld tensile-shear strength improved rapidly with an increase in weld time. Further increments of time result in little increases of weld strengths and then, the strengths decrease with increasing weld time. This is explained by the fact that excess heat generation causes molten metal expulsion at the weld interface. The results of particular tests are shown in Figs. 18-22. These curves were theoretically plotted. The shape of these curves depend, for a given thickness of metal, on current Vs. time.

For a given gauge of metal, the effect of current variation for different weld times are shown in Figs. 23-27. These curves show that the tensile-shear strength of weld joints increases as the current is increased in all cases. This is expected since current is one of the three major variables in the fundamental equation of heat generation: $H = I^2RTK$ (See Review of Literature.) Since the heat generated increases with welding current, the more the heat generated the larger the area that will be fused. As a result, the tensile-shear values increase. However, it is very important to realize that this condition holds true only if there is no expulsion of metal at the interface.

Intuitively, for a particular combination of variables and constant gauge a tensile-shear value of, say, 500 lbs. results. In order to obtain the same 500 lbs. result for a different combination

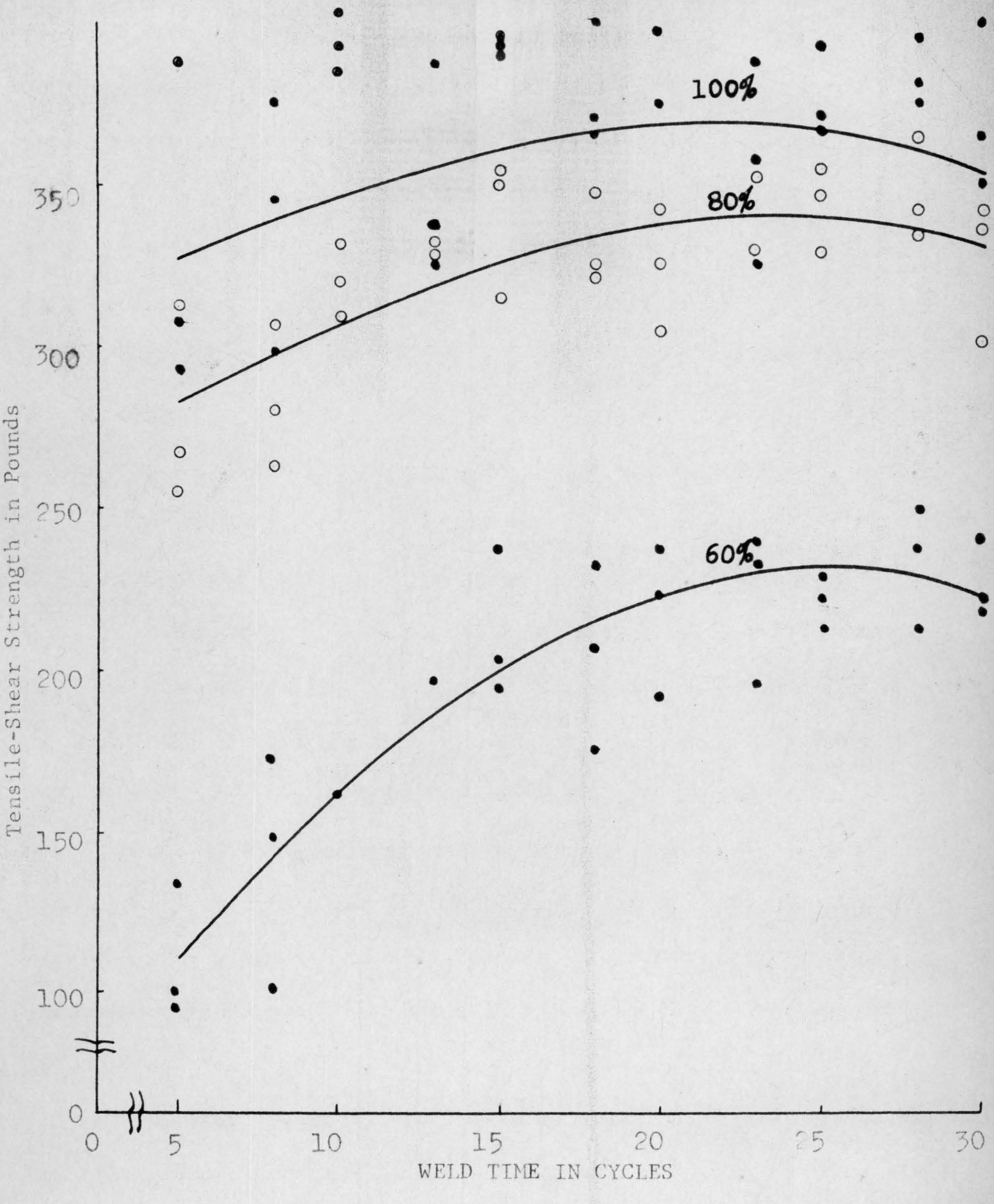


FIG. 18 - Effect of Weld Time on the Tensile-Shear Strength of 28 Gauge SAE CR 1010 Steel.

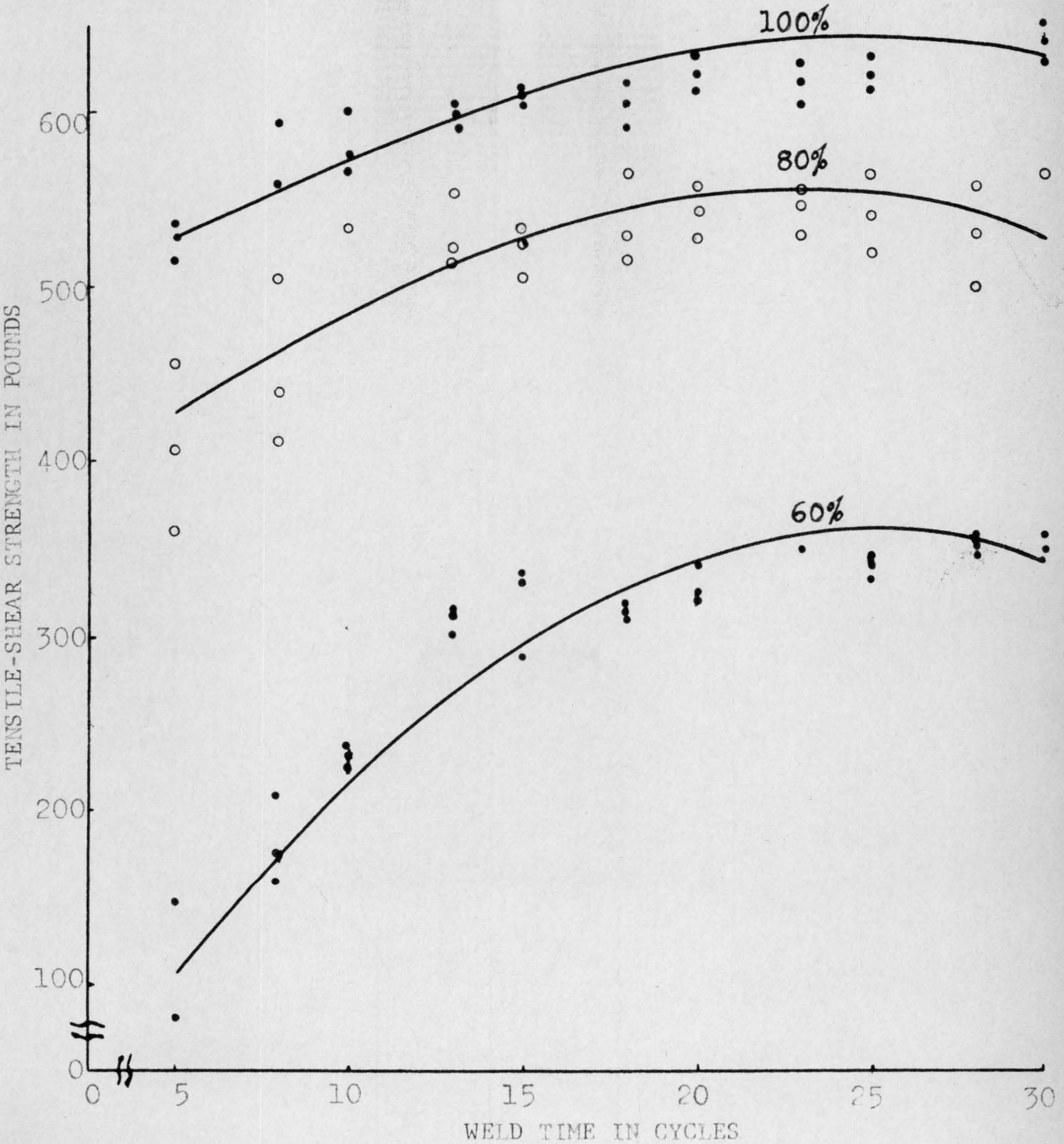


FIG. 19 - Effect of Weld Time on the Tensile-Shear Strength of 24 Gauge SAE CR 1010 Steel.

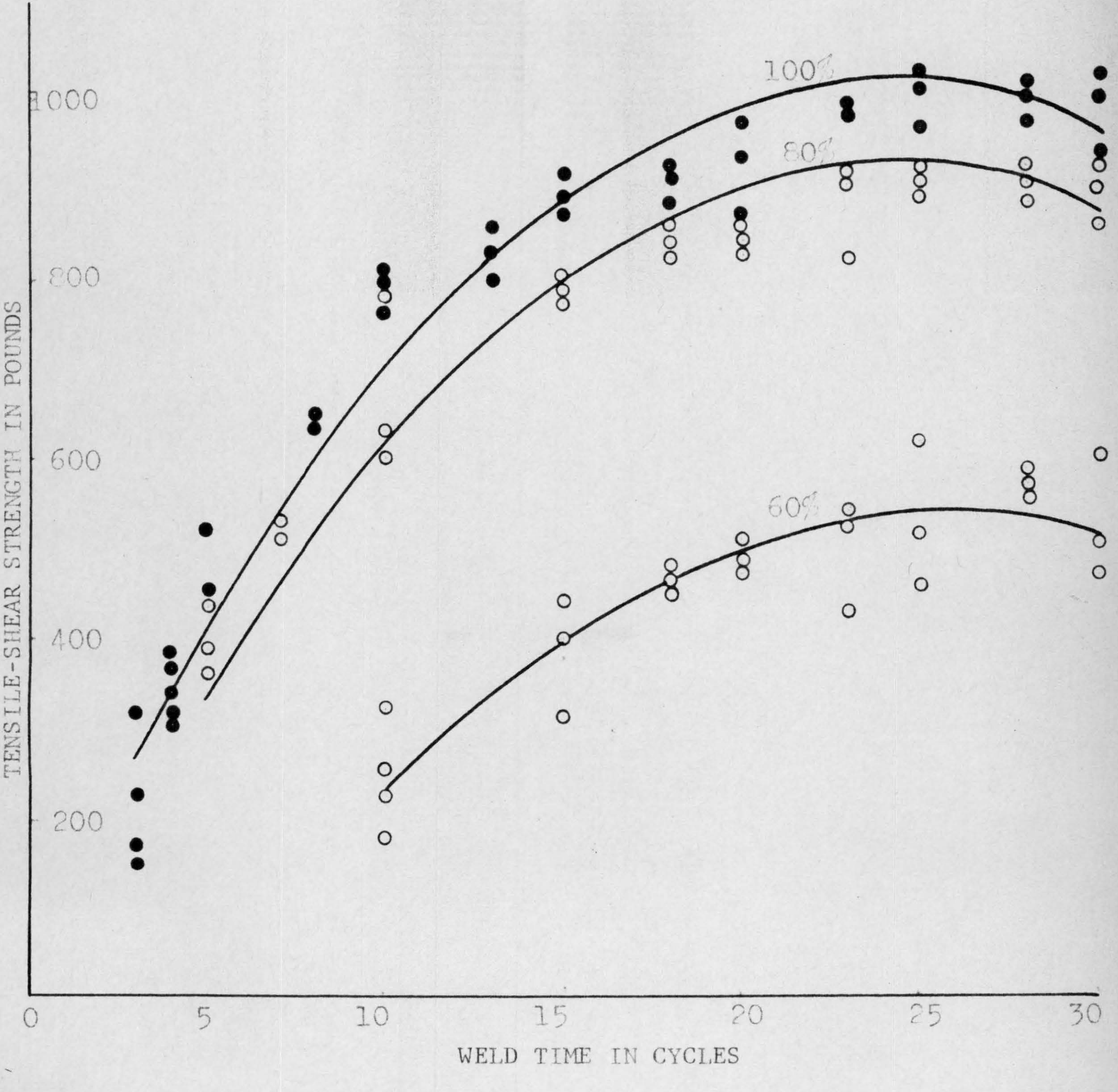


FIG. 20 - Effect of Weld Time on the Tensile-Shear Strength of 20 Gauge SAE CR 1010 Steel.

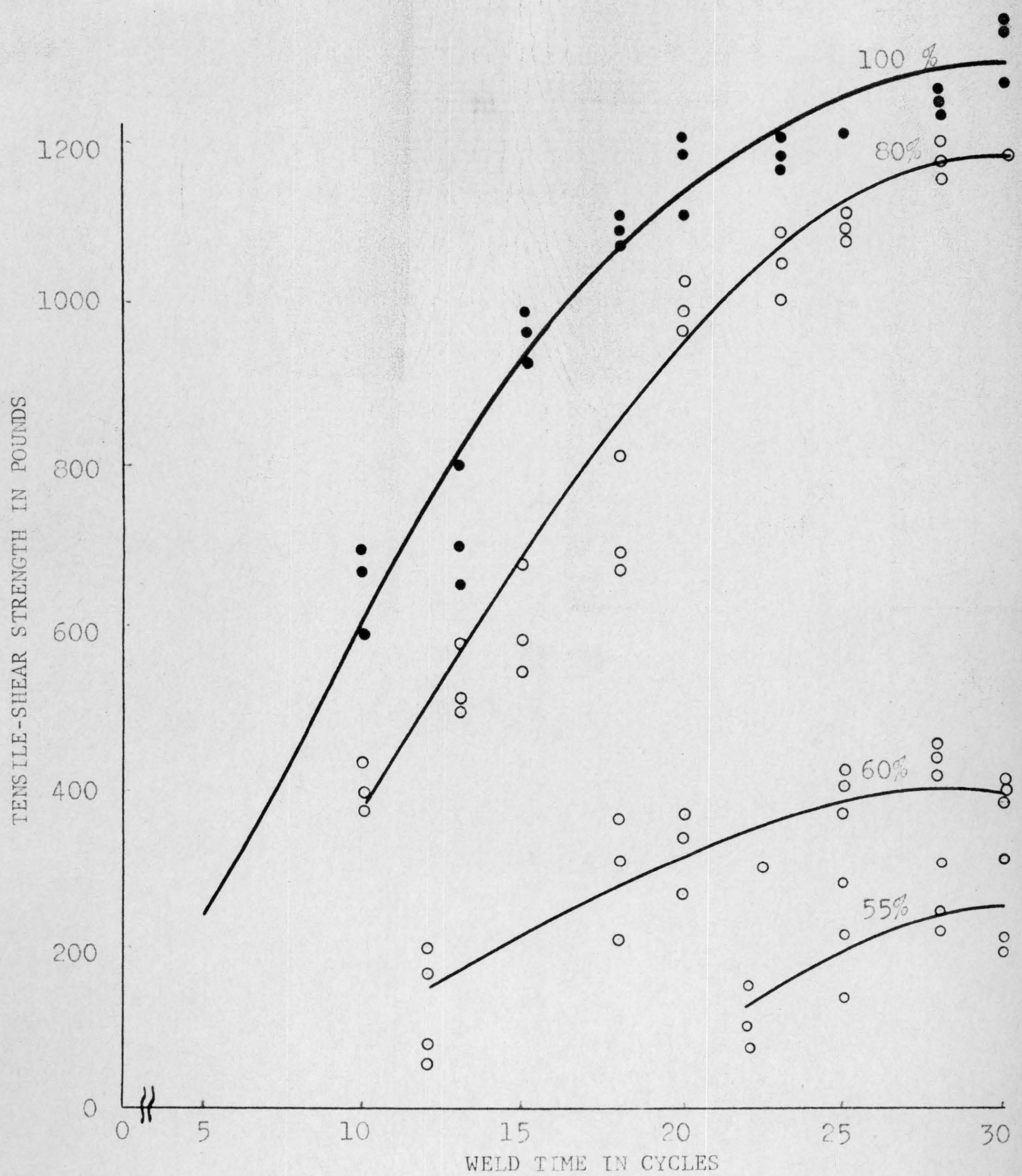


FIG. 21 - Effect of Weld Time on the Tensile-Shear Strength of 18 Gauge SAE CR 1010 Steel.

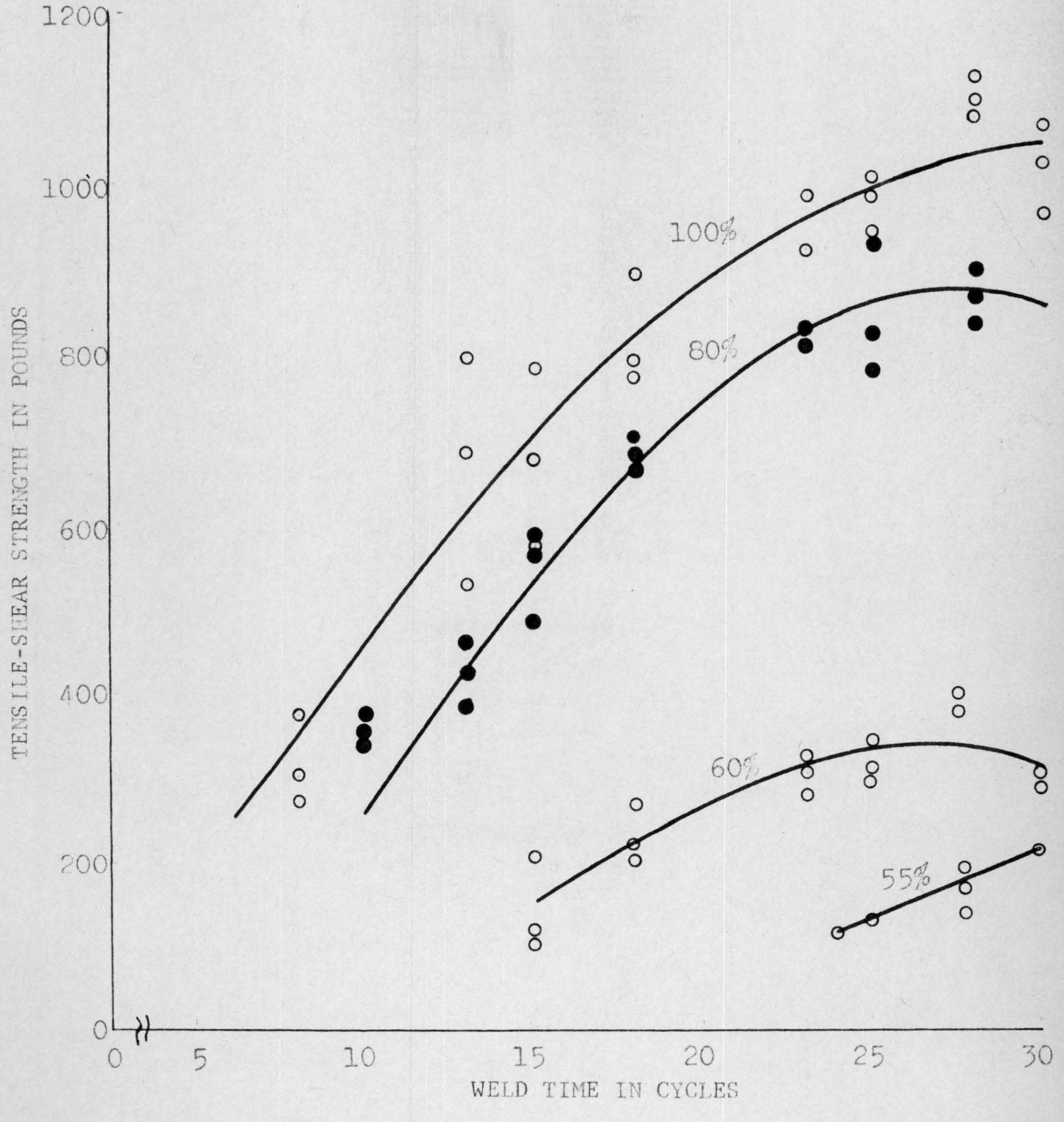


FIG. 22 - Effect of Weld Time on the Tensile-Shear Strength of 16 Gauge SAE CR 1010 Steel.

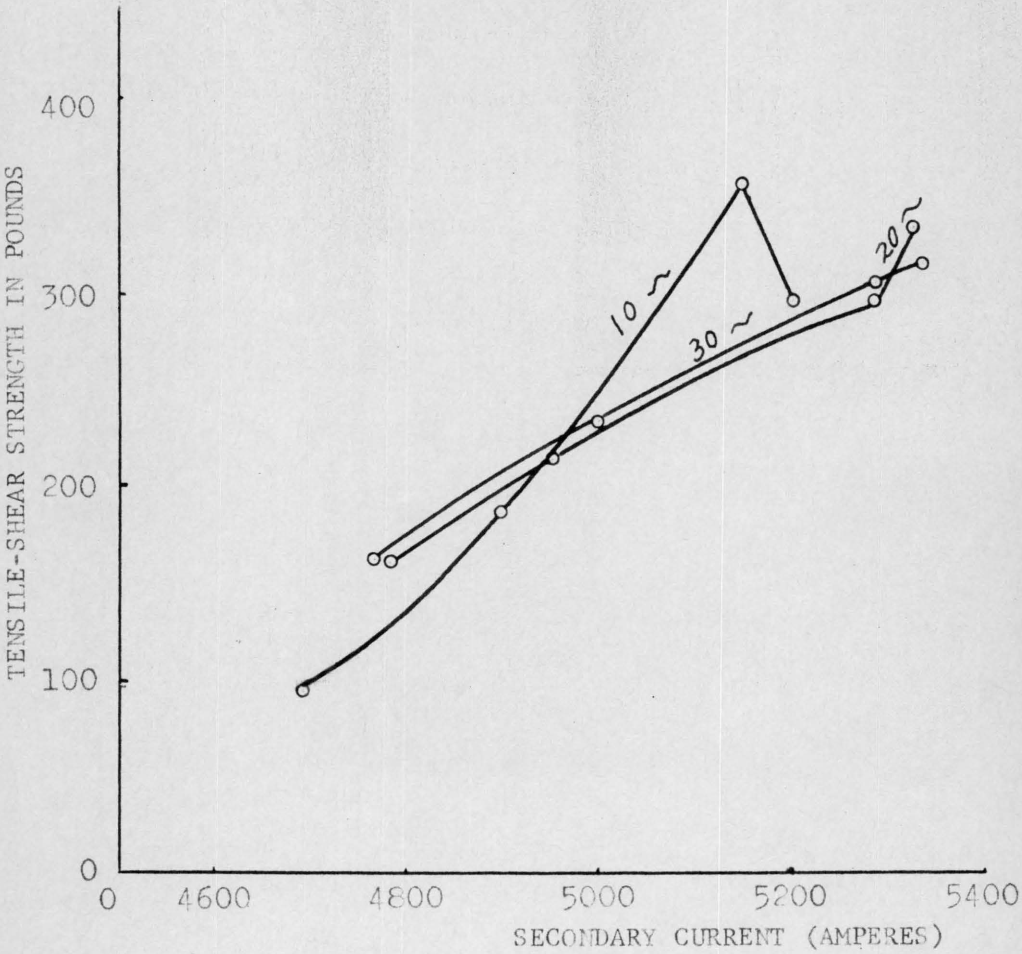


FIG. 23 - Effect of Welding Current on the Tensile-Shear Strength of 28 Gauge SAE CR 1010 Steel.

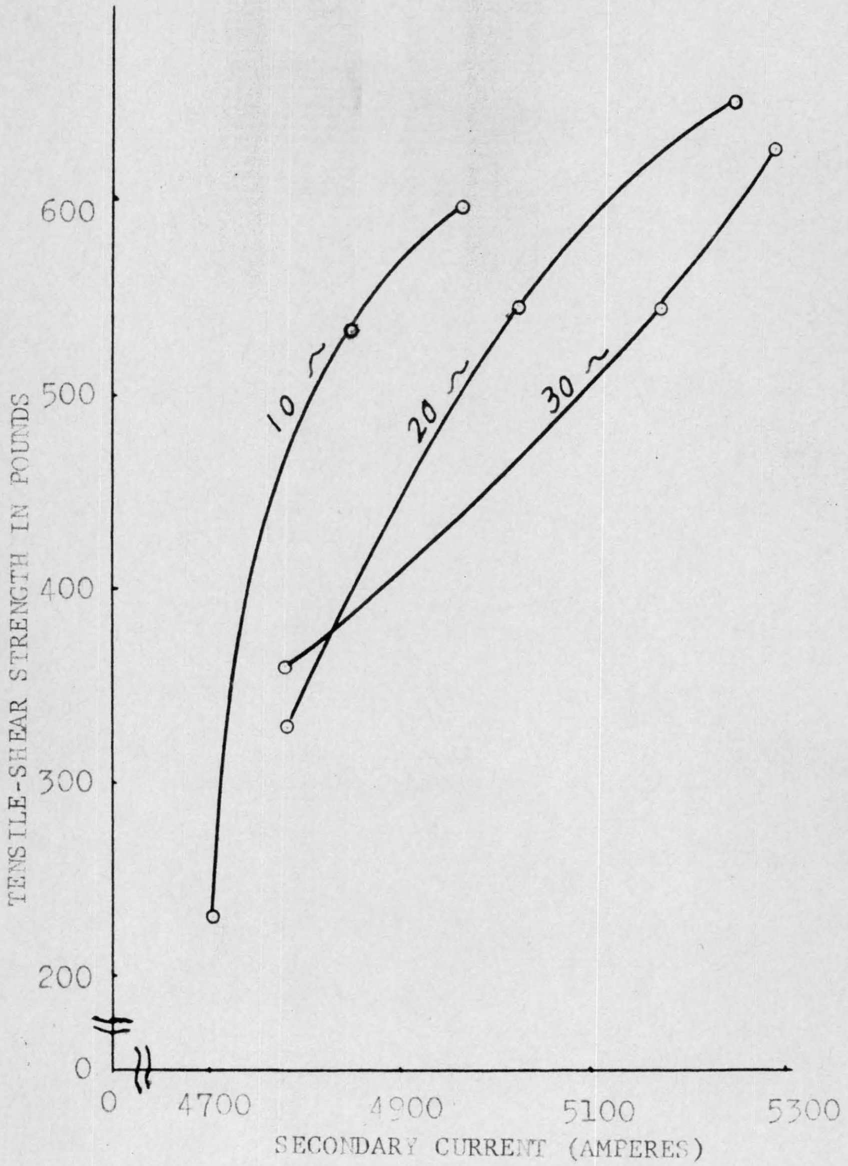


FIG. 24 - Effect of Welding Current on the Tensile-Shear Strength of 24 Gauge SAE CR 1010 Steel.

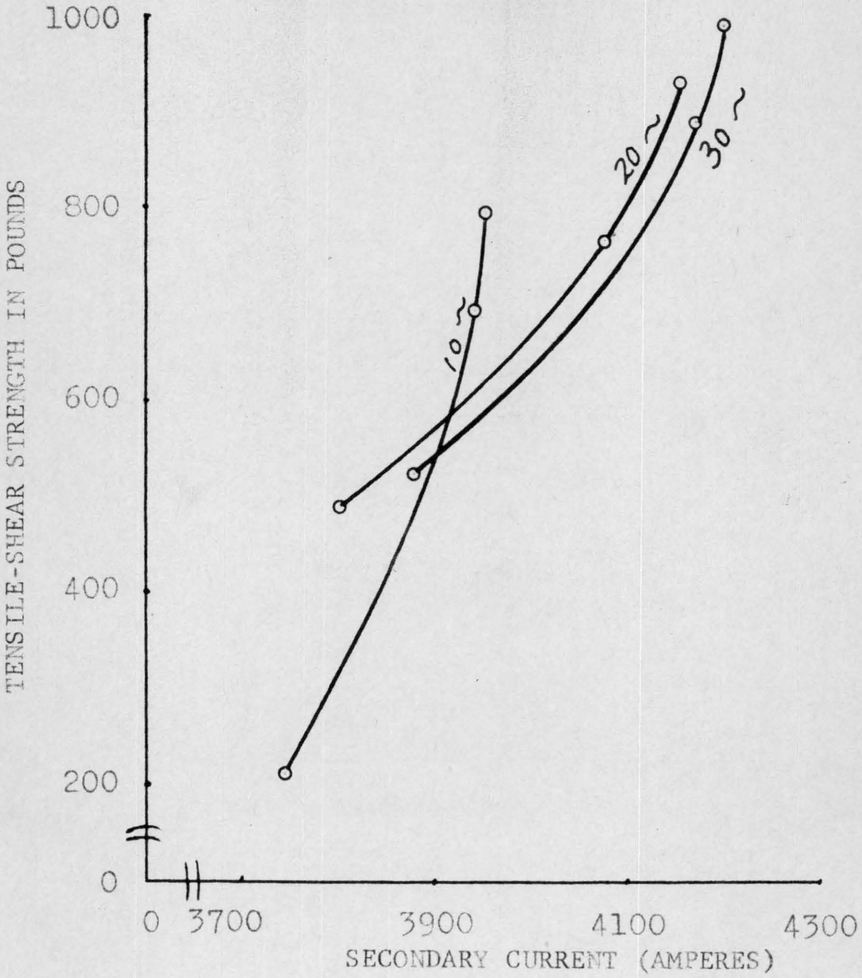


FIG. 25 - Effect of Welding Current on the Tensile-Shear Strength of 20 Gauge SAE CR 1010 Steel.

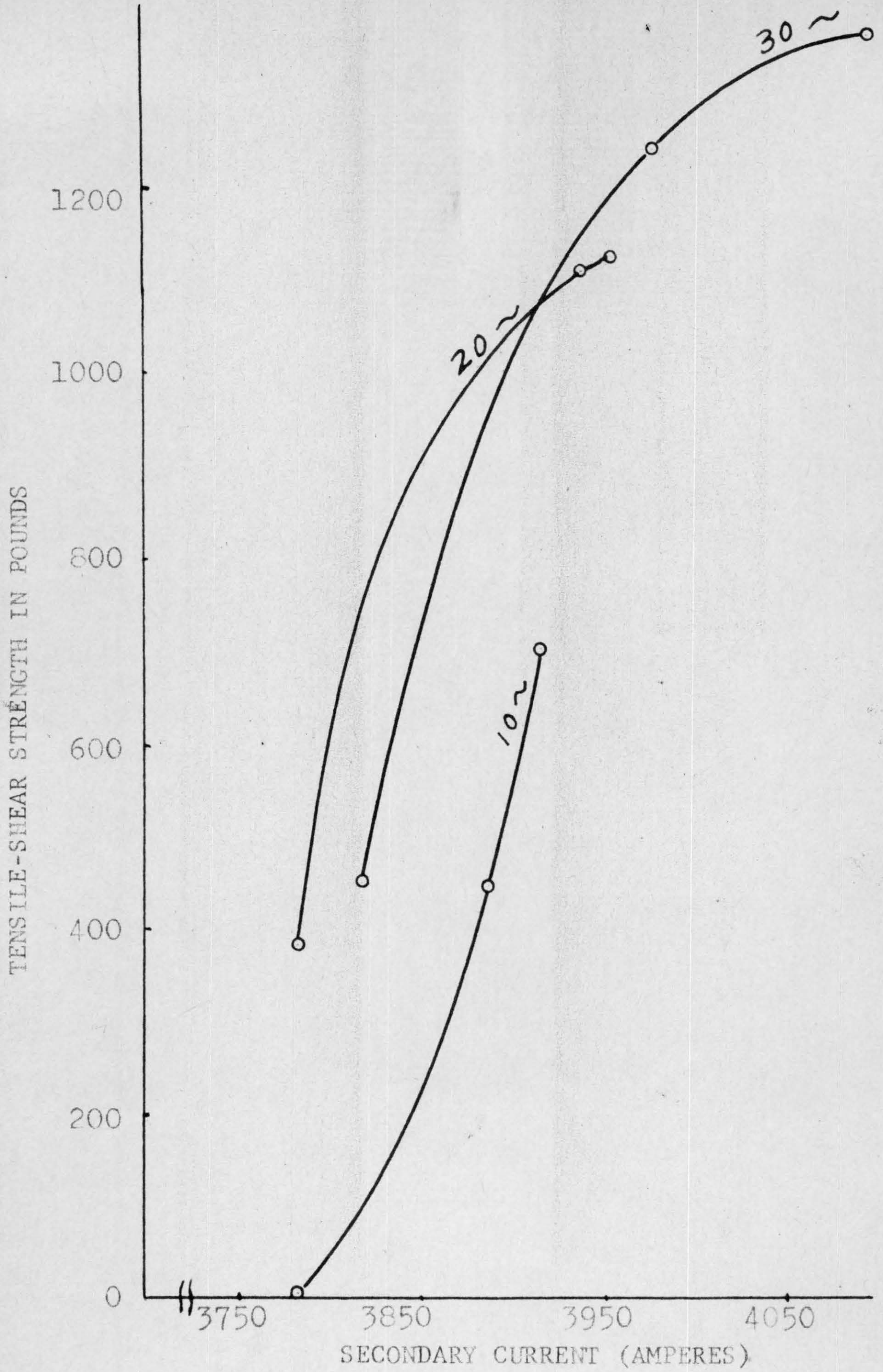


FIG. 26 - Effect of Welding Current on the Tensile-Shear Strength of 18 Gauge SAE CR 1010 Steel.

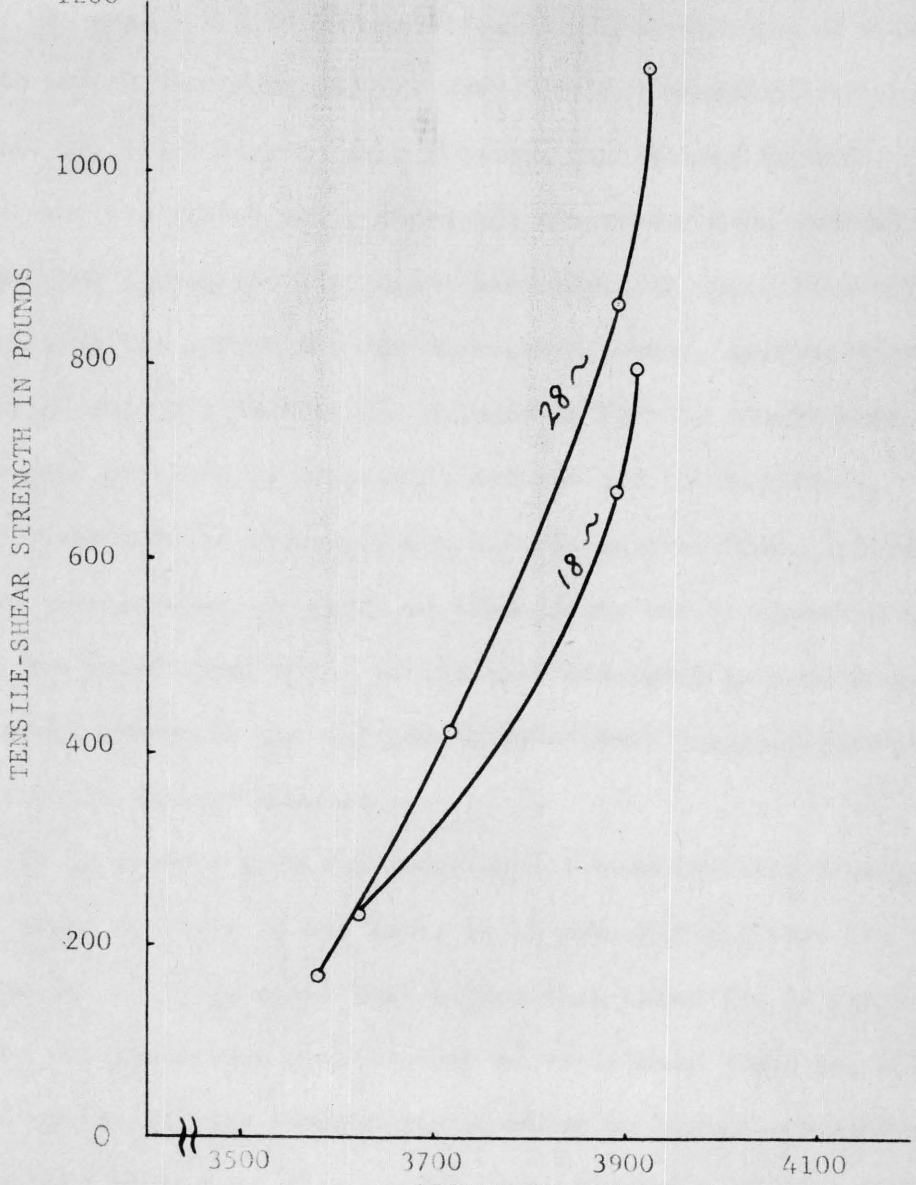


FIG. 27 - Effect of Welding Current on the Tensile-Shear Strength of 16 Gauge SAE CR 1010 Steel.

of variables, the heat generated would be equivalent for each case.

It was also found from the experimental results that a weld made by the same level of heat setting for different gauges shows that the actual secondary current flow for thin gauge was higher than that for thick gauge. As a possible explanation of this behavior one can reason that, since the electrode force applied was held constant throughout the entire investigation, unit electrode force applied was larger for the thin sheet. Thus, contact resistance was reduced and more current was allowed to "pass". Conversely, as applied unit pressure is relatively reduced for thicker sheet, contact resistance is increased and retards current flow. Therefore, a higher tensile-shear strength of weld joints can be expected in welding the thick sheet metal if the heat generated is increased to a sufficient amount to get the same proportional "nugget" penetration depth into the thicker sheet.

It is evident from the experimental tensile-shear strength results given in Table 10 and Table 11 of Appendix III that the weld strengths for 18 gauge steel were higher than those for 16 gauge steel for all equivalent combinations of variables. That is, a 100% heat, 25 cycles of time combination resulted in higher strength for 18 gauge than 16 gauge. Also, a 60% heat, 20 cycles of time combination resulted in higher strength for 18 gauge steel than 16 gauge steel, etc., for all combinations. Not knowing K-heat losses, the following statement cannot be verified quantitatively but qualitatively reasoned.

This is due to the fact that the heat generated by this given machine setting was insufficient to make a proportionally increased nugget penetration into the 16 gauge sheet.

II. The Determination of Parameters (welding current and weld time) and the Explanation

From the Section C , Explanation of Processing Data, in Chapter V, the mathematical model for predicting the tensile-shear value for different values of weld time, when given a current setting and a gauge of metal, was:

$$Y = A + B_1X + B_2X^2$$

The results of the computer program to estimate A, B_1, B_2 for each situation were as follows:

28 Gauge SAE CR 1010 Steel

100% heat: $Y = 286.39577 + 5.3957\ X - .12985\ X^2$*

80% heat: $Y = 230.0378 + 7.22835\ X - .1568\ X^2$*

60% heat: $Y = 69.4285 + 12.75338\ X - .26045\ X^2$

24 Gauge SAE CR 1010 Steel

100% heat: $Y = 424.67543 + 18.40097\ X - .4004\ X^2$

80% heat: $Y = 340.0378 + 19.00278\ X - .4293\ X^2$

60% heat: $Y = 47.10125 + 33.29748\ X - .68055\ X^2$

20 Gauge SAE CR 1010 Steel

100% heat: $Y = 66.72741 + 79.56276\ X - 1.67086\ X^2$

80% heat: $Y = -4.0228 + 76.35968\ X - 1.57812\ X^2$

60% heat: $Y = -221.4991 + 55.59468\ X - 1.0104\ X^2$

18 Gauge SAE CR 1010 Steel

100% heat: $Y = {}^{-}297.54192 + 115.29955 X - 2.0483 X^2$

80% heat: $Y = {}^{-}189.16684 + 71.3752 X - .73654 X^2$

60% heat: $Y = {}^{-}285.16432 + 50.110704 X - .83636 X^2$

55% heat: $Y = {}^{-}2175.6476 + 174.27622 X - 3.07079 X^2$

16 Gauge SAE CR 1010 Steel

100% heat: $Y = {}^{-}149.82652 + 69.33752 X - 1.3334 X^2$

80% heat: $Y = {}^{-}654.74392 + 109.66752 X - 1.98031 X^2$

60% heat: $Y = {}^{-}217.22297 + 25.37563 X - .11528 X^2$

Note: * quadratic term is non-significant.

From these equations, an ANOVA (Analysis of Variance) and t-test's of hypothesis were made to determine if the quadratic term was significant for a particular case. A sample calculation of an ANOVA and a t-test for a particular heat setting and sheet thickness is shown in Table6a of Appendix II. The enumeration of these tests are in Tables 2-6 of Appendix II.

The statistical analysis of the problem was necessary in order to determine the maximum tensile-shear strength and corresponding maximum weld time of all gauges and all levels of heat settings. The minimum weld strength, weld time, and welding current were determined by the welding conditions that just barely produced a weld of measurable strength.

The examination of the 100% and the 80% heat control settings for 28 gauge reveals that an increase of weld time does not improve the tensile-shear strengths of weld joints (See Fig. 18.) It was also found from the t-tests given in Table 2 of Appendix II for these two heat settings that the quadratic term of the prediction models is non-significant. Hence, the maximum weld strength and corresponding maximum weld cycles could not be obtained, for these cases. This may be explained by the following reasoning. There was sufficient heat to get a complete penetration of weld nugget to the full thickness of the sheet over the full range of weld times tested. Therefore, the curve is almost flat.

For all gauges and all levels of heat settings except the 100% and the 80% of 28 gauge steel, the t-tests show that tensile-shear strength is a quadratic function of weld time. Thus, the maxima values of the welding machine parameter, weld time, can be obtained by the method of differentiating the prediction models with respect to the independent variable X, and then equating the expression to zero. For the example of 100% heat setting and 24 gauge steel, the prediction model is

$$Y = 424.67543 + 18.40097\ X - .4004\ X^2 \quad (2)$$

then, $\frac{dY}{dX} = 18.40097 - .8008\ X$

let $\frac{dY}{dX} = 0$, and $18.40097 - .8008\ X = 0$

$$X = 23$$

Substituting into equation (2) for X gives Y = 636.093 lbs.

Therefore, the maximum value of the weld strength is 636.093 lbs. and the corresponding maximum weld cycles are 23.

The maxima and minima values, within limits, of the welding parameter, welding current, were determined from the experimental results by visual inspection.

Tables 2-6 show the maxima and minimum values, within limits, of the welding machine parameters: current and time, for 28 gauge, 24 gauge, 20 gauge, 18 gauge, and 16 gauge.

Table 2

28 Gauge
Maximum Vs. Minimum Tensile-Shear Values

Electrode force: 21.8 psi ± 5%
Electrode Tip Diameter: .187" ± .002"

Heat %	Computed Maximum Weld Time Cycles	Computed Tensile-Shear Lbs.	Actual Tensile-Shear Lbs.	Actual Maximum Welding Current Amp.	Actual Minimum Weld Time Cycles	Actual Tensile-Shear Lbs.	Actual Minimum Welding Current Amp.
100	No Reasonable Value				5	286	5096
						350	5096
						274	5000
80	No Reasonable Value				5	254	4962
						244	4962
						290	5059
60	25	225.4817	220	4962	4	112	4790
			220	4962		122	4809
			210	4962		64	4771

Table 3

24 Gauge
Maximum Vs. Minimum Tensile-Shear Values
Electrode force: 21.8 psi ± 5%
Electrode Tip Diameter: .187" ± .002"

Heat %	Computed Maximum Weld Time Cycles	Computed Tensile-Shear Lbs.	Actual Tensile-Shear Lbs.	Actual Maximum Welding Current Amp.	Actual Minimum Weld Time Cycles	Actual Tensile-Shear Lbs.	Actual Minimum Welding Current Amp.
100	23	636.093	630	5248	3	340	4809
			622	5248		330	4789
			622	5248		334	4789
80	23	550.9557	532	5000	3	204	4752
			556	5020		298	4771
			548	5020		No Weld	4731
60	25	300.07075			5	No Weld	4565
			332	4771		70	4674
			338	4771		148	4639
			342	4790		No Weld	4618
						80	4674

Table 4

20 Gauge
Maximum Vs. Minimum Tensile-Shear Values
Electrode force: 21.8 psi ± 5%
Electrode Tip Diameter: .187" ± .002"

Heat %	Computed Maximum Weld Time Cycles	Computed Tensile-Shear Lbs.	Actual Tensile-Shear Lbs.	Actual Maximum Welding Current Amp.	Actual Minimum Weld Time Cycles	Actual Tensile-Shear Lbs.	Actual Minimum Welding Current Amp.
100	24	1013.8183		4186	3	150	3893
						214	3885
						320	3894
						222	3894
						166	3855
80	25	918.645			4	268	3893
			904	4123		140	3893
			920	4160		No Weld	3893
			888	4084		198	3893
						150	3893
60	28	542.998	586	3969	8	78	3779
			560	3950		No Weld	3721
			570	3950		118	3740
55	30		434	3683	28	400	3702
			412	3702		340	3702
			466	3721		256	3683

Table 5

18 Gauge
Maximum Vs. Minimum Tensile-Shear Values
Electrode force: 21.8 psi ± 5%
Electrode Tip Diameter: .187" ± .002"

Heat %	Computed Maximum Weld Time Cycles	Computed Tensile-Shear Lbs.	Actual Tensile-Shear Lbs.	Actual Maximum Welding Current Amp.	Actual Minimum Weld Time Cycles	Actual Tensile-Shear Lbs.	Actual Minimum Welding Current Amp.
100	28	1324.865	1230	4008	4	98	3969
			1300	3989		108	3989
			1300	3989		88	3969
						56	3969
						112	3989
80	30	1289.2			5	270	3931
			1240	3989		182	3931
			1220	3969		150	3969
			1280	3989		156	3931
						284	3950
60	30	465.6229			11	No Weld	3779
			440	3836		88	3789
			450	3817		94	3760
			460	3798		126	3760
						182	3760
55	29	296.8263	---	----	22	184	3626
						210	3607
						148	3664
						118	3626
						210	3568

Table 6

16 Gauge
Maximum Vs. Minimum Tensile-Shear Values
Electrode force: 21.8 psi ± 5%
Electrode Tip Diameter: .187" ± .002"

Heat %	Computed Maximum Weld Time Cycles	Computed Tensile-Shear Lbs.	Actual Tensile-Shear Lbs.	Actual Maximum Welding Current Amp.	Actual Minimum Weld Time Cycles	Actual Tensile-Shear Lbs.	Actual Minimum Welding Current Amp.
100	30	1103.51			6	200	3912
			1070	4046		280	3931
			1030	4084		330	3893
			1066	4084		268	3869
						134	3989
80	28	863.23			8	306	3855
			896	3931		280	3874
			834	3912		322	3855
			865	3912		284	3893
						220	3893
60	30	338.294			15	120	3626
			308	3817		104	3664
			292	3874		No Weld	3664
			308	3874		184	3702
						No Weld	3626

CONCLUSIONS

The results of this thesis investigation indicated that the following conclusions can be drawn. All these conclusions are of course based on the experimental equipment used in this investigation and the results obtained.

1. Generally speaking, the tensile-shear strength of a weld increases with an increase in weld time for all sheet thicknesses and all levels of heat settings except the 100% and the 80% heat settings for the 28 gauge sheet.

2. Generally speaking, the tensile-shear strength of a weld increases with an increase in welding current for all sheet thicknesses and all levels of weld time.

3. At constant electrode force, the maximum tensile-shear strengths occur at the maximum current setting of 100% in all cases. The maximum corresponding weld cycle time is that time below which no metal expulsion at the interface occurs, and above which metal expulsion occurs.

4. Assuming constant electrode force, a certain combination of variables can produce a weld having a particular tensile-shear value. A different combination of variables can produce a weld having an equal tensile-shear value. For example, a weld made by a 100% heat setting and 18 cycles of weld time for 20 gauge sheet produced 907 lbs. tensile-shear strength. A weld made by a 80% heat setting and 25

cycles of weld time for 20 gauge sheet produced 904 lbs. tensile-shear strength.

5. The maximum tensile-shear strength for all conditions investigated was for 18 gauge steel with a 100% heat setting and 28 cycles of weld time.

6. The maxima and minima values, within limits of experimental error, for the welding parameters were:

28 Gauge SAE CR 1010 Steel

a. For the heat control settings of 100% and 80%, it was concluded that no reasonable maximum values could be found. This is because the curve approached flatness. For the heat setting of 60%, it was found that the maximum values of weld time were 25 cycles, and the 60% heat setting produced a 4962 amperes secondary current.

b. The minimum values of welding parameters were: (1) 100% heat setting: 5 cycles, 5084 amperes; (2) 80% heat setting: 5 cycles, 4994 amperes; (3) 60% heat setting: 4 cycles, 4790 amperes.

24 Gauge SAE CR 1010 Steel

a. The maxima values of welding parameters were: (1) 100% heat setting: 23 cycles, 5248 amperes; (2) 80% heat setting: 23 cycles, 5023 amperes; (3) 60% heat setting: 25 cycles, 4777 amperes.

b. The minima values of welding parameters were: (1) 100% heat setting: 3 cycles, 4796 amperes; (2) 80% heat setting: 3 cycles, 4751 amperes; (3) 60% heat setting: 5 cycles, 4637 amperes.

20 Gauge SAE CR 1010 Steel

a. The maxima values of welding parameters were: (1) 100% heat setting: 24 cycles, 4186 amperes; (2) 80% heat setting: 25 cycles, 4123 amperes; (3) 60% heat setting: 28 cycles, 3958 amperes; (4) 55% heat setting: 30 cycles, 3702 amperes.

b. The minima values of welding parameters were: (1) 100% heat setting: 3 cycles, 3884 amperes; (2) 80% heat setting: 4 cycles, 3893 amperes; (3) 60% heat setting: 8 cycles, 3747 amperes; (4) 55% heat setting: 28 cycles, 3696 amperes.

18 Gauge SAE CR 1010 Steel

a. The maxima values of welding parameters were: (1) 100% heat: 28 cycles, 3995 amperes; (2) 80% heat: 30 cycles, 3982 amperes; (3) 60% heat: 30 cycles, 3817 amperes; (4) 55% heat: 29 cycles, 4683 amperes.

b. The minima values of welding parameters are: (1) 100% heat: 4 cycles, 3969 amperes; (2) 80% heat: 5 cycles, 3941 amperes; (3) 60% heat: 11 cycles, 3770 amperes; (4) 55% heat: 22 cycles, 3618 amperes.

16 Gauge SAE CR 1010 Steel

a. The maxima values of welding parameters were: (1) 100% heat: 30 cycles, 4059 amperes; (2) 80% heat: 28 cycles, 3918 amperes; (3) 60% heat: 30 cycles, 3836 amperes.

b. The minima values of welding parameters were: (1) 100% heat: 6 cycles, 3919 amperes; (2) 80% heat: 8 cycles, 3874 amperes; (3) 60% heat: 15 cycles, 3656 amperes.

LITERATURE CITED

1. A. L. Philps, "Spot, Seam and Projection Welding", Welding Handbook, Section Two. American Welding Society, N. Y. 1958. Chapter 30.
2. E. J. Del Vecchio, Resistance Welding Manual. Resistance Welder Manufacturers' Association, 1956. pp. 1-27.
3. E. R. Funk, H. Udin, J. Wulff, Welding for Engineers. New York: John Wiley and Sons, Inc., 1954. pp. 56-60.
4. W. A. Stanley, Resistance Welding. McGraw Hill Co., Inc., 1950. pp. 17-22.
5. American Welding Society, Resistance Theory and Use. New York: Reinhold Publishing Co., 1956. pp. 16-19.
6. A. M. Unger, "Structural Spot Welding-Consistency Control Methods", Welding Journal, Vol. 20, 1941. pp. 687-693.
7. W. F. Hess and R. L. Ringer, "Studies of the Spot Welding of Low Carbon and Stainless Steel", Welding Journal, Vol. 17, 1938. pp. 39s-48s.
8. E. R. Funk, H. Udin, and J. Wulff, Welding for Engineers. New York: John Wiley and Sons, Inc., 1954. pp. 76-79.
9. E. R. Funk, H. Udin, and J. Wulff, Welding for Engineers. New York: John Wiley and Sons, Inc., 1954. pp. 74-76.
10. W. A. Stanley, Resistance Welding. McGraw Hill Co., Inc., 1950. pp. 17-22.

11. I. W. Johnson, "Spot Welding of Carbon Steel", Welding Journal Vol. 39, March, 1950. pp. 89s-96s.

12. W. R. FitzGerald, "Design of An Experiment to Investigate the Effects of Electrode Bearing Area, Weld-Pressure, and Current on the Penetration and Tensile-shear Strength of Resistance Spot Welding in SAE CR 1010 Steel", M. S. Thesis, VPI, 1964.

13. E. R. Funk, H. Udin, and J. Wulff, Welding for Engineers. New York: John Wiley and Sons, Inc., 1954. pp. 44-50.

14. L. D. Jennings, "Resistance Welding", Iron Age Welding Manual, 1947. pp. 81-86.

15. R. F. Tylecote, "Spot Welding", Part 3, Welding Journal, Vol. 20, 1941. pp. 591s-602s.

16. D. K. Crampton and J. J. Vreeland, "Spot Welding Characteristics of Some Copper-Base Alloys", Welding Journal, Vol. 16, October 1937. pp. 9s-18s.

17. E. J. Del Vecchio, Resistance Welding Manual. Resistance Welder Manufacturers' Association, Pa., 1956. pp. 28-41.

18. H. S. Jeff, "Practice Side of Electric Resistance Welding", Sheet Metal Industry, Vol. 9, 1935. pp. 231-233.

19. W. F. Hess and R. A. Wyant, "Further Studies of Spot Welding of Low Carbon and Stainless Steels", Welding Journal, Vol. 18, October 1939. pp. 348s-354s.

20. J. G. Beach, "Coating", Nonferrous Metals Book. The Penton Publishing Co., Cleveland, Ohio, September 1963. pp. 85-90.

21. E. J. Del Vecchio, Resistance Welding Manual. Resistance Welder Manufacturers' Association, 1956. pp. 181-186.

22. E. R. Funk, H. Udin, J. Wulff, Welding for Engineers. New York: John Wiley and Sons, Inc., 1954. pp. 105-111.

23. J. Dearden, "Influence of Welding Defects on Resistance to Fatigue of Welded Steel Joint", Transaction of Welding, Vol. 6, n3-4, 1943. pp. 120-122.

24. H. G. Taylor, "Recommended Practice for the Spot Welding of Low Carbon Mild Steel", Vol. 11, 1948. pp. 83r-86r.

25. W. Blumenstein, "How to Get Good Spot Welds Consistently", Welding Design & Fabrication, June 1962. pp. 58-80.

26. S. R. Badlaney, "An Investigation of Resistance Spot Welding Characteristics of Different Thicknesses of SAE CR 1010 Steel", M. S. Thesis, VPI, 1963.

27. W. L. Roberts, "Resistance Variation During Spot Welding", Welding Journal, Vol. 30, 1951. pp. 1004-1019.

28. J. Wulff, H. F. Taylor, and A. J. Shaler, Metallurgy for Engineerings. New York. John Wiley and Sons, Inc., 1952.

BIBLIOGRAPHY

1. American Welding Society, Resistance Welding Theory and Use. New York: Reinhold Publishing Corporation, 1956.
2. Badlaney, S. R., "An Investigation of Resistance Spot Welding Characteristics of Different Thicknesses of SAE CR 1010 Steel", M. S. Thesis, VPI, 1963.
3. Bowman, R. E., "Method of Testing Spot Welds", Welding Journal, Vol. 20, October 1941. pp. 478s-482s.
4. Butler, J. B., "Resistance Welding and Statistical Quality Control", Welding Journal, Vol. 24, 1945. pp. 909-914.
5. Clark, E. W., "Resistance Welding Current Measurement", Welding Journal, Vol. 19(3). 1940. pp. 215-218.
6. Dearden, J. and O'Neil, H., "Spot Welds in Mild Steel Plate 1/8 - 3/8 in. Thickness", Welding Journal, Vol. 23, 1944. pp. 58s-59s.
7. Dixon, H. E. and Roberts, J. E., "Statistical Method for Resistance Welding Investigation", British Welding Journal, Vol. 1, 1954.
8. Dixon, W. J., and F. J. Massey, Introduction to Statistical Analysis. New York: McGraw-Hill Book Company, 1957.
9. Doge, C. W., "Spot Welding of Heavy Aluminum Alloys", Welding Journal, Vol. 24, 1954.
10. Fisher, R. A., The Design of Experiments. Edinburg, Oliver and Boyd, 1947.
11. Fitzgerald, W. R., "Design of an Experiment to Investigate the Effects of Electrode Bearing Area, Weld-Pressure, and Current on

the Penetration and Tensile-Shear Strength of Resistance Spot Welding in SAE CR 1010 Steel", M. S. Thesis, VPI, 1964.

12. Hasle, F. C., "Welding Parameters", British Welding Journal, Vol. 5, 1958. pp. 18-20.

13. Hess, W. F. and Hereschaff, D. C., "Spot Welding of SAE CR 1020, 1035, and 1045 Steels in the 0.04 in. Thickness", Welding Journal, Vol. 22, 1943.

14. Hess, W. F., Doty, W. D., and Childs, W. J., "The Fundamentals of Spot Welding Steel Plate", Welding Journal, Vol. 26, 1947. pp. 583s-593s.

15. Johnson, I. W., "Spot Welding of Carbon Steel", Welding Journal, Vol. 39, 1950. pp. 89s-96s.

16. Kouwenhoven, W. B., and Little, H. L., "Contact Resistance", Welding Journal, Vol. 31, 1952. pp. 486s-471s.

17. Meadowcroft, J. W., "Resistance Welding Progress", Welding Journal, Vol. 24, 1945. pp. 538-539.

18. Nippes, E. F., Savage, W. F., and Robelotto, S. M., "Measurement of Shunting Currents in Series Spot Welding", Welding Journal, Vol. 34, 1955. pp. 618s-624s.

19. Radford, J. F., and Waldvogel, R. K., "Quality Control of Resistance Welding by Statistical Methods", Welding Journal, Vol. 32, June 1953. pp. 521-526.

20. Richmond, S. B., Principles of Statistical Analysis. New York: The Ronald Press Co., 1957.

21. Robinson, H., "Determination by Statistical Analysis of Process Minimum", Welding Journal, Vol. 24, 1945. pp. 455-461.

22. Roberts, J. E., "Spot Welding of Mild Steel", British Welding Journal, Vol. 1, 1954. pp. 136-140.

23. Roberts, J. E., "Resistance Welding of Coated Steel", British Welding Journal, Vol. 1, 1954. pp. 233-237.

24. Roberts, W. L., "Resistance Variation During Spot Welding", Welding Journal, Vol. 30, 1951. pp. 1004-1019.

25. Sanborn Company "Sanborn Carrier Pre-Amplifier", Instruction Manual, Massachusetts.

26. Spencer, L. F., "Resistance Welding Procedure and Design", Welding Engineering, Vol. 43, 1958. pp. 44-47.

27. Thomson Electric Welder Company, "Operator's Instruction and Maintenance Manual", Massachusetts.

28. Tylecote, R. F., "Spot Welding", Part I and Part II, Welding Journal, Vol. 20, 1941. pp. 359s-368s.

29. Vecchio, E. J. Del, Resistance Welding Manual, Third Edition, Vol. 1, Resistance Welder Manufacturers' Association, 1956.

30. Westinghouse Electric Corporation, "Heat Control", Manual No. 5670-87, Pa.

31. Wood, L. P., "A Survey of Aircraft Resistance Welding Equipment", Welding Journal, Vol. 20, 1941. pp. 775-780.

32. Woodward, F. R., "Resistance Welding Fundamentals", Welding Journal, Vol. 24, August 1945. pp. 713-726.

APPENDIX I

Randomization Scheme for a Given % Heat

TABLE 1

RANDOMIZATION SCHEME

Specimen Welding					
Serial No.	Weld Cycles	Random Order No.	Serial No.	Weld Cycles	Random Order No.
1	30	20	19	15	10
2	30	16	20	15	33
3	30	5	21	15	1
4	28	25	22	13	35
5	28	32	23	13	4
6	28	8	24	13	14
7	25	27	25	10	22
8	25	19	26	10	7
9	25	2	27	10	12
10	23	23	28	8	28
11	23	34	29	8	15
12	23	9	30	8	29
13	20	26	31	5	21
14	20	36	32	5	18
15	20	13	33	5	31
16	18	17	34	4	24
17	18	6	35	4	3
18	18	30	36	4	11

APPENDIX II

Analysis of Variance (ANOVAR)

1. Table for 28 Gauge
2. Table for 24 Gauge
3. Table for 20 Gauge
4. Table for 18 Gauge
5. Table for 16 Gauge
6. Sample Calculations

TABLE 2

ANALYSIS OF VARIANCE FOR 28 GAUGE

% Heat	Source	SS	d. f.	MS	t-test
100	Regression Error Total	-528.7428 21352.7428	2 30 32	-264.3714 711.758	$t_o = \frac{B_2}{\sqrt{MSEC_{22}}}$ $= 1.5476$ $-2.04 < t_o < 2.04$
80	Regression Error Total	2581.682 273003.118 375584.8	2 30 32	1290.841 12433.437	$t_o = \frac{B_2}{\sqrt{MSEC_{22}}}$ $= .446851$ $-2.04 < t_o < 2.04$
60	Regression Error Total	50553.53 14261.69 64815.22	2 33 35	25276.765 432.1724	$t_o = \frac{B_2}{\sqrt{MSEC_{22}}}$ $= 6.11385^* > 2.03$

* Reject H_o

TABLE 3

ANALYSIS OF VARIANCE FOR 24 GAUGE

% Heat	Source	SS	d. f.	MS	t-test
100	Regression	85934.7897	2	42967.3998	$t_o = \frac{B_2}{\sqrt{MSEC_{22}}}$ $= 4.82^* > 2.03$
	Error	22989.2103	33	696.6427	
	Total	108924	35		
80	Regression	31134.79532	2	15567.3966	$t_o = \frac{B_2}{\sqrt{MSEC_{22}}}$ $= 17.5296^* > 2.04$
	Error	42857.835	30	1428.5945	
	Total	73992.63	32		
60	Regression	117606.09	2	58803.045	$t_o = \frac{B_2}{\sqrt{MSEC_{22}}}$ $= 17.10354^* > 2.04$
	Error	113193.46	30	3773.115	
	Total	230799.55	32		

* Reject H_o

TABLE 4

ANALYSIS OF VARIANCE FOR 20 GAUGE

% Heat	Source	SS	d. f.	MS	t-test
100	Regression	2542778.89	2	1271389.44	$t_o = \frac{B_2}{\sqrt{MSEC_{22}}}$ $= 9.046^* > 2.03$
	Error	137746.1	36	3826.28	
	Total	2680525	38		
80	Regression	1788372.203	2	894186.101	$t_o = \frac{B_2}{\sqrt{MSEC_{22}}}$ $= 24.735^* > 2.04$
	Error	151405.797	30	504.6859	
	Total	1939778	32		
60	Regression	240135.47352	2	120067.7316	$t_o = \frac{B_2}{\sqrt{MSEC_{22}}}$ $= 4.144^* > 2.08$
	Error	44783.52648	21	2132.5488	
	Total	284919	23		

* Reject H_o

TABLE 5

ANALYSIS OF VARIANCE FOR 18 GAUGE

% Heat	Source	SS	d. f.	MS	t-test
100	Regression	6189908.65	2	3094954.325	$t_o = \frac{B_2}{\sqrt{MSEC_{22}}}$
	Error	29556628.35	33	895655.4	
	Total	35746537	35		$= 3.3425^* > 2.03$
80	Regression	3835877.0156	2	1917938.508	$t_o = \frac{B_2}{\sqrt{MSEC_{22}}}$
	Error	24798264.28	30	826608.8	
	Total	28646621.9	32		$= 7.0977^* > 2.04$
60	Regression	328136.433	2	164068.216	$t_o = \frac{B_2}{\sqrt{MSEC_{22}}}$
	Error	231697.967	15	15446.53	
	Total	2560834.4	17		$= 2.447^* > 2.13$

* Reject H_o

TABLE 6

ANALYSIS OF VARIANCE FOR 16 GAUGE

% Heat	Source	SS	d. f.	MS	t-test
100	Regression	1228385.0763	2	614192.5381	$t_o = \frac{B_2}{\sqrt{MSEC_{22}}}$
	Error	142174.734	18	7898.5963	
	Total	1371559.81	20		$= 6.6376^* > 2.10$
80	Regression	483506.7534	2	241753.3767	
	Error	6890.2466	16	418.14	$t_o = 8.49^* > 2.12$
	Total	490397	18		
60	Regression	51326.9647	2	25663.4823	$t_o = \frac{B_2}{\sqrt{MSEC_{22}}}$
	Error	10319.9693	12	859.997	
	Total	61646.934	14		$= 2.3867^* > 2.18$

* Reject H_o

Sample Calculation of Sums of Squares for the Analysis of Variance

Table 2 (100% Heat)

Definition of Terms

S_{yy} = Total sum of squares.

S_{11} = Sum of squares of independent variable X.

S_{22} = Sum of squares of independent variable X^2.

$S_{12} = S_{21}$ = Sum of cross product of independent variables X and X^2.

S_{1y} = Sum of cross product of independent variable X and dependent variable Y.

S_{2y} = Sum of cross product of independent variable X^2 and dependent variable Y.

N = Total number of observations.

Y = Observation under investigation. (Tensile-shear strength)

X = Independent variable. (Weld time)

B_1 = The coefficient of linear term of prediction model.

B_2 = The coefficient of quadratic term of prediction model.

SSR = Sum of squares of the regression.

SSE = Sum of squares due to error.

C_{22} = The ith diagonal element of inverse matrix S.

Sample Calculations - 100% Heat, 28 Gauge Sheet Metal

$$S_{yy} = \Sigma Y^2 - \frac{(\Sigma Y)^2}{N} = 3682825 - 3662001$$

$$= 20824$$

$$S_{11} = \Sigma X^2 - \frac{(\Sigma X)^2}{N} = 12435 - \frac{342225}{33}$$

$$= 2064.546$$

$$S_{22} = \Sigma X^4 - \frac{(\Sigma X^2)^2}{N} = 7362015 - \frac{154629225}{33}$$

$$= 2676280.01$$

$$S_{12} = S_{21} = \Sigma X^3 - \frac{(\Sigma X)(\Sigma X^2)}{N} = 293205 - \frac{(585)(12435)}{33}$$

$$= 72766.3$$

$$S_{1y} = \Sigma XY - \frac{(\Sigma X)(\Sigma Y)}{N} = 196548 - \frac{(585)(10993)}{33}$$

$$= 1672.1$$

$$S_{2y} = \Sigma X^2 Y - \frac{(\Sigma X^2)(\Sigma Y)}{N} = 4188304 - \frac{(12435)(10993)}{33}$$

$$= 74067.8$$

$$B_1 = 5.39579$$

$$B_2 = -0.12985$$

$$SSR = B_1 S_{1y} + B_2 S_{2y}$$

$$= (5.39579)(1672.1) + (-0.12985)(74067.8)$$

$$= 9022.300 - 9551.04281 = -528.7428$$

$$SSE = S_{yy} - SSR = 2084 - (-528.7428)$$

$$= 21352.7428$$

$$MSR = \frac{SSR}{2} = -264.3714$$

$$MSE = \frac{SSE}{N-3} = \frac{21352.7428}{30} = 711.758$$

$$S = \begin{pmatrix} S_{11} & S_{21} \\ S_{12} & S_{22} \end{pmatrix} = \begin{pmatrix} 2064.546 & 72766.37 \\ 72766.37 & 2676280.01 \end{pmatrix}$$

$$|D| = S_{11}\,S_{22} - S_{12}\,S_{21} = 208510284$$

$$C_{22} = \frac{S_{11}}{|D|} = 9.9014 \times 10^{-6}$$

$$t_o = \frac{B_2}{\sqrt{MSEC_{22}}} = \frac{-0.12985}{\sqrt{(711.758)(9.9014 \times 10^{-6})}}$$

$$= \frac{129.85}{83.9} = 1.5476$$

APPENDIX III

Experimental Data According to Replication of % Heat and Weld Time Setting for Different Metal Thicknesses.

TABLE 7a. TENSILE-SHEAR TEST DATA

SHEET: 28 GAUGE

% Heat	Weld Time Cycles	Welding Press. Sanborn psi	Welding Voltage Volts (Maximum)	Secondary Current AMP (Maximum)	Primary Current AMP (Maximum)	Tensile Shear Strength Lbs.
100	30	21.8	2.4	5325	73.08	320
	30	21.8	2.5	5325	73.08	360
	30	21.8	2.4	5344	74.66	310
100	28	20.8	2.4	5344	73.08	345
	28	21.8	2.4	5325	73.08	356
	28	21.8	2.4	5325	73.08	342
100	25	21.8	2.4	5325	73.08	354
	25	21.8	2.4	5325	73.08	336
	25	21.8	2.5	5344	73.08	334
100	23	21.8	2.4	5325	73.88	326
	23	21.8	2.4	5325	73.08	350
	23	21.8	2.4	5325	73.08	300
100	20	20.8	2.4	5325	73.08	358
	20	21.8	2.4	5325	73.08	300
	20	21.8	2.4	5305	70.72	340
100	18	21.8	2.4	5325	71.52	336
	18	21.8	2.5	5305	71.52	360
	18	21.8	2.4	5325	71.52	332
100	15	21.8	2.4	5268	71.52	354
	15	21.8	2.4	5286	71.52	354
	15	21.8	2.4	5286	71.52	358
100	13	21.8	2.4	5268	71.52	310
	13	21.8	2.4	5268	69.16	300
	13	20.8	2.4	5210	68.36	350
100	10	20.8	2.4	5191	68.36	362
	10	21.8	2.4	5153	64.44	348
	10	21.8	2.4	5153	62.87	354

TABLE 7b. TENSILE-SHEAR TEST DATA

28 GAUGE (Continued)

% Heat	Weld Time Cycles	Welding Press. Sanborn psi	Welding Voltage Volts (Maximum)	Secondary Current AMP (Maximum)	Primary Current AMP (Maximum)	Tensile Shear Strength Lbs.
80	15	21.8	2.3	5286	69.94	292
	15	20.8	2.3	5248	69.16	320
	15	20.8	2.3	5286	69.94	324
80	13	21.8	2.2	5229	68.36	304
	13	20.8	2.3	5268	68.36	306
	13	21.8	2.2	5229	68.36	290
80	10	21.8	2.2	5229	68.36	288
	10	21.8	2.3	5172	66.0	306
	10	21.8	2.2	5210	66.8	296
80	8	21.8	2.2	5172	66.8	286
	8	21.8	2.2	5096	65.21	250
	8	21.8	2.2	5096	63.66	264
80	5	21.8	2.3	4962	61.08	254
	5	21.8	2.2	5059	64.44	290
	5	20.8	2.3	4962	61.08	244
80	4	21.8	2.2	4962	60.5	246
	4	20.8	2.2	4924		No Weld
	4	20.8	2.2	4924	60.5	212
60	30	21.8	1.8	5039	62.86	252
	30	20.8	1.7	4981	62.86	216
	30	20.8	1.8	5000	62.86	234
60	28	21.8	1.8	4981	62.08	220
	28	21.8	1.8	4962	62.08	190
	28	21.8	1.8	5000	62.08	240
60	25	21.8	1.7	4962	62.08	220
	25	21.8	1.7	4962	62.08	220
	25	20.0	1.7	4962	62.08	210

TABLE 7c. TENSILE-SHEAR TEST DATA

28 GAUGE (Continued)

% Heat	Weld Time Cycles	Welding Press. Sanborn psi	Welding Voltage Volts (Maximum)	Secondary Current AMP (Maximum)	Primary Current AMP (Maximum)	Tensile Shear Strength Lbs.
100	8	20.8	2.4	5153	64.44	278
	8	21.8	2.4	4924	59.72	316
	8	21.8	2.4	5039	62.08	340
100	5	21.8	2.4	5096	62.86	286
	5	21.8	2.5	5096	62.86	350
	5	21.8	2.4	5000	61.3	274
100	4	21.8	1.5			No Weld
	4	21.8	1.5			No Weld
	4	21.8	1.5			No Weld
80	30	21.0	2.3	5286	71.52	314
	30	21.0	2.3	5286	71.52	282
	30	21.8	2.3	5286	71.52	310
80	28	21.8	2.3	5286	71.52	332
	28	21.8	2.3	5305	72.3	314
	28	21.8	2.2	5286	71.52	308
80	25	21.0	2.2	5286	70.72	324
	25	20.8	2.2	5286	70.72	304
	25	21.8	2.2	5286	70.72	318
80	23	21.8	2.3	5286	70.72	304
	23	21.8	2.3	5305	70.72	322
	23	21.8	2.3	5286	71.52	298
80	20	21.8	2.2	5286	69.94	284
	20	21.8	2.2	5286	70.72	310
	20	21.8	2.2	5286	70.72	314
80	18	20.8	2.2	5286	70.72	318
	18	21.8	2.2	5286	70.72	300
	18	21.8	2.2	5286	70.72	300

TABLE 7d. TENSILE-SHEAR TEST DATA

28 GAUGE (Continued)

% Heat	Weld Time Cycles	Welding Press. Sanborn psi	Welding Voltage Volts (Maximum)	Secondary Current AMP (Maximum)	Primary Current AMP (Maximum)	Tensile Shear Strength Lbs.
60	23	20.8	1.7	4962	62.08	232
	23	20.8	1.7	4962	62.08	226
	23	20.8	1.7	4962	62.08	196
60	20	21.8	1.8	4962	61.28	219
	20	21.8	1.8	4943	60.5	230
	20	20.8	1.8	4943	61.28	194
60	18	20.8	1.8	4962	62.08	180
	18	20.8	1.8	4962	61.28	206
	18	20.8	1.8	4962	61.28	226
60	15	21.8	1.8	4885	59.92	203
	15	21.8	1.8	4962	61.28	230
	15	21.8	1.8	4962	61.28	196
60	13	20.8	1.7	4924	59.92	204
	13	20.8	1.7	4943	60.50	178
	13	20.8	1.7	4924	60.50	216
60	10	20.8	1.7	4866	58.94	166
	10	20.8	1.8	4924	59.92	192
	10	20.8	1.7	4924	60.50	200
60	8	20.8	1.7	4847	57.36	188
	8	20.8	1.7	4847	57.36	120
	8	20.8	1.7	4847	57.36	174
60	5	20.8	1.7	4809	55.0	120
	5	20.8	1.7	4847	56.58	118
	5	21.8	1.7	4811	56.58	148
60	4	21.8	1.7	4790	56.58	112
	4	21.8	1.7	4809	56.58	122
	4	21.8	1.7	4771	56.58	64

TABLE 8a. TENSILE-SHEAR TEST DATA

SHEET: 24 GAUGE

% Heat	Weld Time Cycles	Welding Press. Sanborn psi	Welding Voltage Volts (Maximum)	Secondary Current AMP (Maximum)	Primary Current AMP (Maximum)	Tensile Shear Strength Lbs.
100	30	20.83	1.5	5286	70.72	624
	30	20.83	1.5	5286	70.72	626
	30	20.83	1.5	5286	70.72	616
100	28	20.83	1.4	5286	69.16	630
	28	21.8	1.5	5248	70.72	646
	28	20.83	1.5	5248	69.16	634
100	25	20.83	1.3	5248	69.16	662
	25	20.83	1.5	5268	70.72	632
	25	20.83	1.5	5268	69.16	620
100	23	20.83	1.5	5248	69.16	620
	23	20.83	1.5	5248	69.16	622
	23	20.83	1.5	5248	69.16	616
100	20	21.83	1.5	5248	68.36	630
	20	21.83	1.5	5248	66.0	622
	20	21.83	1.5	5248	66.0	622
100	18	22.8	1.5	5172	65.22	592
	18	20.83	1.5	5229	66.0	606
	18	20.83	1.5	5248	66.0	614
100	15	20.83	1.6	5248	66.8	612
	15	21.8	1.5	5172	64.44	610
	15	22.8	1.5	5153	64.44	612
100	13	21.8	1.5	5172	64.44	602
	13	22.8	1.5	5153	62.86	590
	13	20.8	1.6	5076	62.86	596
100	10	20.83	1.5	5039	62.86	612
	10	21.8	1.5	4981	61.28	600
	10	20.83	1.5	4962	62.08	564

TABLE 8b. TENSILE-SHEAR TEST DATA

24 GAUGE (Continued)

% Heat	Weld Time Cycles	Welding Press. Sanborn psi	Welding Voltage Volts (Max.)	Secondary Current AMP (Max.)	Primary Current AMP (Max.)	Tensile Shear Strength Lbs.
100	8	20.83	2.5	4943	60.50	568
	8	20.83	2.5	4962	61.28	582
	8	20.83	2.5	4943	60.50	594
100	5	20.83	2.5	4866	58.94	536
	5	20.83	2.4	4885	60.72	526
	5	21.8	2.5	4904	60.50	516
100	4	21.8	2.4	4847	58.94	460
	4	21.8	2.5	4847	60.50	466
	4	21.8	2.5	4809	56.58	400
100	3	20.8	2.4	4809	54.24	340
	3	20.8	2.4	4789	54.04	330
	3	21.8	2.4	4789	54.24	334
80	30	21.8	2.5	5172	66.00	542
	30	21.8	2.5	5172	66.00	544
	30	20.8	2.5	5172	66.00	542
80	28	20.83	2.4	5077	64.44	502
	28	20.83	2.4	5039	64.44	527
	28	21.8	2.5	5153	64.44	562
80	25	20.83	2.3	5153	64.44	542
	25	20.83	2.3	5153	64.44	520
	25	20.83	2.3	5039	66.00	548
80	23	21.8	2.4	5000	62.86	556
	23	20.83	2.3	5020	63.66	532
	23	21.8	2.3	5020	63.66	548
80	20	20.83	2.3	5000	62.08	560
	20	20.83	2.3	5020	61.28	542
	20	20.83	2.3	5059	62.86	526
80	18	20.83	2.3	4924	60.50	528
	18	20.83	2.3	4962	61.24	566
	18	20.83	2.3	4924	60.50	516

TABLE 8c. TENSILE-SHEAR TEST DATA

24 GAUGE (Continued)

% Heat	Weld Time Cycles	Welding Press. Sanborn psi	Welding Voltage Volts (Maximum)	Secondary Current AMP (Maximum)	Primary Current AMP (Maximum)	Tensile Shear Strength Lbs.
80	15	21.8	2.3	5039	61.28	506
	15	21.8	2.3	4943	60.50	528
	15	21.8	2.3	4962	62.08	526
80	13	21.8	2.3	4943	60.50	516
	13	20.83	2.3	4943	60.50	522
	13	20.83	2.4	4962	62.08	554
80	10	20.83	2.4	4847	57.36	530
	10	20.83	2.3	4847	57.36	534
	10	20.83	2.3	4847	57.36	532
80	8	20.83	2.4	4866	55.00	442
	8	21.8	2.3	5039	55.00	412
	8	21.8	2.3	4866	55.80	506
80	5	20.83	2.3	4771	55.00	456
	5	20.83	2.3	4752	54.22	360
	5	21.8	2.3	4770	54.22	404
80	3	21.8	2.3	4752	52.86	204
	3	21.8	2.3	4771	54.22	298
	3	21.8	2.3	4731	52.86	No Weld
60	30	21.8	1.8	4790	56.58	360
	30	21.8	1.8	4771	55.80	368
	30	21.8	1.8	4790	56.58	358
60	28	21.8	1.8	4790	56.58	360
	28	21.8	1.8	4790	55.80	356
	28	21.8	1.8	4790	56.58	348
60	25	20.83	1.8	4771	55.00	332
	25	20.83	1.8	4771	56.58	338
	25	20.83	1.8	4790	55.80	342
60	23	21.8	1.8	4790	56.58	348
	23	20.83	1.8	4771	55.00	350
	23	20.83	1.8	4771	56.58	348

TABLE 8d. TENSILE-SHEAR TEST DATA

24 GAUGE (Continued)

% Heat	Weld Time Cycles	Welding Press. Sanborn psi	Welding Voltage Volts (Maximum)	Secondary Current AMP (Maximum)	Primary Current AMP (Maximum)	Tensile Shear Strength Lbs.
60	20	21.8	1.8	4771	55.80	311
	20	21.8	1.8	4771	55.80	339
	20	21.8	1.8	4790	55.00	322
60	18	20.83	1.8	4752	55.00	310
	18	20.83	1.8	4771	55.00	316
	18	21.8	1.8	4752	55.00	320
60	15	20.83	1.8	4771	54.22	330
	15	20.83	1.8	4752	54.22	326
	15	20.83	1.8	4735	53.44	288
60	13	20.83	1.8	4735	53.86	314
	13	20.83	1.7	4752	55.00	312
	13	20.83	1.8	4735	55.00	304
60	10	21.8	1.8	4674	53.86	232
	10	21.8	1.8	4714	53.86	228
	10	21.8	1.8	4735	53.86	232
60	8	21.8	1.8	4695	51.86	176
	8	21.8	1.8	4714	53.86	162
	8	21.8	1.8	4695	51.08	208
60	5	20.83	1.8	4656	51.08	70
	5	20.83	1.8	4674	51.86	No Weld
	5	20.83	1.8	4639	51.08	148
60	5	20.83	1.8	4618	50.28	No Weld
	5	20.83	1.8	4674	51.86	80
	4	20.83	1.8	4618	49.50	No Weld
60	4	20.83	1.8	4656	50.28	No Weld
	4	21.8	1.8	4618	51.86	No Weld
	4	20.83	1.8	4656	51.86	No Weld
	4	20.83	1.8	4639	51.08	No Weld

TABLE 8e. TENSILE-SHEAR TEST DATA

24 GAUGE (Continued)

% Heat	Weld Time Cycles	Welding Press. Sanborn psi	Welding Voltage Volts (Max.)	Secondary Current AMP (Max.)	Primary Current AMP (Max.)	Tensile Shear Strength Lbs.
55	30	22.8	1.6	4735	53.44	248
	30	22.8	1.6	4735	53.44	308
	30	20.83	1.6	4752	53.44	292
55	28	20.83	1.6	4735	52.86	246
	28	20.83	1.6	4735	52.86	226
	28	20.83	1.5	4714	52.86	188
55	25	22.8	1.6	4714	53.44	276
	25	22.8	1.6	4674	51.86	224
	25	20.83	1.6	4656	52.56	262
55	23	21.8	1.6	4695	52.86	230
	23	21.8	1.6	4656	51.08	138
	23	21.8	1.6	4714	52.86	234
55	20	21.8	1.6	4695	52.86	160
	20	20.83	1.6	4656	51.08	118
	20	20.83	1.6	4674	51.12	164
55	18	21.8	1.6	4674	50.28	154
	18	21.8	1.6	4714	51.08	178
	18	21.8	1.5	4695	51.08	160
55	15	21.8	1.6	4695	51.08	No Weld
	15	21.8	1.6	4656	51.08	90
	15	21.8	1.6	4485	46.36	No Weld
55	15	21.8	1.6	4618	49.50	100
	13	21.8	1.6	4656	50.28	86
	13	21.8	1.5	4639	47.14	No Weld
55	13	21.8	1.6	4618	49.50	No Weld
	13	21.8	1.6	4639	49.50	No Weld
	13	21.8	1.6	4639	49.50	No Weld

TABLE 8e. TENSILE-SHEAR TEST DATA

24 GAUGE (Continued)

% Heat	Weld Time Cycles	Welding Press. Sanborn psi	Welding Voltage Volts (Max.)	Secondary Current AMP (Max.)	Primary Current AMP (Max.)	Tensile Shear Strength Lbs.
55	12	21.8	1.6	4639	49.50	No Weld
	12	21.8	1.6	4656	50.28	No Weld
	12	21.8	1.6	4639	49.50	No Weld
50	30	22.8	1.5	4565	49.50	100
	30	22.8	1.5	4525	47.14	No Weld
	30	21.8	1.5	4604	50.28	60
	30	21.8	1.5	4585	49.50	No Weld
	30	21.8	1.5	4585	49.50	No Weld

TABLE 9a. TENSILE-SHEAR TEST DATA

20 GAUGE

% Heat	Weld Time Cycles	Welding Press. Sanborn psi	Welding Voltage Volts (Maximum)	Secondary Current AMP (Maximum)	Primary Current AMP (Maximum)	Tensile Shear Strength Lbs.
100	30	20.83	2.7	4199	58.94	1026
	30	20.83	2.7	4199	58.94	996
	30	20.83	2.7	4199	58.94	940
100	28	20.83	2.7	4199	57.36	1006
	28	20.83	2.7	4199	57.36	1016
	28	20.83	2.7	4160	56.58	972
100	25	20.83	2.7	4199	56.58	1010
	25	20.83	2.7	4199	56.58	966
	25	20.83	2.7	4160	56.58	1026
100	23	21.8	2.8	4199	57.36	999
	23	20.83	2.7	4199	56.58	992
	23	20.83	2.7	4160	56.58	985
100	20	21.8	2.7	4123	53.44	968
	20	20.83	2.7	4160	55.00	870
	20	20.83	2.7	4179	55.00	930
100	18	21.8	2.7	4123	55.00	918
	18	20.83	2.7	4084	53.44	920
	18	20.83	2.7	4123	55.00	882
100	15	20.83	2.7	4123	55.00	894
	15	20.83	2.7	4123	53.44	918
	15	20.83	2.7	4123	53.44	876
100	13	20.83	2.7	4065	52.60	832
	13	20.83	2.7	4065	51.86	857
	13	20.83	2.7	4065	52.60	798
100	10	20.83	2.7	3950	49.50	798
	10	21.8	2.7	3950	50.28	790
	10	20.83	2.7	3950	49.50	790
100	8	20.83	2.7	4027	52.60	626
	8	21.8	2.7	4008	52.60	624
	8	21.8	2.7	4027	52.60	640

TABLE 9b. TENSILE-SHEAR TEST DATA

20 GAUGE (Continued)

% Heat	Weld Time Cycles	Welding Press. Sanborn psi	Welding Voltage Volts (Maximum)	Secondary Current AMP (Maximum)	Primary Current AMP (Maximum)	Tensile Shear Strength Lbs.
100	5	21.8	2.8	3931	49.50	450
	5	21.8	2.8	3989	50.28	524
	5	21.8	2.7	3989	50.28	524
100	4	21.8	2.7	3893	48.72	342
	4	21.8	2.7	3912	48.72	386
	4	21.8	2.7	3931	48.72	322
	4	20.83	2.7	3931	49.50	368
	4	20.83	2.7	3912	48.72	304
100	3	20.83	2.6	3893	47.14	150
	3	20.83	2.7	3855	46.36	214
	3	20.83	2.7	3894	46.36	320
	3	20.83	2.7	3894	47.14	222
	3	20.83	2.7	3855	48.72	166
80	30	21.8	2.5	4179	55.80	926
	30	20.83	2.5	4179	55.80	896
	30	20.83	2.5	4160	56.58	858
80	28	20.83	2.5	4160	57.36	884
	28	20.83	2.5	4160	57.36	926
	28	21.8	2.5	4123	55.80	904
80	25	20.83	2.5	4123	55.00	904
	25	20.83	2.5	4160	56.58	920
	25	20.83	2.5	4084	53.44	888
80	23	20.83	2.4	4123	55.80	902
	23	20.83	2.4	4160	55.80	820
	23	21.8	2.4	4084	55.00	906
80	20	20.8	2.4	4065	52.60	870
	20	20.8	2.5	4065	52.60	846
	20	20.8	2.5	4065	52.60	824

TABLE 9c. TENSILE-SHEAR TEST DATA

20 GAUGE (Continued)

% Heat	Weld Time Cycles	Welding Press. Sanborn psi	Welding Voltage Volts (Maximum)	Secondary Current AMP (Maximum)	Primary Current AMP (Maximum)	Tensile Shear Strength Lbs.
80	18	20.83	2.5	4065	52.60	852
	18	20.83	2.5	4027	52.60	840
	18	20.83	2.5	4027	52.60	822
80	15	20.83	2.5	4027	52.60	774
	15	20.83	2.5	4027	52.60	766
	15	20.83	2.5	4027	52.60	802
80	10	22.8	2.5	3931	49.50	628
	10	20.83	2.5	3950	49.50	607
	10	22.8	2.5	3950	49.50	762
80	7	21.8	2.5	3912	49.36	540
	7	20.83	2.5	3931	49.50	527
	7	20.83	2.5	3893	48.72	534
80	5	20.83	2.4	3893	49.50	362
	5	20.83	2.4	3874	48.72	438
	5	20.83	2.4	3893	47.14	386
	5	20.83	2.4	3893	48.72	354
	5	21.8	2.4	3893	47.14	332
80	4	20.83	2.4	3893	48.72	268
	4	20.83	2.4	3893	47.14	140
	4	20.83	2.4	3893	49.50	No Weld
	4	21.8	2.4	3893	48.72	198
	4	20.83	2.4	3893	46.36	150
80	3	20.83	2.3	3817	46.36	No Weld
	3	20.83	2.3	3836	46.36	No Weld
	3	20.83	2.4	3836	46.36	107
	3	20.83	2.3	3836	46.36	No Weld
	3	20.83	2.3	3931	46.36	78

TABLE 9d. TENSILE-SHEAR TEST DATA

20 GAUGE (Continued)

% Heat	Weld Time Cycles	Welding Press. Sanborn psi	Welding Voltage Volts (Maximum)	Secondary Current AMP (Maximum)	Primary Current AMP (Maximum)	Tensile Shear Strength Lbs.
60	30	21.8	1.9	3893	49.50	589
	30	21.8	1.9	3874	48.72	506
	30	22.8	1.9	3874	49.50	474
60	28	21.8	1.9	3969	51.08	586
	28	21.8	1.9	3950	55.80	560
	28	21.8	1.9	3950	55.80	570
60	25	20.83	1.8	3931	50.28	462
	25	20.83	1.9	3969	51.08	518
	25	20.83	1.9	3950	51.08	620
60	23	21.8	1.9	3931	50.28	532
	23	21.8	1.8	3912	49.50	424
	23	21.8	1.9	3931	50.28	542
60	20	21.8	1.9	3798	47.14	480
	20	21.8	1.9	3798	45.58	506
	20	21.8	1.9	3798	47.14	474
60	18	21.8	1.9	3912	49.50	454
	18	20.83	1.9	3874	48.72	477
	18	20.83	1.9	3931	50.28	466
60	15	22.88	1.9	3779	46.36	440
	15	22.88	1.9	3740	45.58	400
	15	21.8	1.9	3798	45.58	314
60	10	20.83	1.9	3740	44.80	224
	10	20.83	1.9	3760	44.80	180
	10	20.83	1.9	3740	44.80	218
60	8	20.83	1.9	3740	44.80	78
	8	20.83	1.9	3779	46.36	No Weld
	8	20.83	1.9	3721	44.80	118

TABLE 9e. TENSILE-SHEAR TEST DATA

20 GAUGE (Continued)

% Heat	Weld Time Cycles	Welding Press. Sanborn psi	Welding Voltage Volts (Maximum)	Secondary Current AMP (Maximum)	Primary Current AMP (Maximum)	Tensile Shear Strength Lbs.
60	7	20.83	1.9	3760	45.58	No Weld
	7	20.83	1.9	3721	44.80	No Weld
	7	20.83	1.9	3702	44.80	No Weld
55	30	20.83	1.7	3683	44.00	434
	30	21.8	1.7	3702	44.00	412
	30	20.83	1.7	3721	45.58	466
55	28	21.8	1.7	3702	44.00	400
	28	21.8	1.7	3702	42.44	340
	28	22.88	1.7	3683	41.66	256
50	30	22.88	1.5	3588	41.66	178
	30	21.8	1.5	3626	42.44	No Weld
	30	21.8	1.5	3683	41.66	90

TABLE 10. TENSILE-SHEAR TEST DATA

18 GAUGE

% Heat	Weld Time Cycles	Welding Press Sanborn psi	Welding Voltage Volts (Maximum)	Secondary Current AMP (Maximum)	Primary Current AMP (Maximum)	Tensile Shear Strength Lbs.
	30	20.83	2.8	4122	51.08	1400
100	30	20.83	2.8	4122	51.08	1380
	30	20.83	2.8	4046	51.08	1320
	28	21.8	2.8	4008	52.6	1280
100	28	21.8	2.8	3989	51.86	1300
	28	20.83	2.8	3989	51.86	1300
	25	20.83	2.8	4008	51.86	1260
100	25	20.83	2.8	3989	52.6	1260
	25	21.8	2.8	3969	51.86	1260
	23	21.8	2.8	3989	51.86	1250
100	23	21.8	2.8	3969	51.86	1220
	23	21.8	2.8	3969	51.86	1260
	20	22.8	2.8	3931	48.72	1240
100	20	22.8	2.8	3931	47.36	1260
	20	22.8	2.8	3989	50.24	1160
	18	20.83	2.8	3969	51.08	1160
100	18	20.83	2.8	3969	51.08	1126
	18	21.8	2.8	3931	51.26	1150
	15	21.8	2.8	3969	51.08	1028
100	15	21.8	2.8	3969	52.6	979
	15	21.8	2.8	3950	50.28	1062
	13	21.8	2.8	4008	52.6	706
100	13	21.8	2.8	3950	51.08	860
	13	21.8	2.8	3950	51.08	742
	10	21.8	2.8	3893	47.14	750
100	10	21.8	2.8	3969	48.72	640
	10	20.83	2.8	3893	47.14	720
	9	21.8	2.8	3969	53.44	388
100	9	21.8	2.8	3950	51.08	548
	9	20.83	2.8	4008	52.6	436

TABLE 10. TENSILE-SHEAR TEST DATA

18 GAUGE (Continued)

% Heat	Weld Time Cycles	Welding Press Sanborn psi	Welding Voltage Volts (Maximum)	Secondary Current AMP (Maximum)	Primary Current AMP (Maximum)	Tensile Shear Strength Lbs.
100	6	21.8	1.8	3931	49.50	274
	6	21.8	1.8	3989	50.28	244
	6	20.83	1.8	4084	51.08	258
100	5	20.83	1.8	3950	49.50	296
	5	20.83	1.7	3969	50.28	244
	5	20.83	1.8	3989	49.50	272
	5	20.83	1.8	3989	50.20	322
	5	21.8	1.7	3969	49.50	226
100	4	20.83	1.7	3989	50.28	98
	4	20.83	1.7	3969	51.08	108
	4	20.83	1.7	3989	50.28	88
	4	20.83	1.7	3989	51.08	56
	4	20.83	1.7	3989	49.50	112
100	3	20.83	1.7	3950	48.72	No Weld
	3	20.83	1.7	3950	49.50	No Weld
	3	20.83	1.7	3989	51.08	No Weld
	3	20.83	1.7	3989	49.50	No Weld
	3	20.83	1.7	3989	49.50	No Weld
80	30	21.8	2.5	3989	51.08	1240
	30	20.83	2.5	3969	49.50	1220
	30	20.83	2.5	3989	51.08	1280
80	28	20.83	2.5	3950	51.08	1210
	28	21.8	2.5	4008	54.22	1200
	28	20.83	2.5	3950	52.60	1250
80	25	21.8	2.6	4008	51.86	1140
	25	21.8	2.6	3931	51.86	1140
	25	21.8	2.5	3931	51.08	1160
80	23	21.8	2.5	3931	51.08	1058
	23	21.8	2.6	3969	51.86	1182
	23	21.8	2.6	3931	51.08	1132

TABLE 10. TENSILE-SHEAR TEST DATA

18 GAUGE (Continued)

% Heat	Weld Time Cycles	Welding Press. Sanborn psi	Welding Voltage Volts (Maximum)	Secondary Current AMP (Maximum)	Primary Current AMP (Maximum)	Tensile Shear Strength Lbs.
80	20	21.8	2.5	3931	49.50	1040
	20	21.8	2.5	3912	45.36	1040
	20	21.8	2.5	3989	48.72	1080
80	18	21.8	2.5	3950	50.28	716
	18	21.8	2.5	3931	50.28	858
	18	21.8	2.5	3950	51.08	736
80	15	22.8	2.5	3950	51.86	594
	15	21.8	2.5	3969	51.86	730
	15	21.8	2.5	3931	51.86	630
80	13	22.8	2.5	3931	51.08	558
	13	21.8	2.5	3912	51.08	542
	13	20.83	2.5	3931	51.86	622
80	10	20.83	1.7	3893	46.36	480
	10	20.83	1.7	4027	49.50	422
	10	20.83	1.7	3931	49.72	444
80	8	20.83	1.7	3989	48.72	328
	8	21.8	1.7	3989	48.72	370
	8	21.8	1.7	3931	49.50	308
80	7	21.8	1.6	3989	47.84	240
	7	21.8	1.6	3989	49.50	286
	7	21.8	1.6	3989	48.72	238
80	5	21.8	1.6	3931	49.50	270
	5	21.8	1.6	3931	48.72	182
	5	21.8	1.6	3931	48.72	150
	5	21.8	1.6	3969	50.28	156
	5	21.8	1.6	3931	48.72	284
80	4	21.8	1.6	3912	45.36	No Weld
	4	21.8	1.6	3912	45.36	No Weld
	4	21.8	1.6	3912	46.36	No Weld
	4	21.8	1.6	3893	45.36	No Weld
	4	21.8	1.6	3893	45.36	No Weld

TABLE 10. TENSILE-SHEAR TEST DATA

18 GAUGE (Continued)

% Heat	Weld Time Cycles	Welding Press. Sanborn psi	Welding Voltage Volts (Maximum)	Secondary Current AMP (Maximum)	Primary Current AMP (Maximum)	Tensile Shear Strength Lbs.
60	30	20.83	1.9	3836	46.36	440
	30	20.83	1.9	3817	45.58	450
	30	21.8	1.9	3798	44.76	460
60	28	21.8	1.9	3836	49.50	490
	28	21.8	1.9	3779	47.94	474
	28	21.8	1.9	3798	47.36	512
60	25	21.8	1.9	3779	47.94	358
	25	20.83	1.9	3798	47.94	474
	25	21.8	1.9	3798	47.94	460
60	23	21.8	1.9	3798	48.72	358
	23	20.83	1.7	3645	44.76	Broke
	23	20.83	1.7	3683	44.76	Broke
60	20	20.83	1.9	3760	43.22	422
	20	20.83	1.9	3817	45.58	390
	20	21.8	1.9	3779	43.22	324
60	18	20.83	1.3	3817	45.58	340
	18	20.83	1.3	3817	45.58	342
	18	20.83	1.3	3836	45.58	420
60	18	20.83	1.3	3836	45.58	368
	18	20.83	1.3	3836	45.58	260
	13	20.83	1.3	3855	45.58	156
60	12	20.83	1.3	3817	45.58	208
	12	20.83	1.3	3836	44.80	108
	12	20.83	1.3	3817	44.80	130
60	12	20.83	1.3	3855	46.36	250
	12	20.83	1.3	3740	44.80	202
	11	20.83	1.3	3798	44.76	No Weld
60	11	20.83	1.3	3779	44.76	88
	11	20.83	1.3	3760	44.0	94
	11	20.83	1.3	3760	44.0	126

TABLE 10. TENSILE-SHEAR TEST DATA

18 GAUGE (Continued)

% Heat	Weld Time Cycles	Welding Press. Sanborn psi	Welding Voltage Volts (Maximum)	Secondary Current AMP (Maximum)	Primary Current AMP (Maximum)	Tensile Shear Strength Lbs.
60	11	20.83	1.3	3760	44.0	182
	10	21.8	1.3	3779	46.36	No Weld
	10	21.8	1.3	3798	47.40	No Weld
60	10	21.8	1.3	3779	46.36	No Weld
	10	21.8	1.3	3760	46.36	No Weld
	10	21.8	1.3	3720	44.76	No Weld
55	30	20.83	1.2	3702	42.44	250
	30	20.83	1.2	3683	42.44	374
	30	20.83	1.2	3664	41.66	258
55	28	20.83	1.2	3702	43.22	358
	28	20.83	1.2	3664	41.66	288
	28	20.83	1.2	3683	41.66	272
55	25	20.83	1.2	3683	45.58	270
	25	20.83	1.2	3683	45.58	186
	25	20.83	1.2	3683	45.58	340
55	22	21.8	1.2	3664	42.44	184
	22	20.83	1.2	3607	40.86	210
	22	20.83	1.2	3664	41.66	148
55	22	20.83	1.2	3626	41.66	118
	22	20.83	1.2	3568	40.86	210
	21	20.83	1.2	3645	40.76	No Weld
55	21	20.83	1.2	3645	40.76	No Weld
	21	20.83	1.2	3607	40.86	No Weld
	21	20.83	1.2	3568	40.08	No Weld
55	21	20.83	1.2	3702	42.44	No Weld
50	30	20.83	1.1	3492	40.86	No Weld
	30	20.83	1.1	3492	40.86	No Weld
50	30	20.83	1.1	3474	40.08	No Weld
	30	20.83	1.1	3512	40.86	No Weld
	30	20.83	1.1	3474	40.08	No Weld

TABLE 11. TENSILE-SHEAR TEST DATA

16 GAUGE

% Heat	Weld Time Cycles	Welding Press. Sanborn psi	Welding Voltage Volts (Maximum)	Secondary Current AMP (Maximum)	Primary Current AMP (Maximum)	Tensile Shear Strength Lbs.
100	30	20.83	4.1	4084	59.72	1030
	30	20.83	4.1	4084	57.36	1066
	30	20.83	4.1	4046	59.72	1070
100	28	21.8	2.9	3950	50.28	1080
	28	21.8	2.9	3931	49.50	1112
	28	22.8	2.9	3931	50.28	1124
100	25	22.8	2.8	3950	50.28	1012
	25	22.8	2.9	4027	52.60	936
	25	22.8	2.9	3989	51.08	982
100	23	21.8	2.9	3969	50.28	920
	23	21.8	2.9	3969	50.28	920
	23	22.8	2.9	3969	51.08	982
100	20	22.8	4.1	3893	57.36	740
	20	20.83	4.1	4084	60.50	800
	20	20.83	4.1	4084	59.72	804
100	18	22.8	2.9	3969	51.08	774
	18	22.8	2.9	3931	49.50	892
	18	22.8	2.9	3912	49.50	700
100	15	22.8	2.9	3931	50.28	668
	15	22.8	2.9	3950	50.28	788
	15	21.8	2.8	3969	51.86	562
100	13	22.8	2.9	3950	51.08	794
	13	21.8	2.9	3950	50.28	682
	13	22.8	2.9	3893	50.28	522
100	10	20.83	4.0	4065	60.50	366
	10	20.83	4.1	4077	59.72	300
	10	20.83	4.1	4077	59.72	330

TABLE 11. TENSILE-SHEAR TEST DATA

16 GAUGE (Continued)

% Heat	Weld Time Cycles	Welding Press. Sanborn psi	Welding Voltage Volts (Maximum)	Secondary Current AMP (Maximum)	Primary Current AMP (Maximum)	Tensile Shear Strength Lbs.
100	8	21.8	2.8	3893	49.50	279
	8	21.8	2.8	3893	49.50	298
	8	22.8	2.8	3893	50.28	316
100	6	22.8	3.8	3912	51.86	200
	6	22.8	4.1	3931	51.86	280
	6	21.8	4.1	3893	51.08	330
	6	21.8	4.1	3869	51.86	268
	6	22.8	4.1	3989	56.58	134
80	30	21.8	3.8	4150	61.28	850
	30	21.8	3.9	4046	57.36	860
	30	21.8	3.9	4065	57.36	960
80	28	22.8	2.6	3931	50.28	896
	28	21.8	2.5	3912	49.50	834
	28	22.8	2.6	3912	49.50	865
80	25	22.8	2.6	3950	51.86	780
	25	22.8	2.6	3855	49.50	938
	25	21.8	2.5	3912	49.50	820
80	23	21.8	2.6	3912	50.28	818
	23	22.8	2.6	3969	52.60	826
	23	21.8	2.6	3893	51.86	818
80	20	22.8	3.8	4046	57.36	658
	20	21.8	3.8	4046	56.58	578
	20	22.8	3.9	4150	57.36	598
80	18	21.8	2.6	3912	50.28	674
	18	21.8	2.5	3855	51.08	664
	18	22.8	2.6	3950	50.28	682
80	15	22.8	2.5	3912	49.50	485
	15	21.8	2.6	3912	49.50	588
	15	22.8	2.7	3855	48.72	592

TABLE 11. TENSILE-SHEAR TEST DATA

16 GAUGE (Continued)

% Heat	Weld Time Cycles	Welding Press. Sanborn psi	Welding Voltage Volts (Maximum)	Secondary Current AMP (Maximum)	Primary Current AMP (Maximum)	Tensile Shear Strength Lbs.
80	13	21.8	2.6	3855	50.88	464
	13	21.5	2.5	3931	50.28	434
	13	22.8	2.5	3931	50.28	392
80	10	20.83	3.9	3893	56.58	360
	10	20.83	3.9	3931	55.00	394
	10	21.8	3.9	3893	52.60	330
80	8	21.8	3.8	3855	51.08	306
	8	21.8	3.8	3855	51.08	322
	8	21.8	3.8	3874	51.86	280
	8	21.8	3.8	3893	52.60	284
	8	21.8	3.8	3893	52.60	220
60	30	20.83	2.8	3817	49.50	308
	30	20.83	2.8	3874	53.44	292
	30	21.8	2.8	3874	53.44	308
60	28	20.83	1.9	3721	45.58	402
	28	20.83	1.9	3740	45.58	390
	28	20.83	1.9	3740	45.58	464
60	25	21.8	1.9	3779	46.36	298
	25	21.8	1.9	3740	45.58	306
	25	21.8	1.9	3740	45.58	344
60	23	21.8	1.9	3740	45.58	314
	23	21.8	1.9	3740	45.58	326
	23	21.8	1.9	3740	45.58	280
60	20	20.83	2.9	3855	52.60	Weld Broke
	20	22.8	2.8	3836	50.28	Weld Broke
	20	20.83	2.8	3855	50.28	Weld Broke
60	18	21.8	2.9	3645	45.58	218
	18	21.8	2.9	3626	45.58	268
	18	21.8	2.8	3645	45.58	208

TABLE 11. TENSILE-SHEAR TEST DATA

16 GAUGE (Continued)

% Heat	Weld Time Cycles	Welding Press. Sanborn psi	Welding Voltage Volts (Maximum)	Secondary Current AMP (Maximum)	Primary Current AMP (Maximum)	Tensile Shear Strength Lbs.
60	15	21.8	2.8	3626	45.58	120
	15	21.8	2.8	3664	46.36	104
	15	20.83	2.8	3664	46.36	No Weld
	15	21.8	2.8	3702	46.36	184
	15	20.83	2.8	3626	45.58	No Weld
60	14	20.83	2.8	3512	44.8	No Weld
	14	20.83	2.8	3512	44.8	No Weld
	14	20.83	2.8	3483	42.44	No Weld
55	30	21.8	2.4	3568	43.86	224
	30	21.8	2.4	3550	43.86	178
	30	21.8	2.5	3568	41.66	240
55	28	22.8	1.7	3492	42.44	196
	28	21.8	1.7	3492	42.44	194
	28	22.8	1.7	3474	43.86	142
55	25	21.8	1.3	3492	41.66	160
	25	21.8	1.3	3474	43.86	118
	25	21.8	1.3	3512	42.44	Lost
55	24	21.8	1.3	3568	46.36	188
	24	20.83	1.3	3645	46.36	No Weld
	24	21.8	1.3	3626	44.76	Broke
	24	21.8	1.3	3607	44.76	192
	24	21.8	1.2	3645	44.76	194
55	23	21.8	1.3	3512	43.86	No Weld
	23	21.8	1.3	3512	43.86	No Weld
	23	21.8	1.3	3568	44.76	136
	23	21.8	1.3	3607	44.76	100
	23	21.8	1.3	3492	42.44	No Weld
50	30	20.83	0.9	3474	40.76	No Weld
	30	20.83	0.8	3512	42.44	No Weld
	30	20.83	0.9	3512	42.44	No Weld
	30	20.83	0.9	3512	42.44	No Weld
	30	21.8	0.8	3474	40.76	No Weld

ABSTRACT

The primary objectives of this thesis investigation were:

1. To establish the maxima and minima values, within limits of the welding machine parameters: current and time, for 28 gauge, 24 gauge, 20 gauge, 18 gauge, and 16 gauge of SAE CR 1010 steel.

2. To implement and calibrate the instrumentation necessary to determine accurate values, within limits, of the variables under investigation. Also, to devise suitable controls for those fixed variables not investigated.

3. To correlate values of welding current and time with resulting tensile-shear strengths of the lapped welding joints.

4. To establish the combination of welding current and weld time which gives a maximum value of tensile strength for the metal gauges under investigation.

A brief review of the more important literature on resistance spot welding variables was presented. The calibration process of determining voltage, resistance, and current was described.

The mathematical prediction models (relationship between weld strength and weld time) were established for each heat control setting for different thicknesses under investigation, based on non-linear regression techniques. From the prediction models and the use of Calculus, the maximum tensile-shear strengths and corresponding

maximum weld cycles were computed. The minimum weld strengths and weld cycles were determined by the welding conditions that just produced a weld of measurable strength.