PROXIMITY EFFECT IN SPOT WELDING OF STAINLESS STEEL

by

James Augustus Sweeney

S.B., Massachusetts Institute of Technology

1934

Submitted in Partial Fulfillment of the Requirements

for the Degree of

MASTER OF SCIENCE

in Naval Architecture & Marine Engineering

from the

Massachusetts Institute of Technology

1936

Signature of Author Signature redacted

Department of Naval Architecture, June 24, 1936

Professor in Charge of Research Signature redacted

Chairman of Department Committee on Graduate Students Signature redacted

Cambridge, Mass.
24 June 1936.

Professor G. W. Swett
Secretary of the Faculty
Massachusetts Institute of Technology
Cambridge, Mass.

Sir:

In accordance with the requirements for the degree of Master of Science in Naval Architecture and Marine Engineering, I herewith submit a thesis entitled "Proximity Effect in Spot Welding of Stainless Steel".

Respectfully submitted,

Signature redacted

James A. Sweeney

ACKNOWLEDGEMENT

To all, who in any way made possible this thesis the author wishes to offer acknowledgement. In particular, thanks is due Mr. E.D. Debes of the Bethlehem Shipbuilding Corporation who procured the steel and offered many valuable suggestions. To Professors J.R. Jack, J.H. Zimmerman, Mr. R.F. Goodman and the other members of the staffs of the Department of Naval Architecture and the Department of Mechanical Engineering whose suggestions and assistance proved invaluable, the author wishes to extend special thanks.

TABLE OF CONTENTS

I
INTRODUCTION

The rapid increase in the use of welding in both construction and assembly work has brought with it an infinite number of problems that must be solved before further application of welding can be attempted. Some of these problems and difficulties - such as distortion and shrinkage - are common to several or all branches of welding, but a good many are peculiar to but a single branch. The investigation undertaken in the present case pertains to a problem of the latter type which occurs in the field of spot welding, a variation of resistance welding. The study concerns the effect of spacing on the strength of a spot weld. Although it is readily admitted in the welding industry that the problem is important and worthy of study, practically no literature on it is available. A few articles were found that gave it passing mention, but none treated it at any length. The references listed in the bibliography in general treated other phases of spot welding.

In research of any nature, the usual procedure is to base deductions on two sources - data obtained from all available sources, and a theoretical analysis of the problem itself. Because of the dearth of information on the problem at hand, the former source is very limited indeed. Consequently, more emphasis than might be desired must be given to a theoretical analysis. Before proceeding farther then, it might be well to make a broad review of spot welding in general and try to answer the question - what occurs when these spot welds are made under various conditions.

II
DISCUSSION OF PROBLEM PART I

Spot welding is, first of all, a form of resistance welding. A concise, yet exact definition of resistance welding is difficult to make. Resistance welding has been defined frequently as "a method of joining metals under pressure when heated to the plastic state". Such a definition is not altogether correct, however. Some of the non-ferrous metals - such as aluminum alloys - have no transitory plastic state as do the steels; yet thin sections of these metals can be successfully welded. The origin of such a definition can be explained perhaps by the fact that for most cases it provides the basis for a recipe of successful spot-welding. Moreover, it is with those metals lacking a transitory plastic state that difficulty is generally encountered in welding. By way of loose definition, it might be said that resistance welding is essentially a refined and improved version of the old form of welding used by the blacksmith, but much broader in its applications than its forbear.

Just what occurs when two pieces of metal are spot welded is not altogether clear. In a paper discussing the fundamentals of spot welding, Hobrock [3] has advanced the theory that the basis of spot welding is recrystallization. Recrystallization, he says, depends on deformation and temperature. To obtain deformation, pressure is all-important, and it plays three distinct roles. First, it presses together the two surfaces to be welded. Second, it helps to break any film or coating of oxide, dirt, etc. and bring the two surfaces into intimate contact. Third, it deforms the crystals of the material, permitting recrystallization. During this recrystallization, there occurs a growth of grains across the surface boundary between the two pieces being welded. Photomicrographs of spot welds tend to substantiate this theory.

While there is some doubt as to just what occurs during the making of a spot weld, the basic theory behind spot welding is relatively simple. The major difficulties are met in its practical application. Being relatively new, comparatively little is known about it. The effect of varying the conditions under which the spot is made is important and is in need of study. Better and more effective methods of varying the conditions are likewise needed.

With alloys the difficulties met in practice are more acute than with mild steel. Why this is so is easily explained. Alloys posess their outstanding properties because of their chemical makeup and the special treatments they receive. Once these outstanding properties are attained, further heat treatment generally not only robs the alloy of these properties but actually makes it of even less value than the untreated base metal. The heat generated in making a spot weld may be sufficient to nullify these feature properties. In other cases these outstanding properties are such that they resist the formation of the weld.

An example of a common alloy that is welded with difficulty is "18 - 8" stainless steel, the material used in fabricating the test specimens used in conjunction with this thesis. It is known commercially by a wide variety of names, among them being "Alleghany Metals", "Enduro", "Nirosta", "C.R.S. (corrosion resistant steel)" and others. Stainless Steel owes its corrosion resistant properties and its outstanding physical properties to both its chemical makeup and to the special heat treatment it undergoes. Chemically it contains 18% chromium and 8% nickel.

In order to apprehend what effects the making of a spot weld has, it is perhaps best to investigate the results of various treatments on the properties of the alloy.

The corrosion resistant properties are introduced by quenching the alloy from the high temperature used in preliminary stages of its preparation. The immediate result of the quenching is a relatively weak and soft metal, with a tensile strength of about 80,000 lbs. per sq. in. Further heat treatment proves deleterious rather than beneficial to the metal. Cold working hardens it, however, and strengthens it rapidly, a tensile strength as high as 400,000 lbs. per sq. in. being obtainable with sufficient cold working. As it is generally used, C.R.S. has a tensile strength of about 150,000 or 200,000 lbs. per sq. in. and elongation of from 10 to 15% in 2 inches. In this condition it is rather springy and is difficult to cut and machine. Stainless steel with a tensile strength of 400,000 lbs. per sq. in. is almost impossible to shape. Although continued cold working strengthens the alloy, it also weakens its corrosion resistant properties.

Resort to some method other than riveting for fabricating this alloy seemed advisable. It is easy to see why. Any rivet material that would be strong enough in shear to be used with such a high tensile steel would be too difficult to machine and too hard to head over. Rivets of stainless steel are impractical because the hot rivet hardens too rapidly. Welding - both bead and spot - proved a welcome substitute for riveting. Like riveting, though, it, too, presents several difficulties.

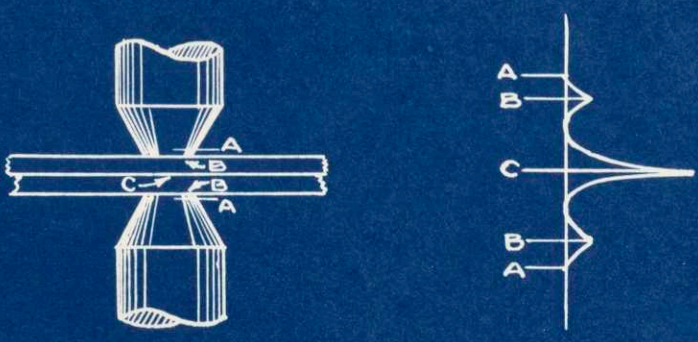
The principal cause of the difficulties encountered with either riveting or welding is heat. It is well then to make a brief study of the effect of heat on the material, and, since we are interested chiefly in spot welding, the role of heat in spot welding itself. In doing so, let it be kept in mind that the reason the ~~reason the~~ material is used is because of its corrosion resistant properties and its high strength.

The corrosion resistance is due in large part to the chromium content. When heated to a temperature of from 1000° to 1500° F, metallurgists claim that the chromium tends to combine with the carbon present to form a carbide, which precipitates at the grain boundaries. This carbide may contain as high as 90% chromium. The metal in the vicinity of this temperature is robbed of much of its chromium. Consequently it is more liable to corrode, and the alloy loses its feature property. Moreover, the corrosion does not confine itself to the point of its origin, but may spread along the grain boundary throughout the steels. Fortunately, however, there is a remedy for this carbide precipitation. If the metal is heated to a high enough temperature, the carbide will redissolve, and the chromium will be redistributed to its former state, and the steel will again have its corrosion resistant properties. A temperature of about 2000° F. will do this if the exposure is sufficient.

The metal after receiving such a treatment has regained its corrosion resistant properties, but only at the loss of its strength, for this reheating has removed all the effect of the cold-working.

The role played by heat in making the spot is vital. If it could be controlled perfectly, most of the difficulties of spot welding would vanish. In the setup for the spot weld (see figures 1 and 2) there are electrodes above and below the spot, and solid metal around it. The electrodes are cooled, so the spot is entirely surrounded by cold metal which naturally carries the heat away rapidly from the spot. This chilling of the spot leaves it comparatively soft and ductile, which is, of course, much to be preferred to a brittle spot. But the metal has passed through the critical state, resulting in the precipitation of the chrome carbide, opening the way for corrosion to set in. The spot itself may have reached a high enough temperature so that the chromium has been redistributed, but somewhere in

DIAGRAMMATIC SKETCH
OF SPOT WELDING PROCESS
FIG 1



THERMAL GRADIENT

SPOT WELDING SET-UP AND
INITIAL TEMPERATURE CURVE
FIG 2

the neighborhood of the spot the metal has been heated to only the critical temperature. The result is the formation of a "precipitation ring". Photomicrographs show that this actually occurs.

The steel cannot be left in this condition. Heat treating it at 2000° F. and then cold working it is either impossible or impracticable. There is a way, however, of avoiding this precipitation, in part, at least. By using a very short interval of current dwell - that is, a very short time - and a high current, it is possible to limit the appearance of the carbide. The combination of a short interval of dwell and a high current means an intense heat for a very short period and establishes a steep temperature gradient. This means a concentration of heat where it is wanted, and less heating of the surrounding metal in order to raise the spot to a welding temperature. Furthermore the surrounding metal cools the spot so rapidly that excessive precipitation does not take place. The critical range is not avoided by this procedure, but its ill effects are lessened.

DISCUSSION OF PROBLEM PART II

In research work involving spot welding it has been common to deal with a single spot, thereby eliminating any effect on the spot that might be caused by another weld nearby. However, practical application of spot welding generally calls for a series of spots, much the same as when riveting is used. When such is the case a proper spacing of spots must be decided upon. The spacing will, in general, be determined by two factors - the strength requirements and the requirements for tightness. If the requirements for tightness are great, "seam welding" is often used. Seam welding is fundamentally a continuous application of spot welding. The ordinary tip electrodes are replaced by rollers, between which passes the seam to be welded. The current flows intermittently through the rollers. Originally a continuous current was tried with these roller-electrodes, but it resulted in irregular or imperfect seams. In present day design the current is allowed to flow long enough to make a single weld and it is then interrupted and does not flow again until the plates have moved a fixed distance. This distance can be varied easily, and if it is small enough, the seam can be made air-tight or even steam-tight. Regulation of this distance, or of the "spacing" of the individual spots, requires very accurate control over the timing of each spot, and the switching on and off of the current. For control purposes, electronic tubes far surpass any mechanical or magnetic methods. The first cost is considerably higher, but they generally last longer and give less trouble besides giving more accurate control. They are also easier to replace. Seam welding can be performed at a fairly good production rate. As high as 100 inches per minute has been obtained, although this is far above the average rate.

When the spots are spaced farther apart than in seam welding, another method of production is sometimes used whereby all the spots are made simultaneously. The machine used for this, known as a hydromatic welding machine, is being used very extensively for fabrication where mass production is important. As an example, in the assembly of the cowl of a well-known make of car, nine parts are welded by such a machine in less than a minute. In this short period 160 welding guns are automatically set and withdrawn.

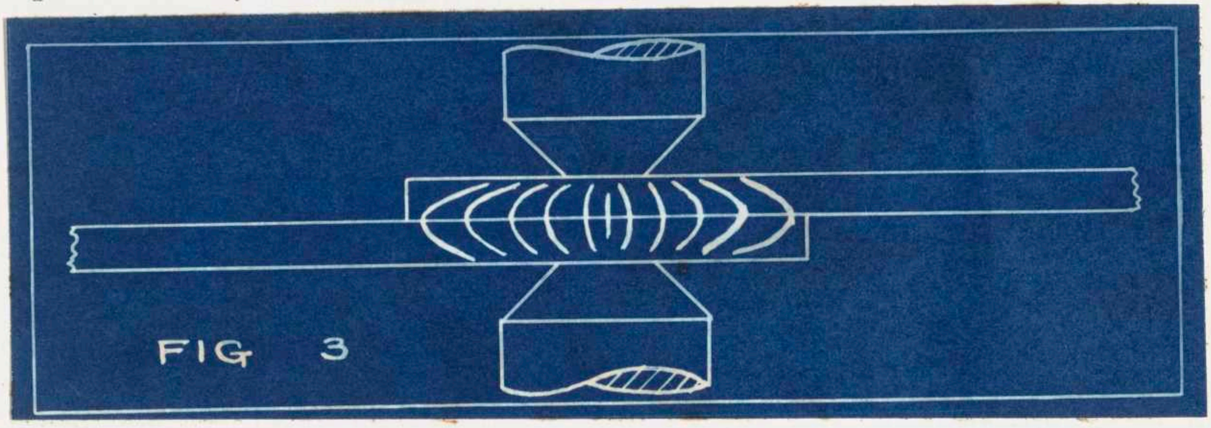
A natural question might be - what effect, if any, has the spacing on the quality and physical properties of the welds. To answer such a question with any degree of reliability would demand a thorough investigation, and so a program of testing was worked out that would deal with the type of weld most likely to be met in industry. The welds were made by an ordinary spot welder having common cone-shaped electrodes, making a single spot at a time. While welds so made are exactly analagous to neither those made by the seam welder nor to those made by hydromatic machine, they furnish the best basis for discussion of all types.

In the investigation undertaken, only two spots were made in each specimen used to study the proximity effect. It would be very desirable to increase this number, but this was not very practical. Moreover, an analysis of the problem will indicate that with wide spacing, it is very probable that any effect on a spot is due almost entirely to the adjacent spot. Incidently, results of the tests seem to be in line with such a conclusion within the limits used in the tests. When the spacing is close, though, such as when there are 12 to 14 spots to the inch, such a conclusion might very well be questioned.

Considering a weld made in the ordinary method by the common spot welder, it is interesting to form a theory as to what effect spacing might have on its properties. Assuming that a spot has already been made and that a second spot is being made nearby, what possible effects could this first have on the second weld? Of prime importance are two things influenced by the existence of this first spot - the path of the electrical circuit used in making the second spot and the heat distribution. The path of the current is deserving of some study, since much of the resistance between the electrodes is supposedly offered by the surfaces of the metals. With a spot nearby, a path is opened for a circuit directly through the metal, eliminating the boundary surfaces. From experience we know that the entire circuit does not follow such a path, but that instead, part of it - or maybe all - takes the shorter path directly across the electrodes. The resistance of this path depends on several variables - the pressure between the electrode tips, the condition of the surfaces, the distance between tips (thickness of the metals), the type and size electrodes, and others.

Whether any of the current used in welding the second spot is short circuited through the first spot is uncertain. If the current is divided, and the machine was set to make the first weld an optimum weld, then the second spot will consequently be inferior. The additional flow of current through the first weld may also prove deleterious to it, also.

No method is available whereby such a stray current could be measured electrically. It is known that when two plates are placed in contact between a set of electrodes, the current does not flow entirely from one electrode to the other in a straight path, but instead spreads out, as indicated in figure 3.



The exact path of the current in any case depends somewhat on the contact of the two plates in the vicinity of the spots. If there is a weld nearby, it should provide an excellent path for the current. Moreover, it is claimed that the reaction of the magnetic field of the welder arms tends to push the current away from the loop formed by the arms. If such is the case, the position of the first weld relative to the loop is very important. No electrical means being available for measuring this current, the alternative adopted was to test its effect. The procedure used will be described later.

Any attempt to analyse the heat distribution or its effect will be even more complex. The only possible heat effect other than that caused by the making of the weld itself would be that due to the temperature gradient, set up in the metal by the making of a spot nearby. Whether or not this is sufficient to make any difference in the strength of the weld is difficult or impossible to say. If there is any such effect, not only the spacing, but the thickness of the metal would be a very significant factor.

In analysing the problem or interpreting any data concerning it, it is important to remember that spacing is but one of several variables that affects the physical characteristics of a weld. For a definite spacing of the welds, there are several variables which can affect it, principal among them being the thickness of the plates, the current (or heat), pressure, time, electrodes, etc. It would be well then to study the effects of these other variables and also the methods used for controlling them.

The heat is varied by means of a heat regulator on the machine, a device consisting of a switch arranged to select taps on the primary coil of the transformer to be selected that will give the desired amount of current in the secondary coil. The pressure is adjusted by changing the compression of a spring in machines fitted with springs, and on air and hydraulic machines by means of a reducing valve. Timing can be controlled manually, but to control it with any degree of accuracy at all, electrical control equipment is necessary. The thickness of the metal is decided by the job at hand. Electrodes are generally interchangeable and can be of whatever shape and material is desired.

Figure 2 will aid in understanding some of the effects of changing these variables. The curve in figure 2 represents the thermal gradient at the instant the current is applied to the spot, just at the beginning of the weld. It shows that the maximum heat is developed at the point where the surfaces are in contact. This is, of course, what is to be desired. The amount of heat, and likewise the shape of the thermal gradient depends on the current flowing and on the resistance of the contact areas. The current can be controlled by the heat regulator, but the contact resistance depends on several factors, including the condition of the surfaces, the conductivity of the material, the size, shape material and surface condition of the electrodes, and the pressure on the surfaces in contact. It must not be forgotten here that we are discussing the thermal gradient which represents an INSTANTANEOUS condition and therefore time is not a factor. For any given problem in spot welding, all these can be varied to get the best results except the material to be welded, and possibly the surface condition of the material.

The curve shown represents the gradient for metals having a resitance several times that of copper. As the resistance of the material decreases, the peaks at B increase, and in the case of copper they are equal to the peak at C. If a weld was attempted under these conditions, the electrodes would be welded to the sheets. On the other hand, if the resistance is considerably greater than that of copper, too much heat is developed at C, the contact surface. This can be remedied easily by adjusting the heat regulator to a lower heat point, thereby reducing the voltage drop across the two pieces of metal. For a given material the resistance depends on the pressure as well as the surface at the contact area. Increased pressure results in decreased resistance, thereby requiring a greater current to produce the same heat in a given period of time. Decreasing the pressure so as to increase the resistance (and therefore the heat generated at the contact area) does not give good results. Moreover a definite minimum pressure is necessary to force the pieces together after fusion has taken place. Some metals possess a rather wide range of values of pressure that give suitable results. With alloys, this range is generally much narrower. For all cases, however, there is an optimum value.

Proper timing is of paramount importance in making a good weld. Referring back to the thermal gradient curve, which represents an instantaneous condition, the peaks disappear as the current continues to flow and and fusion occurs at C. The surfaces at B soften, causing fuller contact also. Besides, the electrodes and surrounding metal being cooler, permit greater dissipation of heat and accelerate the disappearance of the peaks. Since all this depends on the current dwell, or in simpler terms, the time, the degree of penetration is therefore dependent on the time.

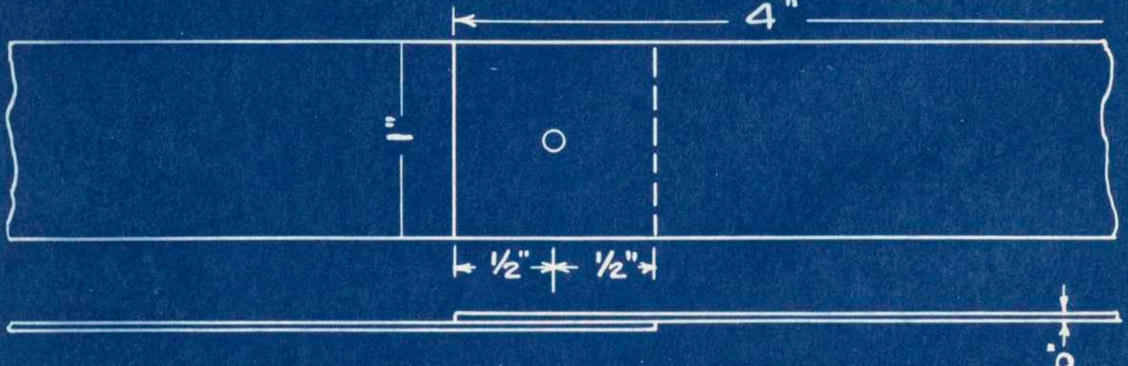
It is important then that all due care be taken in both selecting and controlling the proper values of the many variables.

III
METHOD AND PROCEDURE

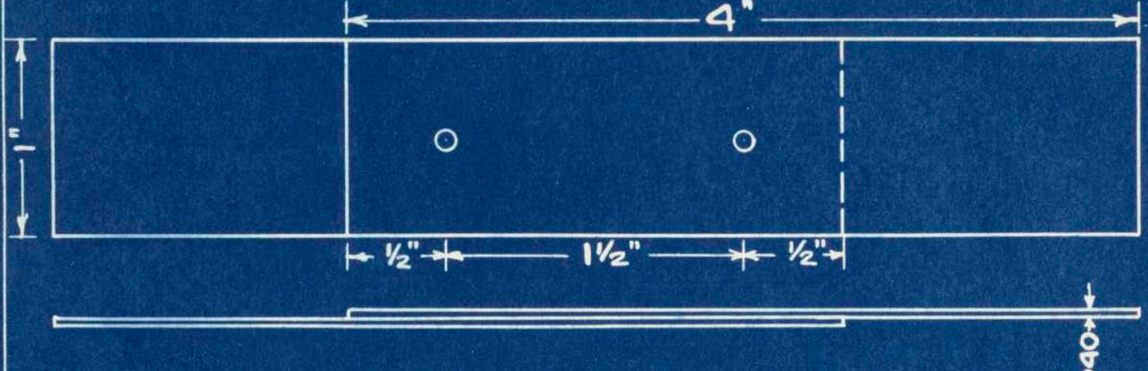
The procedure followed in conducing the experimental work was simple. Over seven hundred specimens similar to that shown in figure 4 were made and tested, involving different conditions of welding. For each test specimen, two strips of 18 - 8 stainless steel, each 4 inches by 1 inch by 0.040 inch thick were welded together by a Thomson-Gibb Spot Welder of the following characteristics:

Primary Volts	220	
Primary Amperes	182	
K.V.A.	40	R.W.M.A. Standards
Cycles	60	

Different adjustments of the variables were easily obtained, but not to any degree of refinement. The pressure between the electrodes was varied simply by turning a valve in the air line, and its magnitude was obtained by inserting between the electrodes a home-made pressure measuring device and then closing the electrodes. The pressures recorded on the data sheets may be in error as much as 10 or 15 pounds, for two reasons. One was the precision of the pressure-measuring device and the other was the fact that after



TEST PIECE CONTAINING
SINGLE WELD



TEST PIECE CONTAINING
TWO WELDS SPACED 1½" APART

TYPICAL TEST PIECES

FIG 4

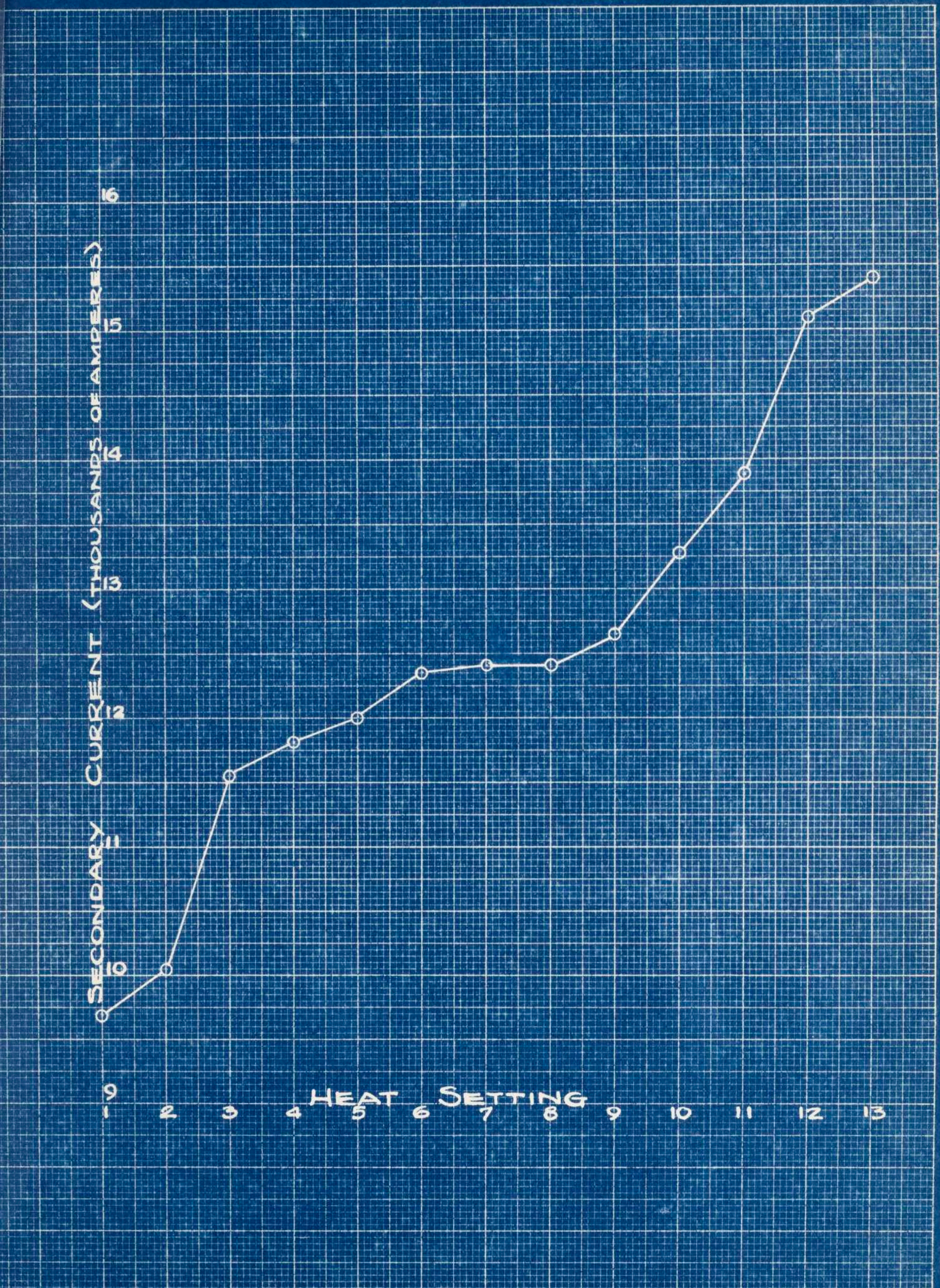
the electrodes were brought together the pressure continued to build up slowly for a few seconds.

Timing was varied by selecting with a dial points that gave the desired number of cycles. Previous to the tests, the location of these points had been established with the aid of a stroboscope. Originally it had been intended to make the welds using timings of $\frac{1}{2}$ cycle, 1, 2, and 3 cycles. Preliminary investigation and the experience of otheres soon prompted the decision to drop the idea of using $\frac{1}{2}$ cycle. Too erratic welds resulted from using $\frac{1}{2}$ cycle. The time was varied in steps of complete cycles because a part cycle would severely saturate the transformer and would also produce erratic welds. The timing element on the machine was arranged so that the current was switched on and off at exactly the proper position on the sine wave in order to get not only uniform but also optimum welds. It is very important that the switch is closed and opened at the proper time, especially when welding metal of high conductivity.

There was no direct-reading current meter on the machine. The current was varied by means of two handles arranged so that 16 different settings of the two were possible. These settings were "heat settings" and were essentially taps on the transformer, so that indirectly they were current-selectors. The accompanying graph illustrates the values of the current for the various heat settings of the machine, as calibrated by Mr. Goodman of the Department of Mechanical Engineering at Massachusetts Institute of Technology. Only the four lowest heat settings were used, because with a timing of 3 cycles, it was found that a higher setting produced a burned weld.

Two sets of test specimens were made. In the first, spacings of $\frac{1}{4}$ inch, $\frac{1}{2}$ inch and 1 inch were used, and in the second the spacings were the same with the addition of one other, $1\frac{1}{2}$ inches. In both sets, specimens were also made with but a single weld. Thus for every combination of pressure, timing and heat setting, there were specimens with a single weld, with two welds $\frac{1}{4}$ inch apart, two welds $\frac{1}{2}$ inch apart, and two welds 1 inch apart. In addition, for some combinations there were specimens with two welds $1\frac{1}{2}$ inches apart. Not less than three test pieces were made for each combination of pressure, timing, heat setting, and spacing. In all,there were about two hundred combinations.

As will be explained later, it was found advisable in the second set of tests to eliminate the 3-cycle

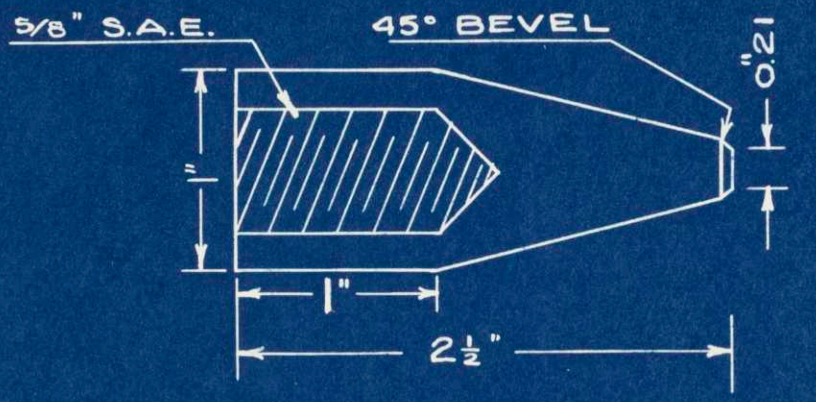


Secondary Current (Thousands of Amperes)
16
15
14
13
12
11
10
9
Heat Setting
1
2
3
4
5
6
7
8
9
10
11
12
13

welds and to add a fifth heat setting to the 1-cycle weld tests.

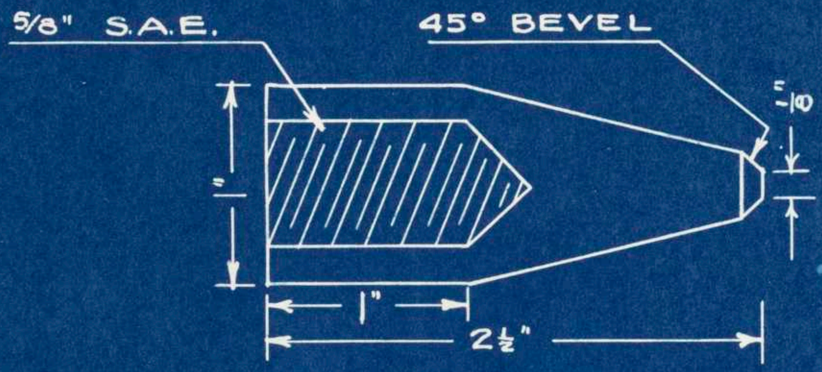
In making the welds, selections of the values of the variables such as pressure, timing, heat setting, and type and shape of electrodes were based chiefly on general practice and on information gained from the experience of other investigators. An excerpt from an article on spot welding sums up admirably what the general character of some of these variables should be. The best weld, it states, is one of "minimum diameter produced between well pointed electrodes transmitting a high current density during a minimum current dwell."

Where two welds were made in a test piece, the first of the two was drilled out. An ordinary drill was incapable of drilling out the spots satisfactorily, because of the high hardness of stainless steel. Punching out the spots was tried but likewise proved unsatisfactory. Finally it was found that with the aid of turpentine, a high-speed drill would do the job. A hole, approximately 0."19 in diameter, was drilled, completely eliminating the weld. The first few specimens tested were pulled in a wire pulling machine, but the set up was not very satisfactory and the time involved was too long. The remaining pieces were all pulled in a hydraulic testing machine (Southwark-Emery, 60000 lbs capacity).



CU-CO-BE ELECTRODES USED IN FIRST SET OF TESTS

FIG 5



CU-CO-BE ELECTRODES USED IN SECOND SET OF TESTS

FIG 6

The pieces were inserted in the jaws and pulled apart. The resulting stress was partly tension and partly shear. Due to either improper alignment or grip, some torsion was introduced in some of the pieces. Consideration was given to the idea of using straps so that the stress would be entirely shear, but it was decided that neither the accuracy nor the value of the results would be enhanced by doing so, since the purpose of the tests was to find the RELATIVE effect of spacing. Moreover the use of straps would only introduce needless complications.

Commenting on the procedure, it might be said that it was rather long, and innumerable little difficulties presented themselves, but once these were overcome the routine was extremely simple. Since there were somewhat over seven hundred specimens to be tested, it was necessary to simplify the testing as much as possible.

IV

ANALYSIS AND DISCUSSION OF RESULTS

Before discussing the results obtained from the experimental work, it might be well to review briefly any previous work on the subject. Only two articles were found that discussed spacing of spot welds. One was very brief and treated it very vaguely, and the other was in Russian. A brief précis of the latter was available in English, however. The original was a paper entitled "Investigation on the Row Electric Spot Welds", written by a Russian, I. M. Erofeeff, and discussed the author's extensive investigation of the row effect. According to the resumé, factors affecting the tensile strength of the welds investigated were: (1) the thickness of the plates, (2) the diameters of the electrodes, (3) the steps of the transformer, (4) the distance between the center of the spot and the edge of the plate, and (5) the distance between the spots. The tests indicated that for best results it is important that the area of the spots be free from oxides; the period (time) should be as short as possible; the diameter of the electrodes should depend on the thickness of the plates, and the electrodes should be level and water cooled. The pressure on the electrodes during welding should not exceed a definite maximum at the spot. The distance between the center of the spot and the edge of the plate should be in direct proportion to the diameter of the electrode. X-Rays showed the presence of gas bubbles and cracks, the number and size of the latter being in a direct relation to the size of the gas bubbles. Erofeeff advanced the belief that both were caused by overheating the metal during welding. It might be of interest to add here that, while no X-Ray or microscopic study was made in the present investigation, a large percentage of the test pieces appeared to have blow holes, and many of them had cracks. They seemed to be the result of either too intense heat or too long a period of dwell, or a combination of both. Very few "blow-holes" appeared in the welds made with a timing of one cycle but in almost all the welds made with longer periods of dwell, the "blow holes" were present. Cracks large enough to be seen with the naked eye appeared in some of the welds made with longer periods and higher heats, but not with any degree of regularity.

Analysis of the data from the first group of tests was not very conclusive. It showed that a variation in spacing was accompanied by a variation in the strength of the welds, but a uniform variation in the former did not produce a uniform variation in the latter. In general it could be said that within the range investigated, the closer the spacing was, then the weaker was the weld, but nothing more exact or definite could be said. The spots in specimens with a single weld were for the most part stronger than corresponding spots in specimens where two spots had been made, but there were a good many exceptions to this. Although the data showed a trend, it was not uniform enough to establish a typical graph indicating the characteristics of the trend.

The effect of variation in heat setting and in timing were much more pronounced according to the data. This was in line with results obtained in studies of such effects by other investigators. However, this was of secondary importance, the primary purpose of the thesis being to study the effect of spacing.

Three possible explanations for the nature of the results were considered. One was that the welds were unrepresentative or of varying quality due to the inexperience of the operator of the spot welder. A second was that insufficient care was taken in making the specimens and testing them. A third was that the effect of the spacing might be such that no more definite trend actually resulted; in other words that the somewhat erratic results presented the true picture.

It was decided that the experience already attained would aid in making a better set of tests, and that conducting such a set of tests would probably eliminate the first two explanations.

A few changes were effected in making the second set of specimens. Smaller tips were used on the electrodes. Literature read after beginning the first set of tests gave reason to believe that better results would be obtained with these smaller size electrodes. The original electrodes were simply machined down to the new size. In order to make the welds as uniform as possible, a pressure regulator was installed in the line, but this did not help much. Moreover it proved disadvantageous in that it lowered the maximum available pressure at the electrodes. It was intended to weld this second group of tests pieces with a pressure of 700 pounds, as the welds in the first group made at this pressure offered the best basis of comparison. With the pressure regulator in the line this pressure was not available however. In making the welds themselves, much greater care was taken, particularly in bringing the electrodes together on the work.

When the second set of specimens was made, the smaller tipped electrodes were used, and it was noticed that with a timing of three cycles, the welds, particularly those with the higher heat settings, were badly burned. A few were made and all were badly burned and it was decided to use only one cycle and two cycle timings, and to investigate another spacing, namely $1\frac{1}{2}$ inches. Although the few specimens made with three cycle welds were badly burned, they proved to be stronger than the others when tested.

The results of the second set were on the whole similar to those of the first. The additional care and precautions undertaken gave no more conclusive results. In making this second group, pieces that were welded under what seemed to be more favorable conditions than others were marked so that they might be compared with other pieces. When they were tested they were as frequently weaker as stronger than the other pieces.

Because of these results, other possible explanations were sought. Several were considered. When the two plates were pulled apart, they bent a little near the spot, causing tension as well as shear on the spot. The amount they bent depended on the pull required to break the spot. This bending usually left the plates free of contact with each other (except at the spot) except at low loads, when they were in contact for a small area in the vicinity of the spot. The drilled hole where the first spot had been was within this area in the cases where $\frac{1}{4}$" spacing was used, and it was possible that burr, resulting from drilling the hole, might have taken part of the load and thus given mis-leading data. It is entirely possible that this might also have occurred in some cases where $\frac{1}{2}$" spacing was used. No dependable check could be devised to see whether or not this was actually occurring. Any method of preventing its happening would have either introduced new forces or upset the ratio of tension to shear so that the results could not be compared with the rest of the data.

The distance of the spot from one jaw of the testing machine was in every case approximately the same, but the distance from the other jaw varied according to the spacing used. Theoretically this should have NO bearing on the breaking load, because the spot was always in the same straight line between the jaws.

Several possible explanations hinge on the size of the spot diameter. Other things being equal, a bigger spot will take a bigger load. This is of course obvious, but the size of the diameter also affects another important item, the relation between tension and shear. This depends on the angle the plate is bent, and this angle in turn depends on the spot diameter, d. (Sin $\alpha = \frac{T_1 + T_2}{d}$

where T_1 and T_2 are the plate thicknesses). With all the variables except spacing held constant, the diameter, d, should not change. Repeated use tends to "mushroom" the electrodes, though, and consequently increase the diameters of the spots produced. This might produce a few slight discrepencies in the data, but could not possibly account for the data obtained in the tests.

The fact that the electrodes are not perfectly flat and level also accounts for some of the discrepencies. Oval and irregular spots are produced as a result. It is not improbable that the condition of the electrodes had considerable to do with the results. As a matter of fact, one of the most irksome tasks of the testing was keeping the electrodes in proper condition, despite the fact that they were made of a hard material.

In certain cases the discrepencies could be blamed to twisting of the pieces while they were being tested. This was caused by improper grip or mis-alignment.

V
CONCLUSIONS

From the data recorded, a few brief inferences can be drawn. Inferences rather than conclusions would seem to be the word, because while the data indicates that these deductions are so, they do not seem to be reliable enough to establish them as absolute facts.

Within the limits observed in the tests, the results show that the effect of spacing is much less pronounced than the effect of some of the other variables, particularly heat (current) and time. This might be due to several reasons. For instance it might be that the range of spacings studied might be that portion of the range where spacing has the least effect. If spots of smaller diameter were made and spaced closer together, it might be that the effect would be more marked. On the other hand the variations in heat and timing were such that a marked (and uniform) variation in the results was to be expected.

The results show very definitely that when all the other variables except heat (hence, current) were held constant, then an increase in heat produced a stronger weld. Likewise, when all the variables except time were held constant then the weld with the longer period proved the stronger. However, the appearance of the welds made with a timing of one cycle was much better than that of those made with timings of two and three cycles. Although it was not investigated very completely because it was not part of the object of the thesis, indications were that a spot of shorter duration and higher heat was both stronger and far better in appearance than one of longer duration and lower heat, bearing out in part the contention that the best weld is one made with a high current density during a minimum period of dwell.

When all the variables except pressure were held constant, the result was not so pronounced. The difference in the strength of the welds was slight, being greater sometimes, less, sometimes when the pressure was increased. Increased pressure results in a decreased resistance, which necessitates an increased current or an increase in time to produce the same quality weld. The effect is not very marked, though.

When all the variables except spacing were held constant, the data would seem to indicate that the closer were the two spots, the weaker was the second spot. No definite relationship between variation in spacing and variation in strength could be established from the data, though. In general, the welds made in plates where another weld was nearby were not as strong as the welds made in plates having no other welds. A notable exception to this was in the case of the welds made with a pressure of 700 lbs. No suitable explanation could be found for this exception. A likely one is that it might have been due to the condition of the electrodes.

Speaking broadly, the effect of spacing does not seem to be very great. However, the author still thinks that a more thorough study with more refined equipment and methods would show that the strength varies more uniformly with the spacing than the results of the present investigation tend to show.

APPENDIX

Note: All pulls recorded are in pounds.

Pressure 400 lbs.

Single Weld

Time - one cycle			Time - two cycles			Time - three cycles		
Heat Setting	Pull	Average Pull	Heat Setting	Pull	Average Pull	Heat Setting	Pull	Average Pull
I	960		I	1205		I	1250	
I	910	895	I	1070	1132	I	1315	1282
I	815		I	1120		I	1280	
II	950		II	1240		II	1685	
II	1105	950	II	1320	1235	II	1465	1485
						II	1450	
II	795		II	1145		II	1340	
III	850		III	1130		III	1430	
III	1040	953	III	1085	1112	III	1530	1475
			III	1095				
III	970		III	1140		III	1465	
IV	885		IV	1490		IV	1555	
			IV	1225				
IV	1100	948	IV	1310	1316	IV	1495	1488
IV	860		IV	1240		IV	1415	

Pressure 400 lbs.

Spacing 1 inch

Time - one cycle			Time - two cycles			Time - three cycles		
Heat Setting	Pull	Average Pull	Heat Setting	Pull	Average Pull	Heat Setting	Pull	Average Pull
I	640		I	970		I	1175	
I	620	630	I	980	1013	I	1280	1228
I	-		I	1090		I	1230	
II	890		II	1350		II	1325	
II	670	780	II	1130	1180	II	1435	1395
II	-		II	1060		II	1425	
III	790		III	1240		III	1455	
III	750	770	III	1200	1222	III	1445	1450
III	-		III	1225		III	--	
IV	750		IV	1270		IV	1515	
IV	895	822	IV	1310	1330	IV	1345	1535
IV	-		IV	1410		IV	1555	

Pressure 400 lbs.

Spacing ½ inch

Time - one cycle			Time - two cycles			Time - three cycles		
Heat Setting	Pull	Average Pull	Heat Setting	Pull	Average Pull	Heat Setting	Pull	Average Pull
I	770		I	1240		I	1440	
I	730	722	I	1050	1127	I	1225	1405
I	665		I	1090		I	1550	
II	835		II	1430		II	1375	
II	725	767	II	1335	1385	II	1320	1340
II	740		II	1400		II	1325	
III	815		III	1300		III	1390	
III	885	870	III	1120	1190	III	1375	1402
III	910		III	1150		III	1440	
IV	930		IV	1275		IV	1495	
IV	990	947	IV	1330	1272	IV	1535	1525
IV	920		IV	1210		IV	--	

Pressure 400 lbs.

Spacing ¼ inch

Time - one cycle			Time - two cycles			Time - three cycles		
Heat Setting	Pull	Average Pull	Heat Setting	Pull	Average Pull	Heat Setting	Pull	Average Pull
I	665		I	925		I	1320	
I	710	690	I	920	920	I	1240	1280
I	695		I	-		I	1010	
II	765		II	1085		II	1225	
II	795	748	II	1075	1080	II	1325	1312
II	685		II	--		II	1310	
III	770		III	1200		III	1420	
III	775	770	III	1085	1137	III	1310	1365
III	-		III	1125		III	1260	
IV	840		IV	1120		IV	1400	
IV	940	853	IV	1150	1135	IV	1570	1485
						IV	1270	
IV	780		IV	1055		IV	1390	

Pressure 500 lbs.

Single Weld

Time - one cycle			Time - two cycles			Time - three cycles		
Heat Setting	Pull	Average Pull	Heat Setting	Pull	Average Pull	Heat Setting	Pull	Average Pull
I	890		I	1330		I	1495	
I	780	858	I	1140	1242	I	1340	1380
I	905		I	1255		I	1305	
II	890		II	1640		II	1475	
II	1020	940	II	1620	1630	II	1345	1440
II	910		II	--		II	1500	
III	1220		III	1370		III	1360	
III	1090	1150	III	1260	1327	III	1485	1538
III	1140		III	1350		III	1770	
IV	1000		IV	1535		IV	1540	
IV	1090	990	IV	1505	1500	IV	1665	1542
IV	880		IV	1460		IV	1420	

Pressure 500 lbs.

Spacing 1 inch

Time - one cycle			Time - two cycles			Time - three cycles		
Heat Setting	Pull	Average Pull	Heat Setting	Pull	Average Pull	Heat Setting	Pull	Average Pull
I	685		I	1230		I	1185	
I	820	758	I	1220	1225	I	1330	1320
I	770		I	--		I	1310	
II	960		II	1385		II	1440	
II	850	877	II	1385	1385	II	1370	1403
II	820		II	--		II	1400	
III	940		III	1445		III	1375	
III	880	917	III	1220	1440	III	1640	1468
III	930		III	1440		III	1390	
IV	1115		IV	1520		IV	1510	
IV	1215	1165	IV	1380	1520	IV	1420	1498
IV	855		IV	1515		IV	1565	

Pressure 500 lbs.

Spacing ½ inch

Time - one cycle			Time - two cycles			Time - three cycles		
Heat Setting	Pull	Average Pull	Heat Setting	Pull	Average Pull	Heat Setting	Pull	Average Pull
I	835		I	1195		I	1505	
I	810	808	I	1265	1248	I	1450	1472
I	780		I	1285		I	1460	
II	850		II	1325		II	1500	
II	875	897	II	1285	1327	II	1510	1505
II	965		II	1370		II	--	
III	1010		III	1385		III	1520	
III	940	997	III	1385	1385	III	1655	1608
III	1040		III	--		III	1650	
IV	1035		IV	1385		IV	1815	
IV	1020	1020	IV	1320	1382	IV	1555	1740
IV	1005		IV	1440		IV	1850	

Pressure 500 lbs.

Spacing $\frac{1}{4}$ inch

Time - one cycle			Time - two cycles			Time - three cycles		
Heat Setting	Pull	Average Pull	Heat Setting	Pull	Average Pull	Heat Setting	Pull	Average Pull
I	725		I	925		I	1075	
I	730	730	I	905	938	I	1205	1205
						I	1375	
I	-		I	985		I	1240	
II	875		II	1140		II	1490	
II	890	882	II	1190	1125	II	1330	1447
II	-		II	1085		II	1520	
III	855		III	1260		III	1260	
III	850	898	III	1240	1250	III	1200	1273
III	940		III	--		III	1360	
IV	930		IV	1320		IV	1500	
IV	920	925	IV	1330	1325	IV	1365	1480
IV	800		IV	--		IV	1460	

Pressure 600 lbs.

Single Weld

Time - one cycle			Time - two cycles			Time - three cycles		
Heat Setting	Pull	Average Pull	Heat Setting	Pull	Average Pull	Heat Setting	Pull	Average Pull
I	895		I	1420		I	1645	
I	775	860	I	1400	1410	I	1750	1657
I	910		I	--		I	1575	
II	1055		II	1520		II	1730	
II	990	1035	II	1560	1540	II	1695	1758
II	1060		II	1330		II	1850	
III	1080		III	1630		III	1870	
III	1140	1100	III	1600	1615	III	1740	1787
III	1080		III	1515		III	1750	
IV	1165		IV	1700		IV	1785	
IV	1240	1205	IV	1765	1710	IV	1680	1788
IV	1210		IV	1665		IV	1900	

Pressure 600 lbs.

Spacing 1 inch

Time - one cycle			Time - two cycles			Time - three cycles		
Heat Setting	Pull	Average Pull	Heat Setting	Pull	Average Pull	Heat Setting	Pull	Average Pull
I	500		I	1160		I	1485	
I	-	500	I	1100	1130	I	1495	1490
I	-		I	--		I	--	
II	820		II	1320		II	1490	
II	860	840	II	1265	1322	II	1560	1520
II	-		II	1380		II	1510	
III	980		III	1505		III	1580	
III	1020	993	III	1480	1468	III	1785	1698
III	980		III	1420		III	1730	
IV	1140		IV	1490		IV	1740	
IV	1150	1145	IV	1555	1512	IV	1740	1740
IV	--		IV	1490		IV	--	

Pressure 600 lbs.

Spacing ½ inch

Time - one cycle			Time - two cycles			Time - three cycles		
Heat Setting	Pull	Average Pull	Heat Setting	Pull	Average Pull	Heat Setting	Pull	Average Pull
I	775		I	1105		I	1535	
I	775	775	I	1125	1115	I	1610	1492
I	-		I	--		I	1330	
II	915		II	1310		II	1665	
II	930	923	II	1320	1315	II	1360	1535
II	935		II	--		II	1580	
III	950		III	1465		III	1580	
III	960	955	III	1420	1428	III	1655	1658
III	-		III	1400		III	1740	
IV	915		IV	1505		IV	1700	
IV	1045	1002	IV	1435	1485	IV	1700	1705
IV	1045		IV	1515		IV	--	

Pressure 600 lbs.

Spacing $\frac{1}{4}$ inch

Time - one cycle			Time - two cycles			Time - three cycles		
Heat Setting	Pull	Average Pull	Heat Setting	Pull	Average Pull	Heat Setting	Pull	Average Pull
I	680		I	1120		I	1210	
I	820	740	I	1090	1115	I	1370	1273
I	720		I	1135		I	1240	
II	875		II	1210		II	1210	
II	780	812	II	1255	1233	II	1490	1432
II	780		II	1030		II	1595	
III	905		III	1320		III	1495	
III	890	898	III	1355	1328	III	1440	1457
III	-		III	1310		III	1435	
IV	935		IV	1140		IV	1600	
IV	1000	958	IV	1250	1285	IV	1500	1527
IV	940		IV	1320		IV	1480	

Pressure 700 lbs.

Single Weld

Time - one cycle			Time - two cycles			Time - three cycles		
Heat Setting	Pull	Average Pull	Heat Setting	Pull	Average Pull	Heat Setting	Pull	Average Pull
I	775		I	1240		I	1335	
I	775	775	I	1215	1212	I	1370	1375
I	-		I	1180		I	1320	
II	850		II	1015		II	1420	
II	800	837	II	1015	1055	II	1395	1432
II	860		II	1135		II	1480	
III	900		III	1645		III	1470	
III	955	927	III	1570	1607	III	1390	1423
III	825		III	1605		III	1420	
IV	890		IV	1250		IV	1390	
IV	1010	958	IV	1220	1237	IV	1485	1455
IV	975		IV	1240		IV	1490	

Pressure 700 lbs.

Spacing 1 inch

Time - one cycle			Time - two cycles			Time - three cycles		
Heat Setting	Pull	Average Pull	Heat Setting	Pull	Average Pull	Heat Setting	Pull	Average Pull
I	840		I	1320		I	1675	
I	780	800	I	1320	1320	I	1555	1607
I	780		I	--		I	1590	
II	880		II	1440		II	1660	
			II	1350	1361			
II	960	920	II	1340		II	1635	1677
II	920		II	1315		II	1735	
III	990		III	1500		III	1835	
III	1020	1005	III	1455	1473	III	1775	1775
III	--		III	1465		III	1715	
IV	1115		IV	1540		IV	1930	
IV	1040	1077	IV	1635	1562	IV	1800	1835
IV	1075		IV	1510		IV	1775	

Pressure 700 lbs.

Spacing ½ inch

Time - one cycle			Time - two cycles			Time - three cycles		
Heat Setting	Pull	Average Pull	Heat Setting	Pull	Average Pull	Heat Setting	Pull	Average Pull
I	670		I	1235		I	1465	
I	730	710	I	1240	1235	I	1560	1528
I	730		I	--		I	1560	
II	840		II	1240		II	1545	
II	915	888	II	1320	1312	II	1595	1605
II	910		II	1375		II	1675	
III	920		III	1425		III	1640	
III	1000	943	III	1380	1387	III	1660	1650
III	910		III	1355		III	--	
IV	1125		IV	1520		IV	1695	
IV	1080	1075	IV	1440	1483	IV	1815	1797
IV	1020		IV	1490		IV	1680	

Pressure 700 lbs.

Spacing ¼ inch

Time - one cycle			Time - two cycles			Time - three cycles		
Heat Setting	Pull	Average Pull	Heat Setting	Pull	Average Pull	Heat Setting	Pull	Average Pull
I	575		I	1100		I	1490	
I	525	613	I	1100	1100	I	1435	1445
I	740		I	--		I	1410	
II	880		II	1165		II	1420	
II	680	780	II	970	1153	II	1450	1448
II	780		II	1140		II	1475	
III	865		III	1360		III	1530	
III	720	827	III	1250	1285	III	1645	1580
III	895		III	1245		III	1565	
IV	650		IV	1160		IV	1660	
IV	970	980	IV	1325	1350	IV	1655	1660
IV	990		IV	1375		IV	--	

Pressure 400'

Single Weld

Time - one cycle

Heat Setting	Pull	Average Pull
I	700	
I	670	673
I	650	
II	750	
II	720	766
II	775	
II	820	
III	940	
III	845	858
III	790	
IV	830	
IV	980	890
IV	860	
V	1060	
V	975	958
V	840	

Time - two cycles

Heat Setting	Pull	Average Pull
I	1100	
I	1265	1162
I	1120	
II	1165	
II	1245	1143
II	1020	
III	1075	
III	865	987
III	1020	
IV	1315	
IV	1275	1238
IV	1125	

Pressure 400'

Spacing $1\frac{1}{2}$ inch

Time - one cycle			Time - two cycles		
Heat Setting	Pull	Average Pull	Heat Setting	Pull	Average Pull
I	635		I	1110	
I	665	680	I	1095	1103
I	740		I	--	
II	910		II	1020	
II	855	862	II	1120	1140
II	820		II	1280	
III	820		III	1100	
III	890	853	III	1130	1140
III	850		III	1190	
IV	935		IV	1570	
IV	815	862	IV	1165	1317
IV	835		IV	1215	
V	1075				
V	1200	1060			
V	905				

Pressure 400'

Spacing 1 inch

Time - one cycle			Time - two cycles		
Heat Setting	Pull	Average Pull	Heat Setting	Pull	Average Pull
I	660		I	990	
I	670	685	I	1070	1007
I	725		I	960	
II	760		II	1050	
II	775	745	II	1020	1057
II	700		II	1100	
III	820		III	1155	
III	880	858	III	1360	1287
III	875		III	1345	
IV	900		IV	1220	
IV	890	857	IV	1320	1300
IV	780		IV	1360	
V	915				
V	855	930			
V	1020				

Pressure 400'

Spacing ½ inch

Time - one cycle			Time - two cycles		
Heat Setting	Pull	Average Pull	Heat Setting	Pull	Average Pull
I	775		I	1175	
I	700	740	I	1140	1145
I	745		I	1120	
II	1200		II	1020	
II	740	798	II	1145	1052
II	855		II	990	
III	860		III	1160	
III	915	865	III	1130	1135
III	820		III	1115	
IV	860		IV	1205	
IV	1030	977	IV	1165	1150
IV	1040		IV	1080	
V	930				
V	995	1020			
V	1135				

Pressure 400'

Spacing $\frac{1}{4}$ inch

Time - one cycle

Heat Setting	Pull	Average Pull	Heat Setting	Pull	Average Pull
I	555		I	1000	
I	595	568	I	965	977
I	555		I	965	
II	700		II	995	
II	670	693	II	1010	977
II	710		II	985	
III	835		III	1140	
III	835	835	III	1115	1130
III	835		III	1135	
IV	945		IV	1165	
IV	855	922	IV	1185	1190
IV	965		IV	1220	
V	850				
V	960	903			
V	900				

SUMMARY OF TEST VALUES

Average Pulls

Time - one cycle

Pressure	Spacing	Heat Settings I	II	III	IV	V
400 #	Single	895	950	953	948	
	1 inch	630	780	770	822	
	½ inch	722	767	870	947	
	¼ inch	690	748	770	853	
500 #	Single	858	940	1150	990	
	1 inch	758	877	917	1165	
	½ inch	808	897	997	1020	
	¼ inch	730	882	898	925	
600 #	Single	860	1035	1100	1205	
	1 inch	500	840	993	1145	
	½ inch	775	923	955	1002	
	¼ inch	740	812	898	958	
700 #	Single	775	837	927	958	
	1 inch	800	920	1005	1077	
	½ inch	710	888	943	1075	
	¼ inch	613	780	827	980	
400 # (2nd set)	Single	673	766	858	890	958
	1½ inch	680	862	853	862	1060
	1 inch	685	745	858	857	930
	½ inch	740	798	865	977	1020
	¼ inch	568	693	835	922	903

SUMMARY OF TEST VALUES

Average Pulls

Time - two cycles

Pressure	Spacing	Heat Settings I	II	III	IV
400#	Single	1132	1235	1112	1316
	1 inch	1013	1180	1222	1330
	½ inch	1127	1385	1190	1272
	¼ inch	920	1080	1137	1135
500#	Single	1242	1630	1327	1500
	1 inch	1225	1385	1440	1520
	½ inch	1248	1327	1385	1382
	¼ inch	938	1125	1250	1325
600#	Single	1410	1540	1615	1710
	1 inch	1130	1322	1468	1512
	½ inch	1115	1315	1428	1485
	¼ inch	1115	1233	1328	1285
700#	Single	1212	1055	1607	1237
	1 inch	1320	1361	1473	1562
	½ inch	1235	1312	1387	1483
	¼ inch	1100	1153	1285	1350
400# (2nd set)	Single	1162	1143	987	1238
	1½ inch	1103	1140	1140	1317
	1 inch	1007	1057	1287	1300
	½ inch	1145	1052	1135	1150
	¼ inch	977	997	1130	1190

SUMMARY OF TEST VALUES

Average Pulls

Time - three cycles

Pressure	Spacing	Heat Settings I	II	III	IV
400#	Single	1282	1485	1475	1488
	1 inch	1228	1395	1450	1535
	½ inch	1405	1340	1402	1525
	¼ inch	1280	1312	1365	1485
500#	Single	1380	1440	1538	1542
	1 inch	1320	1403	1468	1498
	½ inch	1472	1505	1608	1740
	¼ inch	1205	1447	1273	1480
600#	Single	1657	1758	1787	1788
	1 inch	1490	1520	1698	1740
	½ inch	1492	1535	1658	1705
	¼ inch	1273	1432	1457	1527
700#	Single	1375	1432	1423	1455
	1 inch	1607	1677	1775	1835
	½ inch	1528	1605	1650	1797
	¼ inch	1445	1448	1580	1660

BIBLIOGRAPHY

1. Hall, G.H. "Resistance Welds Widely Used" - Electrical World, Jan. 18, 1936 p. 32.

2. Frost, L.H. "Resistance Welding" The Welding Engineer, Jan. 1936 p. 44 Feb. 1936 p. 38; Mar. 1936 p. 32.

3. Hobrock, R.H. "Some Fundamentals of Spot Welding, Especially of the Light Alloys" Metals and Alloys, Jan. 1935 p. 19, Feb. 1935 p. 41; Mar. 1935 p. 67.

4. Erofeeff, I.M. "Investigation on the Row Electric Spot Welds" Autogennoie Delo, No. 9, 1934 p. 15. Abstracted in Metals and Alloys, April 1935, p. 150.

5. Dussourd, "Contribution to the Study of Mechanical Properties of Electric Spot Welds" Bulletin de la Societe des Ingenieurs Soudeurs Vol. 5. Aug. - Oct. 1934, p. 1391-1419. Abstracted in Metals and Alloys, April 1935 p. 150.

6. Ronay, "Outline of Resistance Welding and its Uses" American Society of Naval Engineers Journal - Feb. 1935 p. 27.

7. Briggs, "Size and Spacing of Spot Welds" American Welding Society Journal, Nov. 1934, p. 25.

8. Perry, "An Investigation of the Electrical Characteristics of Short-Time Spot Welding" M.S. Thesis, M.I.T. 1935.

9. Jones, "A Study of Electrode Deterioration in Spot Welding Thin Stainless Steel" Thesis, M.I.T. 1935.

10. White, "Spot Welding Technique on '18 - 8' Stainless Steel Sheet" Thesis, M.I.T. 1934.

11. Zimmerman, "Spot Welding Problems" American Welding Society Journal, Dec. 1935 p. 20.

12. Stansbury, "Precision Spot Welding with Tube Controlled Contactors" American Weld Society Journal Dec. 1933, p.17.

13. Wright, "Timing of Spot Welders with Respect to Current Flow" American Welding Society Journal Dec. 1933 p. 13.

14. Larsen, "Fundamentals of Spot Welding with Particular Reference to Electrode Life" American Welding Society Journal, April 1936, p. 25.