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A METHOD FOR WELDING SHEET ALUMINUM TO SAE 4140 STEEL

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ADVANCE RESTRICTED REPORT

A METHOD FOR WELDING SHEET ALUMINUM TO SAE 4140 STEEL

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SUMMARY

This investigation involves a study of a large variety of different metals used as an intermediate metal between aluminum and steel for the purpose of securing a good bond both from the viewpoint of strength and thermal conductivity.

The principal result of this investigation was that it was found possible to secure a satisfactory bond between aluminum and steel by electroplating the steel with a layer of silver of proper thickness. The welding equipment was then used to make a proper bond between the aluminum and the silver plating. In order to effect this bond it was found desirable to secure a heat balance by means of a high resistance insert between the electrode and the aluminum. A very important part of the problem which was properly solved by the method just mentioned was the effect of the welding operation upon the properties of the steel. The steel used in aircraft cylinder barrels, being of a very hardenable variety, would be damaged severely in its physical properties if it were necessary to make the bond between the aluminum and the steel at a temperature above the austenitizing temperature of the steel.

Another important part of the investigation includes the study of the best possible electroplating technique for securing bonds of maximum strength between the plated metal and the steel. Electroplating procedures were very carefully studied and optimum conditions developed for the plating of bonds of maximum strength upon steel. The results of this phase of the investigation may be of value in other problems. It should also be pointed out that the method of joining aluminum to steel herein developed, should be of importance to the solution of any problem involving the welding of aluminum to steel where strength is the primary consideration, whether or not thermal conductivity is important.

INTRODUCTION

The possibility of increasing the horsepower output of aircraft engines by improving the cylinder cooling, has raised the problem of welding fins of material of high thermal conductivity to steel cylinders for aircraft engines. The specific problem herein studied involves the welding of half-hard 3S aluminum fins to SAE 4140 steel cylinders.

The problem involved in this investigation involves not only the bonding of aluminum to steel but also the problem of making this bond at a temperature sufficiently low to avoid damage to the heat-treated steel. The natural tendency of aluminum and steel is to form very brittle compounds when fused together. If, during the making of the bond between aluminum and SAE 4140 steel, the temperature goes above the austenitizing temperature of the steel, the rapid quench following the welding operation will result in extremely hard and brittle structures in the SAE 4140 steel. Thus, the problem was complicated by two sources of embrittlement, the formation of iron-aluminum compounds and the formation of a martensitic structure in the steel.

Early experiments by other investigators and confirmed in this laboratory, showed that the seam welding of aluminum fins directly to SAE 4140 steel cylinder barrels was unsuccessful because of the difficulties mentioned above.

In order to overcome the difficulty of welding aluminum directly to steel, the idea of using a third metal between the aluminum and steel was investigated. It was hoped that a third metal would be found which would alloy sufficiently with steel and aluminum to permit the production of a strong bond between them but would prevent the combination directly of aluminum and steel which would result in the formation of brittle compounds. In a recent group of experiments (reference 1) the insertion of a third metal in the form of a foil between the aluminum and the steel was tried in the effort to prevent the formation of objectionable iron-aluminum compounds. It was found that with certain metals such as silver, more ductile welds were obtained, but that the conditions for obtaining such a bond were very critical, owing to the difficulty of simultaneously welding aluminum to foil and foil to steel. In order to overcome this difficulty, it appeared necessary to completely absorb the foil in the aluminum. To accomplish this it was necessary to heat the aluminum above its melting point for so long a time that it was almost impossible to avoid melting the aluminum through to the outside surface. This result pointed to the necessity for using thinner and thinner foil, which became difficult to handle.

The difficulty of bonding aluminum to foil and simultaneously, foil to steel, indicated the desirability of obtaining one of the bonds outside of the welding machine. Since some companies were already making aluminum coated steel, it was decided to try welding aluminum fins to aluminum coated steel. It proved to be a simple matter to weld the aluminum fin material to the aluminum coated steel. However, the strength of the bond between the coating and the steel was so low that the fin material pulled the coating away from the steel in a brittle manner. As a result of the experiences described above, it was decided to undertake the present investigation based on the experience gained in the previous tests, namely that a third metal is necessary for the proper bonding of aluminum to steel, and to make use of electroplating as a method of bonding the third metal to the steel surface in preparation for subsequent welding of the aluminum fins to this surface.

For the sake of simplicity this investigation was divided into three parts. The first of these was the general problem of bonding aluminum to steel through the use of an intermediate electro-deposited metal. The next part of the problem involved the study of the possibility of making a bond at a temperature below the austenitizing temperature of the cylinder barrel steel. If this were possible, the bonding process could be accomplished without metallurgical damage to the steel. The third phase of the problem was considered to be the development of a laboratory setup by which an actual cylinder barrel could be covered with fins bonded in accordance with the principles and practices developed in this investigation.

The report has been divided in two sections: the first discussing the bonding of aluminum to steel, and the second, the welding of aluminum to chrome-molybdenum steel which includes both the avoidance of hardening and the seam welding problems.

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ANALYSIS AND DISCUSSION OF PROBLEM

I. BONDING OF ALUMINUM TO STEEL

Metallurgical Considerations

Interference of the oxide. - Due to its high heat of oxide formation, aluminum oxide is always present to a greater or less thickness on the surface of aluminum. This oxide would tend to prevent the alloying action of aluminum with iron and would produce oxide inclusions in the weld. If the steel were heated in air to the melting temperature of aluminum, the surface of the steel would become oxidized. This oxide would cling to the steel and would be difficult to flux and float off as the steel would remain solid during the welding operation. This oxide would thus prevent complete and satisfactory alloying and as a result a bond which has low strength and low thermal conductivity would be produced. In order to prevent oxide formation on the steel, a process such as seam or spot welding must be used. A process such as this, however, demands materials of consistent electrical surface contact resistance, and thus the nature and thickness of the aluminum-oxide film must be carefully controlled.

The nature of the alloys of iron and aluminum. - If the oxide on the surface of the aluminum is adequately absorbed in the molten mass of aluminum during the welding operation, aluminum will alloy with the surface layers of the solid iron. Owing to the fact that the diffusion of aluminum into solid iron is relatively slow compared with the diffusion of iron into molten aluminum, a large amount of high aluminum, low iron alloy will be formed compared to the amount of low aluminum, high iron alloy. According to the iron-aluminum equilibrium diagram (see fig. 1, also reference 2), this will result in a large amount of compound formation as the high aluminum, low iron alloys contain the compounds $FeAl_3$, $FeAl_2$, and Fe_2Al_3. Since these compounds are brittle in character, the resulting welds are likely to be brittle. Actual tensile testing of the welds, however, is the only practical way of evaluating this brittleness. As only small amounts of aluminum diffuse into the steel and since the aluminum is soluble in the alpha solid solution up to 33-percent aluminum, there is likely to be little danger of brittle alloy formation in this region during the welding operation. However, when the cylinder is placed in operation, the ordered lattice Fe_3Al, may form. The effect of this formation would be to strengthen the metal and decrease its ductility, but as far as this influence is concerned, it will be negligible compared with the effect of the brittle phase formations occurring in the high aluminum alloys.

<u>The need for a third metal</u>. - As the difficulty with brittleness occurs in the aluminum-steel welds, the introduction of a third metal between the iron and aluminum may be utilized to eliminate this difficulty. Various types of alloy may be tried. These types may be classified as mutually soluble in iron and aluminum, soluble in either iron or aluminum, and insoluble in iron and aluminum. The solubility of two component alloys may be determined from the binary diagrams appearing in Hansen (reference 2), while the ternary alloys on the whole have not been investigated but may be estimated by considering the binary alloy diagrams. As solubility is influenced by temperature and phase changes and since the solubility at the welding temperature, that is, the melting point of aluminum is of greatest interest, the third metal will be classified as to its solubility in the range of 1200° F as well as at room temperature.

<u>Tin</u>. - No third metal shows complete solubility in both iron and aluminum but tin is one of the closest approaches to this situation. Although tin and aluminum are completely insoluble in each other at room temperature, they are mutually soluble in the molten state, that is, at 1200° F. About 19-percent tin is soluble in alpha iron at 1200° F. This means that tin can diffuse into the iron and a good bonding action can be expected without any detrimental effects being produced. About 2-percent iron is soluble in tin at 1200° F while the structure from 2- to 19-percent iron consists of molten tin solution and solid $FeSn_2$. This means that when some of the iron diffuses into the molten tin and reaches the saturation limit, $FeSn_2$ will form at the iron-aluminum interface. This action will effectively prevent further iron diffusion into the molten tin but may produce a brittle weld. As the tin layer between the iron and aluminum is likely to be very thin, the iron and aluminum will both dissolve in the molten tin and will come in contact with each other. This may lead to the formation of an iron-aluminum compound and thus a brittle weld. However, if the thickness of the tin is sufficient and the diffusion rates slow enough, this action will not occur.

<u>Zinc</u>. - Zinc is similar to tin in many respects and, in general, the diagrams show about the same structural features. Zinc forms two compounds with iron. Both of these compounds are known to be brittle and thus a brittle weld would be expected.

While both tin and zinc are mutually soluble in iron and aluminum, they both tend to form brittle compounds and as a result the brittleness of a weld may be due to the formation of these compounds rather than the formation of an iron-aluminum compound in the mass of the tin or zinc. In view of this fact, a mutually soluble metal which is free from compound formation should be tried, but none exist and thus tin and zinc are typical possibilities.

Silver. - Silver is typical of alloys which are soluble in aluminum but not in iron, as is shown in the constitutional diagrams. (See figs. 2 and 3.) At 1200° F silver is completely insoluble in iron and vice versa. Also at this temperature, aluminum and silver alloys from 20- to 100-percent aluminum are in the molten state and completely soluble. On decreasing the aluminum content below 20 percent, the melting point of the alloys rapidly rises until the melting point of silver at 1761° F is reached. On welding these alloys, no alloying action would occur between the iron and silver, but the aluminum would be expected gradually to wash and diffuse silver into the molten aluminum. As the pure silver will remain solid during the welding, only small amounts of aluminum will be able to dissolve into the silver since the diffusion rate through a solid state is extremely slow. As a net result, if the welding time is extremely short and the silver layer reasonably thick, the aluminum will not completely dissolve the silver film nor reach the iron interface and thus there is no danger of the formation of a brittle iron-aluminum phase. This silver bond should have excellent thermal conductivity since silver is a good thermal conductor. The strength of the bond depends entirely upon the bond between the iron and silver. As the bonding strength between two grains of the same phase and grains of different phases has not been definitely established, the bond may be very strong and if so, this should be a very satisfactory method of bonding steel to aluminum.

Copper. - Copper also lies in this same class with silver, although there is some solubility of iron in copper and vice versa. The range of solubility of copper in aluminum is more limited, aluminum and copper alloys at 1200° F are soluble in the liquid state from 40- to 100-percent aluminum. On decreasing the aluminum content below 40 percent, the melting point of the alloys increases until the melting point of copper is reached at 1981° F. On welding these alloys, as with silver, no alloying action would occur between the iron and the copper but the molten aluminum would dissolve the copper gradually. Since the copper remains solid during welding, the formation of brittle iron-aluminum compounds is avoided as was explained in the case of silver. However, formation of the brittle theta phase $CuAl_2$ is likely to give brittle welds.

Nickel. - Although nickel and iron form either the face or body centered solid solutions at 1200° F, since the nickel remains solid during the welding, its case is similar to that of copper. Nickel, however, is soluble in the liquid state only from 94- to 100-percent aluminum at 1200° F. As with copper, brittle phase formations are likely to occur in the nickel-aluminum alloys.

Chromium. - Chromium at 1200° F forms a continuous solid solution with iron, while it is practically insoluble with aluminum. However, in the range from 79- to 99.6-percent aluminum, two phases, melt and Al_7Cr exist above 1222° F. Here again, the formation of brittle iron-aluminum phases is avoided since the chromium does not melt during the welding. However, the formation of brittle chromium-aluminum phases is likely.

Cadmium. - No metal is completely insoluble in both iron and aluminum. Cadmium, however, approaches this better than most metals and thus will be considered as typical of this class. At 1200° F molten cadmium has no solubility in iron and vice versa. A compound Cd_2Fe, however, is possible in this system. Cadmium and aluminum are completely insoluble with respect to each other up to 1200° F. Above this temperature, the alloys are completely molten but exist as insoluble liquid phases of a 5-percent cadmium-95-percent aluminum alloy and pure cadmium. As the temperature rises, these compositions remain more or less the same until well above the temperature range of interest in this welding process. On welding these alloys, cadmium and aluminum would both melt but the diffusion of aluminum into cadmium will not take place. Molten aluminum, however, will dissolve up to 5-percent cadmium. This would aid in assuring a good bond as it would tend to move the cadmium-aluminum interface away from its original position where a thin layer of aluminum oxide exists as a diffusion barrier and a plane of weakness. If the cadmium plate is thin or the welding electrode pressure excessive, the cadmium may be completely dissolved in the aluminum or be pushed away from the weld region. This therefore would result in the alloying of iron and aluminum and the production of a brittle weld.

Experimental Procedure

General aspects. - Since an adequate supply of SAE 4140 was not readily available or absolutely necessary for a study of this problem, a low carbon, rimming steel was selected for the study of the general problem of bonding aluminum to steel. As 3S half-hard aluminum was to be used as the fin metal, this material was selected as representative of aluminum and its alloys. The increased strength of the half-hard material over the annealed 3S stock insures ample rigidity and resistance to deformation in service.

The introduction of the third metal was accomplished by electroplating. The use of metal foils instead of electroplating was tried previously (reference 1), but the possibility of oxides on two interfaces and the difficulty of thin foil production and handling, compared to plating, made the plating method seem much more practical.

Seam welding of the fins to the chrome molybdenum cylinders is the ultimate goal of this process. However, many variables are difficult to control in a seam-welding operation and thus spot welding was selected for use in the study of the bonding problem. Welding pressures, currents, and times were investigated for the various metal plates and plate thicknesses. The character of the resulting welds was investigated by a tensile test and the amount of fusion in the aluminum determined by a quick section test. Thermal conductivity tests have not been made up to the present time, but it is felt that if the weld has good strength, an intimate metal contact must exist. This intimate contact would thus insure a good thermal bond since the thickness of any alloy or third metal which is used to aid bonding is practically negligible.

<u>Preparation of the steel for electroplating</u>. - Steel specimens of 0.037-inch automobile body stock were sheared into sections 4 by 1 inches. These specimens were then straightened in a vise and degreased by boiling in a saturated solution of trisodium phosphate for 10 minutes, washing in boiling water, wiping with a clean towel, rinsing for 5 minutes in carbon tetrachloride, and drying with a clean towel. The specimens were further prepared by pickling in 50-percent concentrated hydrochloric acid for 1 minute, rinsing in cold water, drying with a clean towel, flash pickling in 50-percent concentrated hydrochloric acid, rinsing in cold water, and drying with a clean towel. These specimens were then immediately plated. If the specimens could not be plated immediately, they were stored in a desiccator and flash pickled in 50-percent concentrated hydrochloric acid prior to plating.

<u>Electroplating techniques</u>. - Methods for the production of strongly adherent deposits of tin, zinc, silver, copper, nickel, chromium, and cadmium were studied. These are described in the following paragraphs. Various thicknesses of plates on the steel were made by variation of the plating time.

(1) Tin plating. - A sodium stannate bath (reference 3) was used to tin plate the steel. This bath consisted of:

$Na_2SnO_3 \times 3H_2O$	-	75 grams per liter
$NaOH$	-	6 grams per liter
$NaC_2H_3O_2$	-	12 grams per liter
H_2O_2 (3 percent)	-	4 milliliters per liter

This bath operates satisfactorily under the following conditions:

Bath temperature	- 165° F
Anode current density	- 25 amperes per square foot
Cathode current density	- 25 to 30 amperes per square foot

The control of the anode current density is quite important in this bath. If the anode current density is too low, little or no oxygen is produced at the anode and an appreciable amount of tin is dissolved in the stannous state. The presence of excessive stannous ions in the bath produces unsatisfactory deposits. The solution should possess a light gray to light straw color. Stannous ions readily turn the color of the bath to a brownish-black. The addition of hydrogen peroxide will immediately correct this difficulty by oxidation of the stannous tin to the stannic form. If inadequate hydroxide is in the solution, the anodes coat over with oxide and the solution is depleted of stannic ions with the resulting loss in plating efficiency. The proper hydroxide balance is maintained by addition of sodium hydroxide or acetic acid. Too high caustic content will promote unsatisfactory deposits by causing the stannous ion content to rise.

(2) Zinc plating. - The zinc plating bath (reference 4) was of the alkaline cyanide type and consisted of:

ZnO	-	45 grams per liter
$NaCN$	-	74 grams per liter
$NaOH$	-	15 grams per liter

The bath was operated under the following conditions:

Cathode current density	- 15 amperes per square foot
Bath temperature	- 115° F

In alkaline plating solutions, zinc may be found either as sodium zincate Na_2ZnO_2 or the double cyanide $Na_2Zn(CN)_4$. For best results a mixture of these two salts is desirable. Zinc oxide and sodium cyanide react as follows:

$$2ZnO + 4NaCN \rightarrow Na_2ZnO_2 + Na_2Zn(CN)_4$$

The plating solution, which is a high alkali bath, contains 1.5N total cyanide, 1.3N total alkali, and 1.0N zinc and hence may be considered as containing 0.75N $Na_2Zn(CN)_4$, 0.25N Na_2ZnO_2, and 0.8N free NaOH.

(3) Silver plating. - If a steel article is immersed in the regular plating bath, a loosely adherent silver plate forms by replacement. In order to avoid this difficulty, the steel must first be plated for a short time in a strike solution. The strike solution has such a low concentration of silver that no plate forms upon simple immersion. After striking, plating is continued in the regular plating bath. (See references 5 and 6.)

In the regular plating bath the metal content is furnished by the double cyanide $KAg(CN)_2$. Excess free cyanide is maintained and is helpful in increasing conductivity, throwing power, and anode corrosion. Potassium carbonate also increases the conductivity of the solution.

Carbon disulphide is used in baths as a brightener and as such only a trace is required. Nothing much is known of the action of this addition agent except that its use results in finer grained and denser deposits.

The strike solution had the following composition:

AgCl	-	1.5 grams per liter
NaCN	-	110 grams per liter

It was operated under the following conditions:

Cathode current density	-	20 amperes per square foot
Bath temperature	-	70° to 80° F
Time of plate	-	20 seconds

The plating bath which was used had the following composition:

AgCl	-	39 grams per liter
KCN	-	70 grams per liter
K_2CO_3	-	38 grams per liter
CS_2	-	0.9 milligram per liter

It was operated under the following conditions:

Cathode current density	-	6 amperes per square foot
Bath temperature	-	70° to 80° F

(4) Copper plating. - The copper plating bath (reference 4) was of the alkaline cyanide type and consisted of:

CuCN	-	22.5 grams per liter
NaCN	-	34 grams per liter
Na_2CO_3	-	15 grams per liter

The bath was operated under the following conditions:

Cathode current density	-	10 amperes per square foot
Bath temperature	-	95° to 104° F

In the alkaline copper baths, the main constituent is sodium cuprocyanide $Na_2Cu(CN)_3$ containing copper in the cuprous state. The bath previously described contains as active agents 0.25N CuCN and 0.65N NaCN and hence may be considered 0.25N $Na_2Cu(CN)_3$ and 0.15N "free cyanide." The addition of sodium carbonate Na_2CO_3 decreases the tendency for the cyanide to decompose.

(5) Nickel plating. - The nickel plating bath (reference 4) was the "single salt solution" and consisted of:

$NiSO_4 \times 7H_2O$	-	105 grams per liter
NH_4Cl	-	15 grams per liter
$NiCl_2 \times 6H_2O$	-	15 grams per liter
H_3BO_3	-	15 grams per liter

This bath was operated under the following conditions:

Cathode current density	-	15 amperes per square foot
Bath temperature	-	68° to 85° F
pH	-	5.3

The $NiSO_4 \times 7H_2O$ provides the nickel ion, NH_4Cl and $NiCl_2 \times 6H_2O$ increase the conductivity of the solution and promote anode corrosion, while the H_3BO_3 acts as a buffer. When the pH of the bath rises, say to 6, deposits are dark and are likely to curl. On the other hand, if the pH drops, say to 4, the deposits are bright, pitted, and cracked.

(6) Chromium plating. - The bath used for chromium plating (reference 4) consisted of:

CrO_3	-	250 grams per liter
H_2SO_4	-	2.5 grams per liter

The plating was done at 125° F with the following procedure:

(1) Reverse plate (specimens anodic) for 10 seconds with current density of 320 amperes per square foot

(2) Plate for 1 minute at 200 amperes per square foot

(3) Finish plating at 320 amperes per square foot

The improvement in plating chromium on steel by making the specimens first anodic has been explained in several ways. In one explanation, its anodic action is thought to render the steel surface passive, while in another explanation the surface impurities such as carbon are thought to be removed by the oxidizing action.

The use of low-current density for the first minute of plating was found to improve the appearance of the plate. Past experience has shown that the character of a chromium plate is determined by the first moments of plating.

(7) <u>Cadmium plating</u>. - The cadmium plating bath (reference 4) was of the alkaline cyanide type and consisted of:

CdO - 32 grams per liter
$NaCN$ - 75 grams per liter

Its operating conditions were:

Cathode current density - 40 amperes per square foot
Bath temperature - 70° to 80° F

In alkaline plating solutions, cadmium is found as the double cyanide $NaCd(CN)_3$. Baths usually contain appreciable amounts of free cyanide and alkali. Cadmium oxide and sodium cyanide react as follows:

$$CdO + 3NaCN + H_2O \rightarrow NaCd(CN)_3 + 2NaOH$$

Cadmium, unlike zinc, does not react with sodium hydroxide. The plating solution previously described contains 0.5N cadmium and 1.5N sodium cyanide and hence may be considered containing 0.5N $NaCd(CN)_3$, 0.75N free NaCN, and 0.5N free NaOH.

Preparation of the aluminum for welding. - 3S half-hard specimens of 0.040-inch stock were sheared into 1- by 3-inch sections and straightened in a vise without marring the surface. As stated before, aluminum oxide, owing to its high heat of formation, is always found to a greater or less extent on the surface of aluminum. This oxide film, which would cause poor metallurgical bonding conditions, should be removed. Although this film cannot be completely removed, its thickness was greatly reduced by chemical methods.

In this chemical method (reference 7), the specimens are degreased by a 5-minute treatment in a 180° F cleaning solution containing 3 ounces of Oakite aviation cleaner per gallon of water. After rinsing in hot water, a consistent oxide film is produced by a 5-minute treatment in a 180° F treating solution containing 6 ounces of Oakite 84-a cleaner per gallon of water. This treating bath contains sodium-acid sulfate as an oxide-removing agent and organic compounds as wetting agents. The effect of this bath in producing an aluminum surface which will possess consistent contact resistances was studied.

All contact-resistance measurements were made in a hydraulic press equipped with 4-inch-radius dome welding electrodes, as illustrated in figure 4. Pressure, which was maintained at 1000 pounds, was measured by means of a calibrated spring. Resistance measurements were made with a Kelvin double bridge, as illustrated in figure 5. It was found that consistent contact resistances of approximately 100 microhms were obtained between two 0.040-inch 3S half-hard sheets treated for 5 minutes with Oakite 84-a. The results of these tests are shown in table I and figure 6. It is noticed that contact resistance falls during the first minute of treatment as the original oxide layer is dissolved. Then, for several minutes, the contact resistance remains constant and finally rises again, owing to another film forming on the surface.

Spot welding. - The concentration of heat at the iron-aluminum interface is a major problem in this spot-welding investigation. Another problem of major importance when spot welding aluminum to steel is the question of electrode indentation. In the region of the melting point, aluminum is weak and thus, if flat tips are used, severe indentation occurs on welding. In order to eliminate this effect and concentrate the development of heat in the aluminum, a 4-inch-radius dome was used as the aluminum welding electrode. In order to minimize heating of the steel, which for higher carbon and alloy steels might result in objectionable hardening, a flat electrode was used against the steel to reduce the current density in the steel. One of the objectionable features of welding aluminum is the pickup of aluminum which occurs on the welding electrodes. Periodically, for example every 50 welds, this pickup must be removed. The use of No. 240 emery cloth has been found to be the most satisfactory method of cleaning the electrodes. When the pickup becomes severe, the electrodes must be remachined.

Welding was performed on a Federal 175-kilovolt-ampere spot welder having a turns ratio of 80:1. The primary voltage was maintained at 350 volts, while the magnitude and length of current flow was controlled by a thyratron control panel. Primary currents were measured by a pointer-stop ammeter. Electrode pressures were adjusted and controlled by pressure control of the air to the bellows of the welding machine.

When a set of specimens was welded, a rough evaluation of the welding heat was made by investigating the amount of fusion produced in the aluminum. After determining the range of currents to be used, welds were made at various intermediate currents and each current was measured by the pointer-stop ammeter. Two additional similar sets of welds were made, giving three specimens made under identical conditions but not in immediate succession. This process tends to minimize the effect of a small amount of pickup on the welding electrode in contact with the aluminum and, at the same time, provides three specimens for tensile testing.

<u>Testing of welds</u>. - The welded strips of aluminum and iron were pulled in Templin grips on a 60,000-pound Southwark-Emery hydraulic testing machine using the 5000-pound testing dial. A testing rate of 0.06 inch per minute was used. When the ultimate strength was observed, the load was released and the character of the failure noted. Failures were classified as "ductile tear," "ductile shear," or "brittle shear." In a ductile-tear failure, the weld failed by pulling a plug out of the aluminum sheet. A ductile-shear failure occurred when the weld interface failed but not until considerable bending of the aluminum sheet had taken place. If the weld separated at the interface with little or no bending of the aluminum sheet, the type of failure was termed "brittle shear."

The extent of fusion was then determined by the quick section test. This test involves sectioning the weld with a saw, filing a smooth surface, and etching the surface from 1 to 3 minutes in a solution of 1.5-percent hydrofluoric acid. This etching reveals the outline of the fused aluminum nugget as is shown in figure 7, a photomacrograph at 12X. An evaluation of the nugget size is made by estimating the percent penetration of the fused region into the aluminum sheet, which has been designated as nugget penetration.

Discussion of Results

Welding variables. - There are five variables which must be established in this spot-welding investigation: electrode pressure, welding time, welding current, the third metal, and the thickness of the third metal.

Generally, it was found that electrode pressures of over 1000 pounds resulted in too much indentation in the aluminum sheet. On the other hand, electrode pressures of less than 600 pounds gave very erratic results as determined by tensile and quick-section tests. For these reasons, the electrode pressure was standardized at 800 pounds.

Since seam welding would be the final application of this investigation, the shortest satisfactory welding time would be of the greatest interest. On the other hand, very short welding times would have more of a tendency to heat the steel above its critical temperature. This results from the fact that a large portion of the heat is developed in the steel and this heat must be conducted to the aluminum. In order to obtain the same amount of fusion in the aluminum in both a short and long time weld, approximately the same amount of heat must be developed. When this heat is developed in a much shorter time, higher temperatures will be reached in the steel. In order to strike a satisfactory balance, 10 cycles were chosen as the welding time.

The current used in the welding operation influences the amount of fusion in the aluminum sheet. In all cases, current was controlled between two critical values; a current which just produced fusion in the aluminum and a higher current which produced 100-percent fusion, in which the aluminum was fused completely through from steel to electrode. In the final application, as low a current as will produce satisfactory welds should be employed since this will lessen the danger of heating the steel above its critical temperature and reduce the aluminum pickup on the electrodes.

Welding of aluminum to tin-plated steel. - In welding of tin-plated steels to aluminum, four trends were disclosed:

(1) Tin plating does not increase the strength and ductility of the iron-aluminum bond.

(2) Only brittle shear type failures occur.

(3) When shear type failures occur, consistent strengths are not obtained.

(4) For a given plate thickness, higher currents and thus larger nuggets produce greater strength.

For various tin-plate thicknesses, the effect of current on the spot shear strength, nugget penetration, and type of failure is shown in table II and figure 8. The type of failure designated as BS indicates a brittle shear failure, and DS and DT, while not encountered in the testing of tin-plated specimens, indicate ductile shear and ductile tear failures, respectively.

As the nugget penetration increased, the spot shear strength increased as indicated in the data of table III, for a 0.125-mil tin-plate thickness. The average values of the spot shear strength at 20-, 40-, 60-, 80-, and 100-percent nugget penetration were obtained graphically from these data as illustrated in figure 9. This procedure, when repeated for the various plate thicknesses, compiles the effect of tin plate thickness on the shear strength for various nugget penetrations as shown in table IV and figure 10.

The strength and ductility of the iron-aluminum bond are not increased, owing possibly to the formation of a brittle compound. Two possibilities of this compound formation are likely. The tin and iron may form the compound $FeSn_2$ which might produce this effect. However, since little difficulty is encountered in hot dipped tin plate, this possibility of brittleness is considered highly unlikely. The second possibility is the formation of a brittle iron-aluminum compound. This compound might form at the welding temperature if the pressure forced the molten tin from the welding interface or if the tin were completely absorbed in the molten aluminum. Visual observation of the shear failures and microscopic examination of the weld interface gave substantiation to this second possibility since tin was not evident in the bond.

In all cases, in the welding of tin-plated steel to Oakite-treated aluminum, brittle shear type failures were found. This type of failure is due to a combination of low bond shear strength and low ductility. Low ductility materials will not yield when subjected to a concentrated stress and thus do not allow a more even distribution of stress. As a result, these materials allow high stresses and high stress gradients to occur and thus failure occurs locally and progresses across the load-carrying area. This progressive failure effectively lowers the load-carrying capacity of the stressed section and results in a shear type failure. These progressive failures do not, in general, produce consistent tensile results.

Higher currents produce greater strength for any plate thickness. This improvement of strength is explained by the larger interface area and a better bonding per unit area, which results from larger nuggets formed by higher currents. A larger nugget produces better unit-area bonding since a larger pool of molten metal may remove by turbulence more of the aluminum oxide from the plane of the aluminum interface.

<u>Welding of aluminum to zinc-plated steel</u>. - The welding investigation of zinc-plated steel to aluminum discloses the same general trends as were noted in tin. (See tables V and VI and figs. 11 and 12.) The relative strength and ductility was less for the zinc-plated steels. This is possibly due to the formation of more brittle compounds in the iron-zinc system.

<u>Welding of aluminum to silver-plated steel</u>. - In the investigation of the welding of silver-plated steel to Oakite-treated aluminum, it was found that as the plate thickness increased, the type of failure became more ductile. Figure 13 shows the general effect of plate thickness on the relationship between strength and welding current. The heavy dashed line in this figure represents the approximate dividing line between ductile tear failure and ductile or brittle shear failure. It will be noted that a plate thickness of above 0.05 mil produces a ductile tear failure if the current is sufficient to produce only a little fusion in the aluminum. Considering the welds made using specimens with thinner silver plates, ductile tear failures in the aluminum occur only if a higher current and greater nugget penetration are employed. This is revealed by examination of table VII. The effect of silver plate thickness on the spot shear strength for various nugget penetrations is shown in figure 14 and table VIII. Higher currents, which result in greater nugget penetration and heat-affected areas, increase the ductility of the half-hard aluminum sheet. As a less ductile material does not have the ability to distribute the stress over a larger area, high stress gradients will result at the bond interface. The existence of high stress gradients at the bond

interface will, in general, result in lower load-carrying capacity and shear type failure. In view of the above, the effect of welding current and nugget size upon the strength and type of failure is readily apparent.

As the thickness of the silver plate increases, a certain critical thickness is reached, above which complete solution of the silver in the molten aluminum nugget does not occur during welding. Figure 15, a photomicrograph at 1000X of the weld interface, confirms the presence of this thin silver film which insures the absence of any brittle iron-aluminum compound formation. Hence, the resultant weld exhibits a ductile tear failure. The slight increase in weld strength as the current rises is undoubtedly due to the decreased stress gradients and increased ductility caused by the greater welding current.

Silver has been found in this investigation to be very satisfactory as an interface metal between iron and aluminum. Silver plate thicknesses greater than the critical thickness produce consistent, tear type failures with a minimum amount of fusion occurring in the aluminum. This results in stronger welds and less aluminum pickup on the welding electrodes as less aluminum is heated to a temperature where recrystallization and alloying with the copper electrodes can occur.

<u>Welding of aluminum to copper-plated steel</u>. - The results of welding of alumimum to copper-plated steel, shown in tables IX and X and figures 16 and 17, were somewhat similar to that of silver. As the plate thickness increased, the type of failure became more ductile. Microscopic investigation proved that only the 0.05-mil plate was entirely absorbed during the welding. The thicker copper plates, however, gave a more limited range of ductile tear failures and generally less consistent welds than did the silver plates. This may be explained by the formation of the brittle theta phase ($CuAl_2$). Brittle shear and ductile shear failures consistently occurred at the copper-aluminum interface in the thicker plates. As the plate thickness increases, the current necessary for welding increases much more rapidly for copper than for silver, although both metals have like thermal and electrical conductivities. Differences in the grain structures of the plated metal might account for this anomaly.

<u>Welding of aluminum to nickel-plated steel</u>. - The results as shown in tables XI and XII and figures 18 and 19 indicate that only shear type failures are obtained when welding aluminum to nickel-plated steel. However, the shear type failures become

more ductile as the nugget penetrations increase, undoubtedly because of the effect of the higher currents on the softening of the aluminum sheet. The heavy dashed lines in the figures indicate the approximate dividing line between ductile and brittle shear failures. Microscopic examination showed that nickel was only slightly dissolved during welding even in the thinner plates. Visual examination of the shear failures indicated that fracture occurred at the aluminum-nickel interface. This indicated the presence of a somewhat brittle aluminum-nickel phase.

Welding of aluminum to chromium-plated steel. - Slight expulsion of aluminum from the weld interface was consistently observed when welding aluminum to chromium-plated steel. This expulsion is due to the large amount of heat produced by the abnormally high contact resistance of chromium.

The results of the welding of aluminum to chromium-plated steel are shown in tables XIII and XIV and figures 20 and 21. Shear type failures resulted in all cases, but as the plate thickness increased and as the nugget penetration increased, the failures became more ductile. Chromium was not appreciably dissolved during welding and failures occurred at the aluminum-chromium interface, indicating the formation of a somewhat brittle aluminum-chromium compound.

Welding of aluminum to cadmium-plated steel. - With respect to the tensile strength and character of fracture, cadmium plates appear better than tin and zinc plates but not so satisfactory as silver and copper plates. The strength and fracture characteristics are given in table XV, while figure 22 shows the current-strength relationships. Table XVI and figure 23 show the effect of plate thickness on shear strength for various nugget penetrations. If the cadmium interface had remained in place, the welds should have possessed properties similar to the welds made with a silver interface. However, owing to the low melting point of cadmium and the welding pressure used, it was found that the molten cadmium was ejected from the weld interface and some direct alloying of iron and aluminum occurred. This, of course, would result in the production of a more brittle weld.

Conclusions of Part I - Bonding of Aluminum to Steel

1. A third metal is necessary to effect a satisfactory bond between aluminum and steel, since no satisfactory method of joining these two metals has been found.

2. Electroplating of the third metal to the steel is the most satisfactory method of applying the interface metal.

3. The surface treatment of aluminum in preparation for welding must receive the same careful attention as is required for the spot welding of the structural aluminum alloys.

4. Tin and zinc when used as the third metal produce only brittle welds.

5. Nickel, chromium, and cadmium have only a very limited range of moderately satisfactory welding conditions.

6. Copper is more satisfactory than the metals previously mentioned but requires very high currents for welding. Furthermore, the consistency of strength and the range of plating thickness and welding current in which ductile welds can be produced is limited.

7. Silver is the most satisfactory third metal to accomplish the bonding of aluminum to steel. High strength, ductile welds can be produced over a wide range of welding current and plating thickness.

II. WELDING OF ALUMINUM TO SAE 4140 STEEL

Introduction

The problem of spot welding aluminum to steel was solved by silver plating the steel. This section of the report considered the further problems incident to the hardening of the SAE 4140 steel as a result of welding, and the actual seam welding of aluminum fins to SAE 4140 cylinder barrels.

Metallurgical and Welding Considerations

At the present time, airplane cylinders are made of SAE 4140 steel which has been heat-treated to a hardness of about 320 Vickers (Rockwell C-35). This hardness corresponds to a heat treatment of oil quenching followed by a 1250° F draw and thus this steel can be considered to be relatively soft and tough. If this steel were to be welded by ordinary welding processes - that is, by fusion or pressure-plastic processes - the steel would be raised above its critical temperature (Ae_3-1445° F; Ae_1-1365° F) and the resulting cooling rate after welding would produce a weld martensitic in character. While this might not be too detrimental in many applications where tempering treatments can be applied, it is highly undesirable under the service conditions existing in an airplane cylinder where fatigure and impact stresses are likely to be very high and the drawing operations after welding likely to be difficult. It is therefore obvious that a highly specialized method of joining must be utilized.

It is readily apparent that if this silver-plated steel could be joined to the aluminum at a temperature well below the critical temperature, that is, 1365° F, the danger of the martensitic formation would never occur, as austenite would not be formed. As pure aluminum melts at 1218° F and a 5-percent silicon alloy at a temperature of approximately 1150° F, there exists the possibility of a metallurgical bond being formed without actually heating the steel to its critical temperature.

In the investigation of the bonding of aluminum to steel, the materials were of like thickness, 0.040-inch 3S half-hard aluminum being welded to plated 0.037-inch rimming steel. Because of weight considerations, the proposed aluminum fin thickness is 0.030 inch, while the design thickness of the SAE 4140 cylinder barrel available for use in this investigation from a previous investigation for Pratt & Whitney Aircraft, was 0.090 inch. Since the resistivity of steel is greater than that of aluminum, as the ratio of steel thickness to total thickness increases, the ratio of steel resistance to total resistance increases rapidly. This will cause a major portion of the heat to be developed in the steel, and thus vastly increase the possibility of heating the steel above its critical temperature during welding.

Experimental Procedure

<u>General aspects</u>. - Even though seam welding of aluminum fins to chrome molybdenum cylinders was the goal, spot welding was selected for the study of the martensitic formation in the SAE 4140. This decision was made in order to eliminate as many variables as possible. When the solution to this problem was found, it would be a natural step to apply it to the seam-welding operation.

<u>Preparation of the steel for electroplating</u>. - In cleaning SAE 4140 steel before plating, it was discovered that the surface obtained by pickling with the usual commercial pickles was

unsatisfactory since well adherent silver plates were not obtained. Two solutions to this problem were discovered. In one method, the steel was vapor degreased with trichloroethylene and then electrolytically polished and etched by means of the following bath:

Perchloric acid (sp. gr. 1.61 65 percent)	- 185 cubic centimeters
Acetic anhydride	- 765 cubic centimeters
Water	- 50 cubic centimeters
Aluminum	- 0.5 percent

This bath was operated under the following conditions:

Temperature	- 70° to 80° F
Anode current density	- 45 amperes per square foot
Time of treatment	- 5 minutes

This electrolytic polishing and etching was followed by water rinsing and immediate plating. In the other method, which gave equally satisfactory results, the surface was mechanically cleaned with emery papers down to grit No. 0, vapor degreased with trichloroethylene, wiped clean, again vapor degreased, and finally plated.

In commercial production, cleaning of the steel would be no problem, since well adherent silver plates can be deposited on freshly machined, grease-free surfaces.

Silver was plated on the SAE 4140 steel as described in part I of this report. The best results in the welding of aluminum to silver-plated rimming steel were obtained by using either 0.25- or 0.50-mil plate thickness. The 0.25-mil silver plate thickness was chosen instead of 0.50-mil, since it was cheaper and quicker to apply.

Preparation of the aluminum for welding. - During the fundamental investigation of the bonding of aluminum to steel, new baths were being discovered for the removal of the oxide film from the surface of aluminum prior to welding.

Two surface treatments developed by the Aircraft Spot Welding Research at Rensselaer Polytechnic Institute were used:

Solution 5 (reference 8), which required 6-minutes treating time at 180° F consisted of:

H_2SO_4(sp. gr. 1.84, 98 H_2SO_4)	- 10 cubic centimeters per liter (active agent)
Nacconal NR	- 2 grams per liter (wetting agent)

Solution 14 (reference 9), which required 6-minutes treating time at room temperature, consisted of:

H_2SiF_6 (27 to 30 percent) - 3.0 percent by volume or 1.18 percent by weight
Nacconal NR - 0.1 percent

With both of these solutions, consistent low contact resistances from 2 to 5 microhms were obtained. Prior to surface treatment, the aluminum was vapor degreased with trichloroethylene, wiped clean, and again vapor degreased. The results of a typical contact resistance run with solution 5 are shown in table XVII and figure 24. For these resistance measurements 0.030-inch specimens of Alcoa No. 1 Brazing sheet were used, which consisted of 3S half-hard composition clad on one surface with a 7-percent thickness of a 5-percent silicon alloy. Since these solutions gave very low contact resistances over a wider range of treating time, they were used in preference to Oakite 84-a, used for the earlier work.

Detailed welding procedure. - In order to avoid hardening and even remelting of the SAE 4140 steel during welding, several procedures were investigated, which are described in the following paragraphs.

(1) Use of longer welding times. - The first procedure investigated was the use of longer welding times, since it was thought that the lower temperature gradients which result from this method would lessen the possibility of heating the steel above its critical transformation temperature.

(2) Use of preheating and postheating. - If the steel were preheated in the range of 650° to 750° F, and maintained at temperature during the welding operation and shortly thereafter, the portions of the steel which had become austenitic during welding could only transform to bainite upon cooling. According to the S curve for SAE 4140, figure 25, the bainite, formed by isothermal transformation in the temperature range from 650° to 750° F, would have a Rockwell C hardness from 48 to 40 and would be tough. This compares favorably with the original hardness of the cylinder barrel, Rockwell C-35, and is far superior to the brittle martensitic zones of Rockwell C-60 hardness. The S curve indicates that a holding time from 150 to 250 seconds is necessary for complete transformation.

To test this procedure, silver-plated SAE 4140 steel specimens were preheated to 700° F and rapidly welded to aluminum, after which the welds were immediately postheated at 700° F for 3 minutes.

(3) Use of a lower melting point aluminum alloy. - If a lower melting point aluminum alloy were welded to the silver-plated steel, obviously lower temperatures would be attained in the steel during the process. A lowering of 50° to 100° F in the necessary bonding temperature might eliminate martensite formation in the steel. The fins could be fabricated entirely from an aluminum brazing alloy or from 3S half-hard aluminum clad with the brazing alloy. The latter is preferable for a fin material on the basis of its higher thermal conductivity.

To test the effect of a lower melting point aluminum alloy, 0.030-inch specimens of Alcoa No. 1 Brazing sheet (3S half-hard clad on one side with a 7-percent cladding of a 5-percent silicon alloy) were welded to silver-plated 0.090-inch SAE 4140.

(4) Use of a stainless steel insert. - In order to supply more heat to the aluminum and develop less heat in the steel, an 18 Cr 8 Ni stainless steel insert might be utilized as illustrated in figure 26. Since austenitic stainless steel has a higher electrical resistivity than plain carbon or SAE 4140 alloy steel, passage of current during welding would heat up the stainless steel insert and supply extra heat for the fusion of the aluminum. The difficulty of securing proper fusion at the aluminum-silver interface is largely due to the rapid heat extraction from the high conductivity aluminum through the copper electrode. Not only would the low thermal conductivity stainless steel insert prevent this heat extraction, but, in addition, it would tend to supply heat by conduction to the aluminum, assisting in proper fusion of aluminum at the silver interface. By assisting in supplying proper heat for the fusion of aluminum, an insert of proper thickness might be expected to produce the necessary heat by a current of such a value that proper bonding of the aluminum could be obtained and martensitic formations avoided in the steel.

Discussion of Results

Avoidance of martensitic formations in SAE 4140. - In the spot welding of 0.030-inch aluminum to silver-plated SAE 4140 steel, martensitic formations and even remelting were found in the steel. A small martensitic zone is illustrated in figure 27 in a photomacrograph at 12X. The indentations resulted from a Vickers hardness survey, which is also shown in figure 27, indicating a maximum hardness of VPN 700 (Rockwell C-60).

The use of longer welding times did not solve the problem of the avoidance of martensitic formations. It was found that even with welding times as long as 25 cycles, martensite was obtained almost to the same extent as with 5 cycle welds. Even though the use of longer welding times resulted in shallow temperature gradients, large portions of the steel were still being heated above the critical temperature and thus hardened. Furthermore, longer welding times are objectionable since they are less adaptable to seam welding.

When welds were made with preheating and postheating at 700° F, as indicated by the S curve, the heat affected zones of the SAE 4140 consisted of a bainitic structure with a Rockwell C hardness of 47.5 (VPN 505). Although this procedure avoids the formation of martensite, it is objectionable from the standpoint of easy fabrication. Although silver-plated surfaces are not affected at these temperatures, the formation of oxides on the aluminum surfaces are detrimental to consistent welding.

The use of a lower melting point aluminum alloy lowered the necessary bonding temperature and thereby lessened the heating of the SAE 4140 steel above the critical temperature. As is shown in table XVIII, at the maximum current which just avoided martensite in the SAE 4140, the welds made by use of the brazing clad material are far superior to that made by use of unclad 3S half-hard. However, this procedure cannot be considered the solution to the problem, since the maximum weld properties could not be attained without forming martensite in the steel.

Under proper conditions, the use of a stainless steel insert, to supply extra heat for the fusion of the aluminum, resulted in the avoidance of martensitic formations in the SAE 4140 steel. The correct welding conditions resulted when a proper balance was obtained between two variables; the thickness of the stainless steel insert, and the welding time. Three thicknesses of stainless steel were examined: 0.006, 0.011, and 0.023 inch; while four welding times were investigated: 3, 5, 10, and 23 cycles. The results of these tests are shown in table XIX. Because short welding times rapidly develop a large amount of heat in the stainless steel, objectionable alloying action was noted at the aluminum-stainless steel interface. With long welding times, the tendency for martensite to form in the SAE 4140 became evident. The long welding time allowed the heat developed in the stainless steel to flow through the aluminum and add to that developed in the SAE 4140. Since the minimum bonding temperature of the aluminum-silver interface is somewhat above 1220° F, the melting point of aluminum, the possibility of martensitic formation is greatly increased.

With the 0.006-inch stainless steel insert, not quite enough heat was developed at the aluminum-silver interface for proper bonding. However, this was not the case with the thicker inserts, and the 0.023-inch stainless insert developed so much heat that aluminum-stainless steel alloying occurred. The best conditions, which avoid both martensitic formations in the steel, and alloying of of aluminum with the stainless steel, were found with 5-cycle welds using an 0.011-inch stainless steel insert.

The seam welding of fins to the SAE 4140 cylinder barrels. - In order to show that the results obtained from the investigations previously described in this report could be applied to an actual bonding of aluminum fins to an SAE 4140 cylinder barrel, an experimental arrangement was prepared to make these welds to a cylinder barrel in a seam-welding machine. The laboratory was fortunate in having in its possession a cylinder barrel and a number of fins which had been supplied by the Pratt & Whitney Aircraft Corporation for some previous experiments in this field. Individual fins made from the No. 1 Brazing sheet had been punched out and formed to fit over the machined cylinder barrel, with the brazing alloy surface in contact with the cylinder barrel.

The results of the investigation for the avoidance of martensitic formations in the SAE 4140 steel were applied to seam welding. For this operation, which was carried out on a Federal 175-kilovolt-ampere seam-welding machine, it was decided to weld brazing clad 3S half-hard fins to the barrels employing a stainless steel insert, as shown in figure 28. The 0.011-inch stainless steel insert had to be bent on an angle to avoid accidental current flow from the side of the welding electrode to the adjacent portion of the fin. When this accidental short-circuiting occurred, so much current was diverted that unsatisfactory welds were obtained.

Proper conditions were determined for this seam-welding operation. It was found that satisfactory overlapping spot welds could be made at a wheel speed of 80 inches per minute using a seam-welding sequence of 5 cycles on, 2 cycles off, the value of secondary current being 8600 amperes for an electrode pressure of 800 pounds. The electrodes consisted of a 6-inch diameter wheel over which the barrel fitted and a 9-inch diameter seam-welding wheel with 1/8-inch width of contact. No external water spray was used.

Difficulty was experienced with mechanical alinement of the aluminum fin and the stainless steel insert. Proper jigging would overcome this difficulty for commercial adaptation. Possibly a copper alloy seam-welding wheel with a stainless steel tire might be substituted for the insert.

In figure 29, photographs of a seam-welded cylinder barrel are exhibited. This cylinder barrel is being forwarded in a separate enclosure with this report to the NACA. It is hoped that a thermal efficiency test and such other tests as may be desired by the NACA Power Plants Committee may be made on this cylinder barrel. A probable criticism of the welded cylinder barrel is that the fins are not sufficiently close together for maximum efficiency. With the fins and facilities available for this investigation closer spacings were not feasible. In a commercial application of this method, closer spacing could be achieved. In a commercial installation it might also be preferable to use the fin material in the form of a continuous length wound spirally and welded without interruption.

Summary and Conclusions of Part II

Welding of Aluminum to SAE 4140 Steel

The following paragraphs summarize the accomplishments of the second part of this investigation.

1. The avoidance of martensitic formations in the cylinder barrel steel was accomplished by use of a sufficiently low welding current to avoid the development of too much heat in the steel. This was made possible by supplying a part of the heat for the fusion of the aluminum by means of a high resistance insert between the electrode and the aluminum surface.

2. A welding machine was adapted and used in welding aluminum fins to a cylinder barrel. This makes possible a study of the cooling efficiency of such a combination, although the available fins were not properly designed to permit as close a spacing as might be desired.

CONCLUSIONS FOR COMPLETE REPORT

1. Silver is the most satisfactory metal for electroplating steel cylinder barrels to permit the bonding of aluminum fins. The optimum plating thickness is 0.25 mil.

2. Careful attention to the silver-plating technique, as outlined in this report, must be given since the strength and permanence of the bond depends to a large extent upon the perfection of the bond secured during the plating operation.

3. The bonding of aluminum to SAE 4140 steel may be accomplished below the critical temperature for this steel. Thus, objectionable rehardening during welding is avoided. An 0.011-inch stainless steel strip between the electrode and the aluminum provides a proper heat balance.

4. A seam-welding machine can be used for automatically bonding a flanged continuous aluminum strip to a silver-plated steel cylinder barrel during the winding of this strip in the form of a close spiral over the surface of the cylinder.

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Rensselaer Polytechnic Institute,
Troy, N. Y., August 1943.

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TABLE I

Contact Resistance Measurements

Stock - 0.040" 3S half hard

Treatment - Oakite 84a, 6 oz. / gal. 180°F.

4" radius dome tips

1000 lbs. pressure

Time of Treatment Minutes	Contact Resistance Measurements Microhms	Average Contact Resistance Microhms
0	over 1000	over 1000
2	95, 99, 103	99
3	98, 107, 101	102
4	109, 96, 98	101
5	105, 98, 102	102
6	108, 100, 110	106
10	160, 145, 154	153

TABLE IV

Effect of Tin Plate Thickness on Spot Shear Strength for Various Nugget Penetrations

Nugget Penetration Percent	Average Spot Shear Strength in Pounds for the following Plate Thicknesses in Mils					
	.000	.025	.050	.125	.250	.500
20	170	150	115	90	125	175
40	290	250	215	180	215	275
60	375	325	300	270	305	375
80	430	400	385	360	390	460
100	460	460	465	450	475	540

TABLE II

EFFECT OF TIN ON THE WELDING OF ALUMINUM TO STEEL

Welding Current Amperes	Spot Shear Strength Pounds	Type of Failure	Nugget Penetration Percent
Aluminum directly to Steel			
15,200	310	BS	40
15,700	340	BS	50
16,100	440	BS	60
16.600	470	BS	75
Tin Plate Thickness-0.025 mil			
15,600	150	BS	10
16,300	240	BS	15
16,700	380	ES	60
16,900	410	BS	60
Tin Plate Thickness-0.05 mil			
16,000	120	BS	15
16,300	140	BS	25
16,600	430	BS	90
16,800	460	BS	95
Tin Plate Thickness-0.125 mil			
15,800	70	BS	15
16,200	90	BS	20
16,600	290	BS	60
17,000	360	BS	90
Tin Plate Thickness-0.25 mil			
15,800	50	BS	2
16,200	80	BS	10
16,600	220	BS	60
17,000	430	BS	75
Tin Plate Thickness-0.50 mil			
16,000	40	BS	2
16,400	170	BS	30
16,800	340	BS	60
17,200	490	BS	95

Note: All values represent average of 3 specimens

TABLE III

Effect of Nugget Penetration on Spot Shear Strength for Aluminum Welded to Tin Plated Steel

0.125 mil Tin Plate Thickness

Nugget Penetration Percent	Spot Shear Strength Pounds
2	20
10	40
10	110
15	80
30	70
30	160
40	180
50	310
70	250
90	380
90	400
95	450

TABLE V

EFFECT OF ZINC ON THE WELDING OF ALUMINUM TO STEEL

Welding Current Amperes	Spot Shear Strength Pounds	Type of Failure	Nugget Penetratio Percent
	Aluminum directly to Steel		
15,200	310	BS	40
15,700	340	BS	50
16,100	440	BS	60
16,600	470	BS	75
	Zinc Plate Thickness-0.05 mil		
16,500	430	BS	75
16,800	430	BS	80
17,100	470	BS	80
17,400	430	BS	75
	Zinc Plate Thickness-0.125 mil		
16,600	310	BS	40
17,000	370	BS	75
17,200	420	BS	60
17,400	480	BS	80
	Zinc Plate Thickness-0.25 mil		
17,200	170	BS	1
17,500	230	BS	10
17,800	190	BS	10
18,000	320	BS	30
	Zinc Plate Thickness-0.50 mil		
18,600	390	BS	50
19,000	400	BS	75
19,300	430	BS	80
19,400	400	BS	70

TABLE VI

Effect of Zinc Plate Thickness on Spot Shear Strength for Various Nugget Penetrations

Nugget Penetration Percent	Average Spot Shear Strength in Pounds for the following Plate Thicknesses in Mils				
	.000	.050	.125	.250	.500
20	170	260	285	295	305
40	290	340	345	350	355
60	375	395	395	400	400
80	430	435	440	440	440
100	460	470	470	470	470

TABLE VIII

Effect of Silver Plate Thickness on Spot Shear Strength for Various Nugget Penetrations

Nugget Penetration Percent	Average Spot Shear Strength in Pounds for the following Plate Thicknesses in Mils				
	.000	.050	.125	.250	.500
20	170	450	455	460	535
40	290	500	500	535	555
60	375	525	525	570	580
80	430	550	545	580	595
100	460	550	555	590	600

TABLE VII

EFFECT OF SILVER ON THE WELDING OF ALUMINUM TO STEEL

Welding Current Amperes	Spot Shear Strength Pounds	Type of Failure	Nugget Penetration Percent
	Aluminum directly to Steel		
15,200	310	BS	40
15,700	340	BS	50
16,100	440	BS	60
16,600	470	BS	75
	Silver Plate Thickness-0.05 mil		
16,000	360	BS	30
16,400	490	DS	40
16,700	540	DT	50
17,100	560	DT	70
	Silver Plate Thickness-0.125 mil		
16,600	520	DT	40
17,000	520	DT	40
17,500	530	DT	70
18,100	540	DT	80
	Silver Plate Thickness-0.250 mil		
16,800	470	DS	10
17,400	490	DT	30
17,800	530	DT	60
18,300	570	DT	60
	Silver Plate Thickness-0.5 mil		
18,400	570	DT	50
18,900	570	DT	50
19,400	590	DT	60
19,800	590	DT	60

TABLE IX

EFFECT OF COPPER ON THE WELDING OF ALUMINUM TO STEEL

Welding Current Amperes	Spot Shear Strength Pounds	Type of Failure	Nugget Penetration Percent
	Aluminum directly to Steel		
15,200	310	BS	40
15,700	340	BS	50
16,100	440	BS	60
16,600	470	BS	75
	Copper Plate Thickness-0.050 mil		
16,900	230	BS	25
17,200	240	BS	40
17,800	290	BS	60
18,300	480	BS	90
	Copper Plate Thickness-0.125 mil		
18,000	180	BS	30
18,500	270	BS	20
18,800	320	BS	70
19,200	480	DT	80
	Copper Plate Thickness-0.250 mil		
19,200	420	BS	30
19,900	490	BS	40
20,600	530	DS	50
21,400	560	DT	70
	Copper Plate Thickness-0.50 mil		
21,400	450	BS	20
22,300	480	DS	25
23,200	540	DT	40
24,800	570	DT	50

TABLE XI

EFFECT OF NICKEL ON THE WELDING OF ALUMINUM TO STEEL

Welding Current Amperes	Spot Shear Strength Pounds	Type of Failure	Nugget Penetration Percent
	Aluminum directly to Steel		
15,200	310	BS	40
15,700	340	BS	50
16,100	440	BS	60
16,600	470	BS	75
	Nickel Plate Thickness-0.050 mil		
14,900	170	BS	35
15,300	370	DS	60
15,700	470	DS	75
16,100	520	DS	95
	Nickel Plate Thickness-0.125 mil		
14,700	200	BS	35
15,100	320	BS	55
15,400	350	BS	40
15,700	430	DS	70
	Nickel Plate Thickness-0.250 mil		
14,600	210	BS	35
15,000	300	BS	45
15,100	440	BS	70
15,400	490	DS	80
	Nickel Plate Thickness-0.50 mil		
15,000	150	BS	50
15,400	320	BS	70
15,700	480	DS	90
16,000	470	DS	90

TABLE X

Effect of Copper Plate Thickness on Spot Shear Strength for Various Nugget Penetrations

Nugget Penetration Percent	Average Spot Shear Strength in Pounds for the following Plate Thicknesses in Mils				
	.000	.050	.125	.250	.500
20	170	160	190	290	450
40	290	275	300	490	550
60	375	360	380	540	575
80	430	430	440	575	580
100	460	475	480	590	590

TABLE XII

Effect of Nickel Plate Thickness on Spot Shear Strength for Various Nugget Penetrations

Nugget Penetration Percent	Average Spot Shear Strength in Pounds for the following Plate Thicknesses in Mils				
	.000	.050	.125	.250	.500
20	170	120	120	120	120
40	290	240	240	240	240
60	375	365	365	365	360
80	430	475	475	470	470
100	470	530	530	530	530

TABLE XIII

EFFECT OF CHROMIUM ON THE WELDING OF ALUMINUM TO STEEL

Welding Current Amperes	Spot Shear Strength Pounds	Type of Failure	Nugget Penetration Percent
	Aluminum directly to steel		
15,200	310	BS	40
15,700	340	BS	50
16,100	440	BS	60
16,600	470	BS	75
	Chromium Plate Thickness-0.050 mil		
18,600	320	BS	40
19,300	340	BS	50
20,000	350	BS	60
20,700	450	BS	95
	Chromium Plate Thickness-0.125 mil		
18,600	350	BS	40
19,300	360	BS	45
19,900	450	BS	70
20,700	420	DS	70
	Chromium Plate Thickness-0.250 mil		
18,600	370	BS	40
19,300	440	BS	45
19,900	460	BS	70
20,600	470	DS	80
	Chromium Plate Thickness-0.50 mil		
18,400	430	BS	35
19,000	470	DS	40
19,800	470	DS	40
20,400	500	DS	50

TABLE XIV

Effect of Chromium Plate Thickness
on Spot Shear Strength
for Various Nugget Penetrations

Nugget Penetration Percent	Average Spot Shear Strength in Pounds for the following Plate Thicknesses in Mils				
	.000	.050	.125	.250	.500
20	170	175	175	240	275
40	290	290	300	370	460
60	375	375	390	450	530
80	430	430	460	505	560
100	460	460	515	550	580

TABLE XVI

Effect of Cadmium Plate Thickness
on Spot Shear Strength
for Various Nugget Penetrations

Nugget Penetration Percent	Average Spot Shear Strength in Pounds for the following Plate Thicknesses in Mils				
	.000	.050	.125	.250	.500
20	170	115	190	230	185
40	290	285	335	345	340
60	375	415	435	410	440
80	430	480	510	470	495
100	460	525	550	525	525

TABLE XV

EFFECT OF CADMIUM ON THE WELDING OF ALUMINUM TO STEEL

Welding Current Amperes	Spot Shear Strength Pounds	Type of Failure	Nugget Penetration Percent
	Aluminum directly to Steel		
15,200	310	BS	40
15,700	340	BS	50
16,100	440	BS	60
16,600	470	BS	75
	Cadmium Plate Thickness-0.05 mil		
14,900	40	BS	10
15,400	190	BS	30
16,200	330	BS	50
16,600	460	DS	70
16,900	520	DS	95
	Cadmium Plate Thickness-0.125 mil		
15,400	120	BS	10
15,800	340	BS	50
16,400	490	DS	70
16,700	540	DS	90
	Cadmium Plate Thickness-0.25 mil		
15,400	360	BS	50
16,000	400	BS	50
16,400	480	DS	80
16,700	500	DS	95
	Cadmium Plate Thickness-0.50 mil		
15,800	210	BS	40
16,200	420	BS	50
16,600	470	DS	60
17,000	500	DS	75

TABLE XVII

Contact Resistance Measurements

Stock-0.030" 3S half-hard clad with
4% silicon brazing alloy
(aluminum fin material)

Treatment-Solution #5, Sulfuric Acid (conc.) - 10 ml./liter
Nacconal NR-2g./liter, pH-1.05, temperature-180° F

4" radius dome tips

1000 lbs. pressure

Time of Treatment Minutes	Average Contact Resistance-Microhms	
	3S half-hard surface	Brazing alloy surface
0	over 1000	over 1000
2	16	14
4	3,7	3
6	3.7	2
8	4	3.7
15	7.7	5.3

TABLE XVIII

Effect of Brazing Alloy Cladding

on Spot Welding of 0.030" 3S half-hard to 0.090" SAE 4140

Electrodes-4" R dome in contact with aluminum

1-1/4" flat in contact with steel

No Stainless Steel Insert Used

Weld Pressure 800 lbs.

Weld Time 23 cycles

	Welds made with 3S half-hard	Welds made with 3S half-hard clad with brazing alloy
Minimum Current for producing fusion in aluminum	11,000 amps.	10,500 amps.
Maximum Current for avoidance of martensite in SAE 4140	11,800 amps.	11,800 amps.
Properties of welds made at 11,800 amps.		
Spot Shear Strength	320 lbs.	475 lbs.
Nugget Penetration	3%	10%
Type of Failure	B.S.	D.S.

TABLE XIX

Effect of Welding Time and Stainless Steel Insert Thickness on Spot Welding of 0.030" 3S half-hard to Silver Plated 0.090" SAE 4140

Stainless Steel Insert Thickness

	0.006"	0.011"	0.023"
3 cycle weld	Stainless steel-aluminum alloying	Stainless steel-aluminum alloying	Stainless steel-aluminum alloying
5 cycle weld	-------------	O.K.	Some stainless steel-aluminum alloying
10 cycle weld	Martensite forms in 4140 before maximum bonding occurs	O.K., but close to martensite forming conditions	O.K., but close to stainless steel-aluminum alloying
23 cycle weld	--------------	Martensite forms in 4140 before maximum bonding occurs	---------------

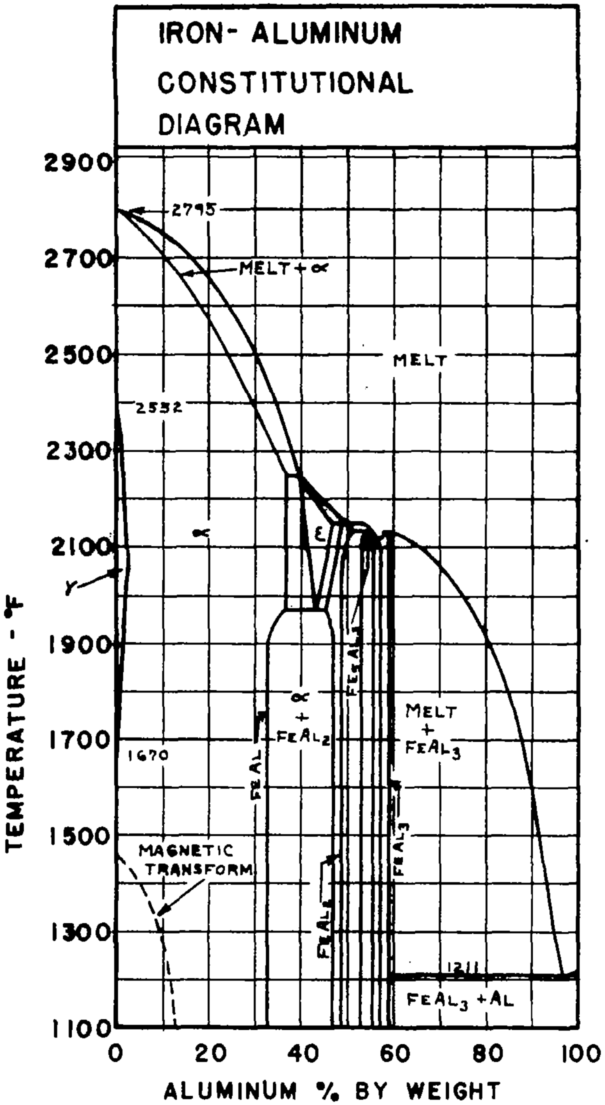

IRON- ALUMINUM
CONSTITUTIONAL
DIAGRAM
2900
2700
2500
2300
2100
1900
1700
1500
1300
1100
2795
MELT + α
MELT
2532
α
γ
ε
α
+
FeAl2
FeAl
FeAl2
FeAl3
MELT
+
FeAl3
FeAl3
1670
MAGNETIC
TRANSFORM
1211
FeAl3 + Al
0
20
40
60
80
100
TEMPERATURE - °F
ALUMINUM % BY WEIGHT

FIG. 1

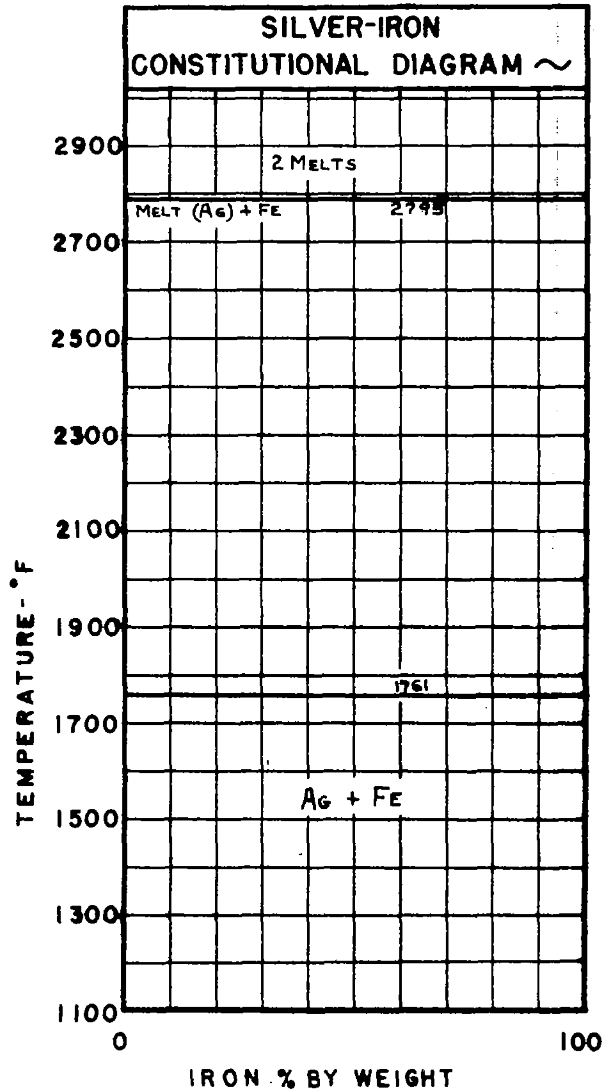

SILVER-IRON
CONSTITUTIONAL DIAGRAM
2900
2700
2500
2300
2100
1900
1700
1500
1300
1100
2 MELTS
MELT (AG) + FE
2795
1761
AG + FE
0
100
TEMPERATURE - °F
IRON % BY WEIGHT

FIG. 2

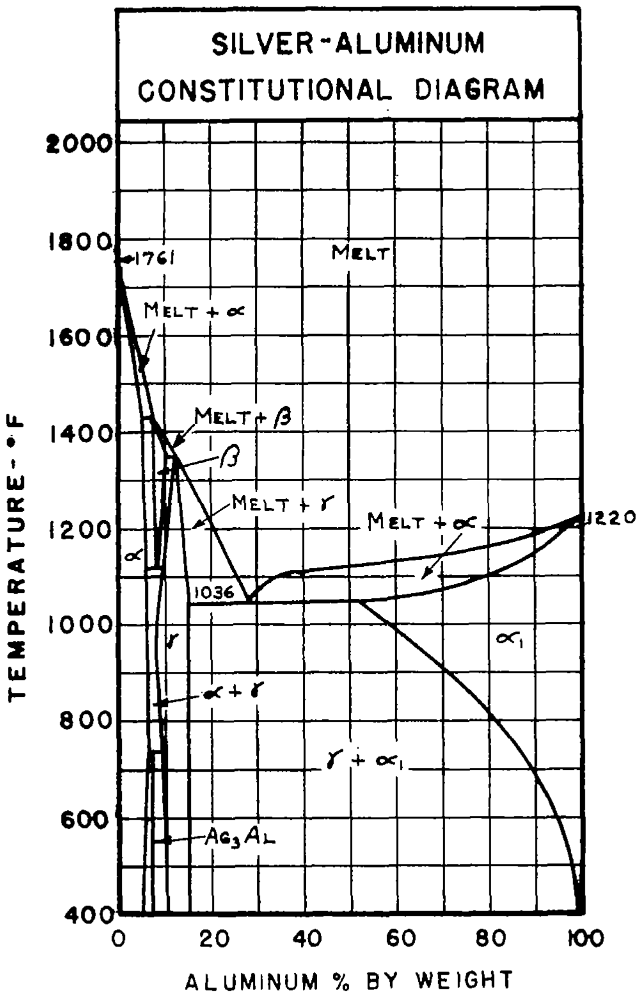


FIG. 3

PRESS FOR THE MEASUREMENT OF CONTACT RESISTANCE

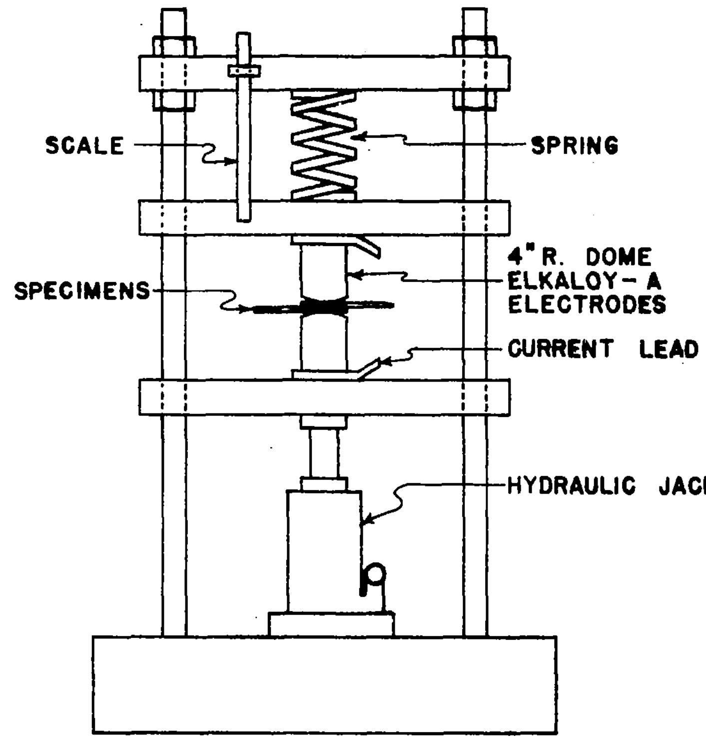
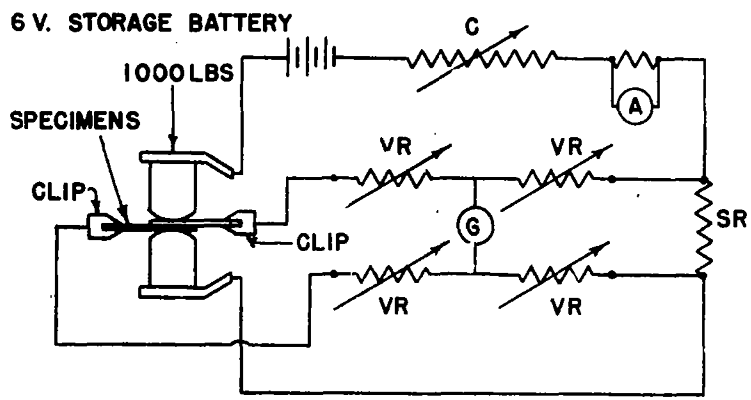


FIG. 4

KELVIN DOUBLE BRIDGE CIRCUIT



A - AMMETER
G - GALVANOMETER
C - CARBON PILE RESISTOR
VR - VARIABLE RESISTANCE ARM
SR - STANDARD RESISTANCE = 6.33×10^{-6} OHMS

FIG. 5

CONTACT RESISTANCE MEASUREMENTS

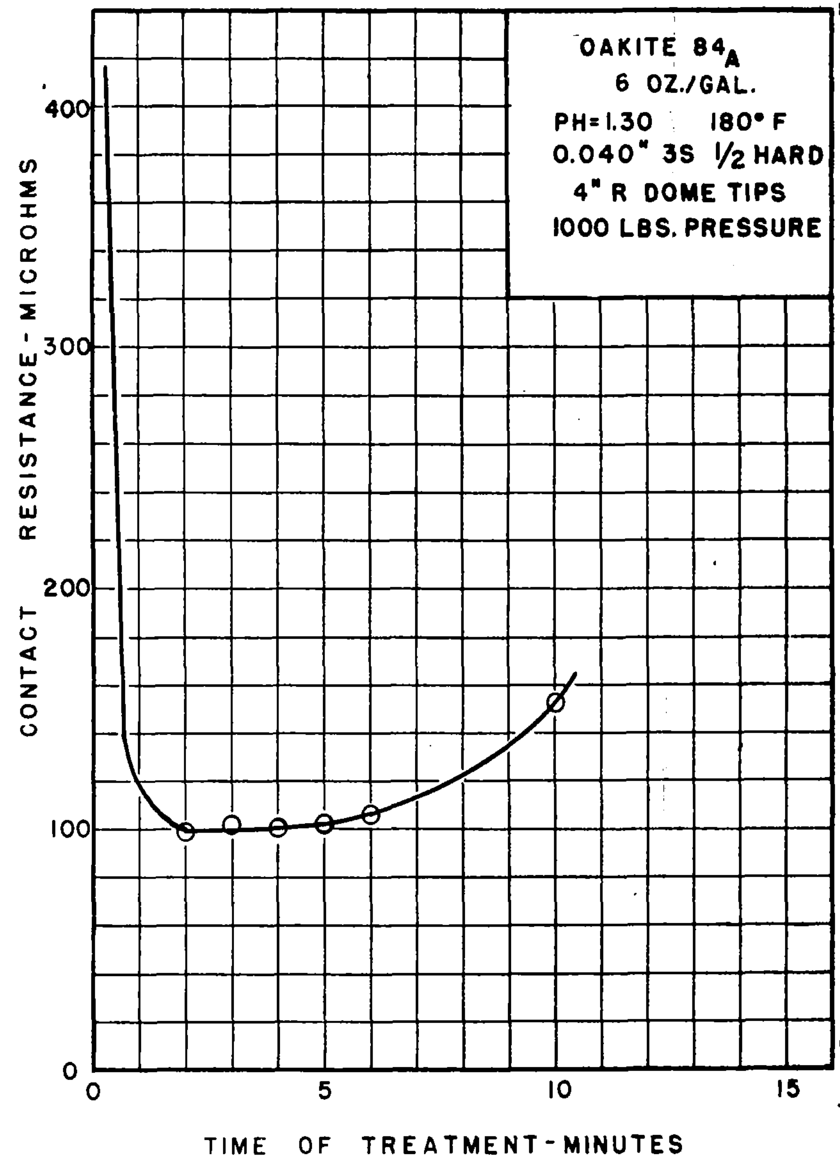


FIG. 6

Figure 7.- Photomacrograph of aluminum welded to steel. Etched with 1.5 percent HF. Black area in aluminum sheet is the fused zone or weld nugget. 12 X

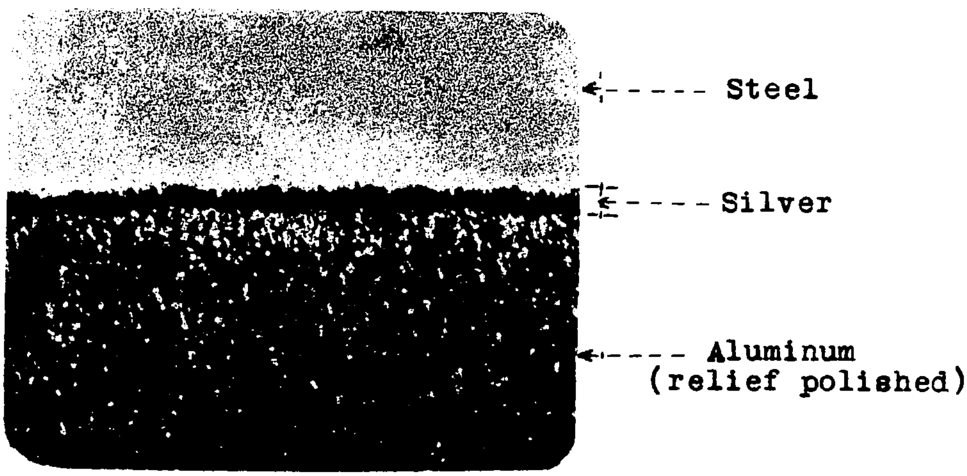


Figure 15.- Photomicrograph of weld interface. Aluminum welded to 0.25 mil silver plated steel. 1000X polished, unetched.

EFFECT OF TIN THICKNESS ON WELD PROPERTIES

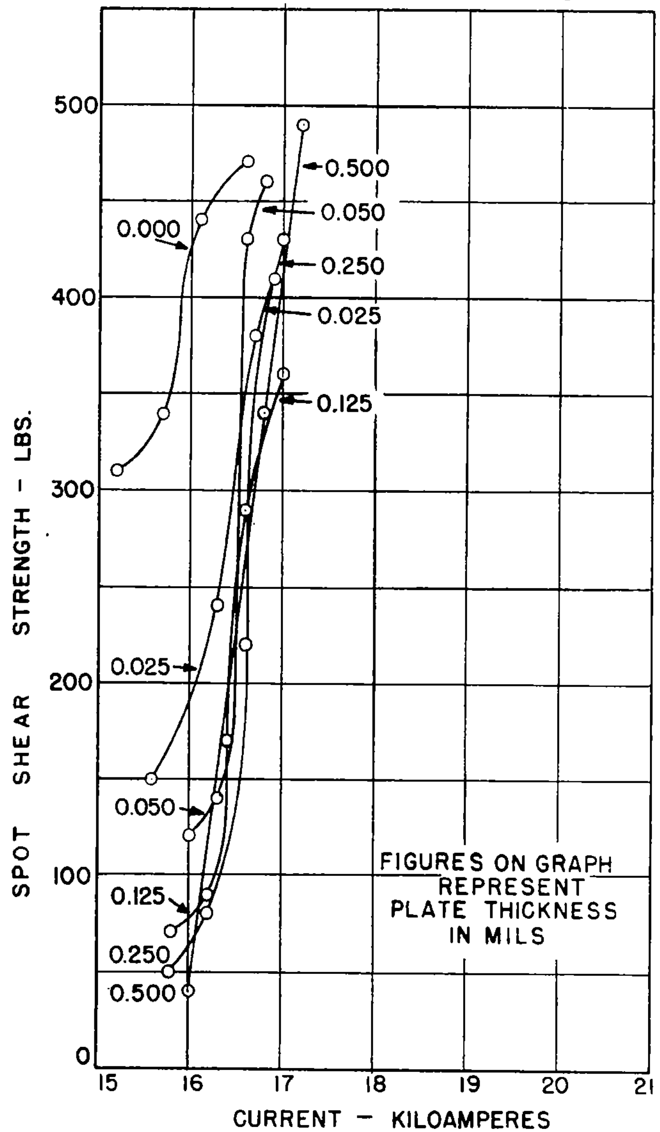


FIG. 8

EFFECT OF NUGGET PENETRATION ON SPOT SHEAR STRENGTH FOR ALUMINUM WELDED TO TIN PLATED STEEL

PLATE THICKNESS - 0.125 MIL

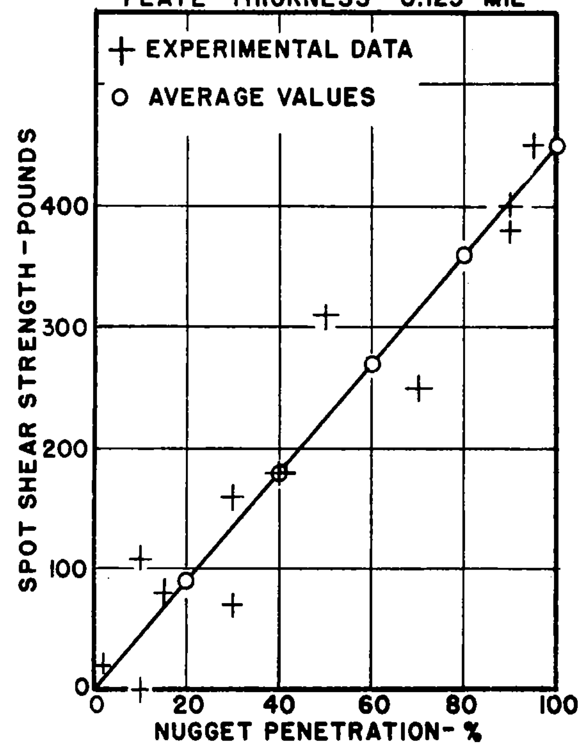


FIG. 9

EFFECT OF TIN PLATE THICKNESS ON SHEAR STRENGTH FOR VARIOUS NUGGET PENETRATIONS

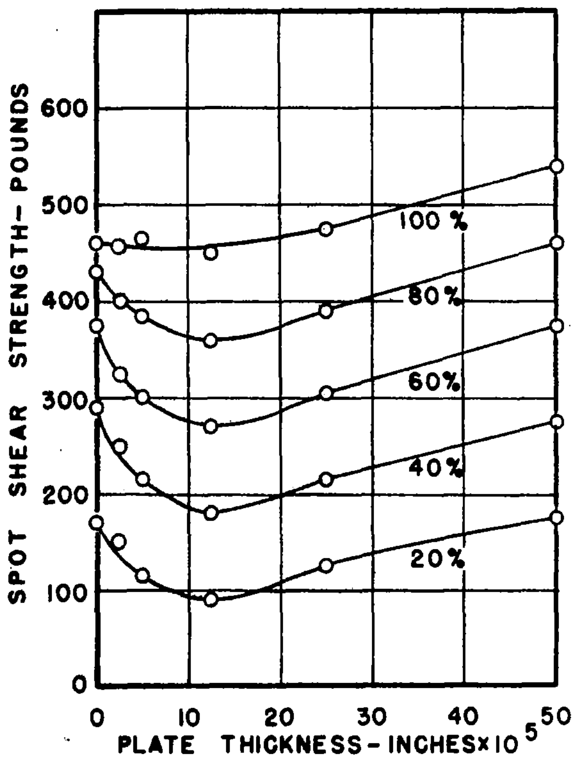


FIG. 10

EFFECT OF ZINC THICKNESS ON WELD PROPERTIES

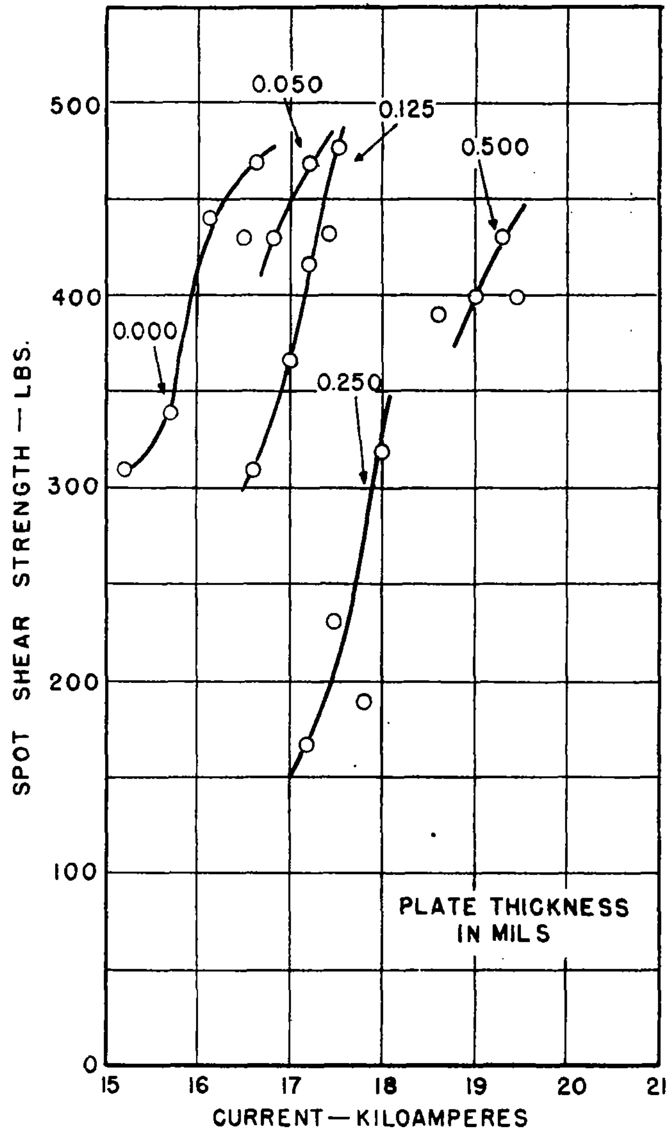


FIG. 11

NACA

Figs. 10,11

EFFECT OF ZINC PLATE THICKNESS ON SHEAR STRENGTH FOR VARIOUS NUGGET PENETRATIONS

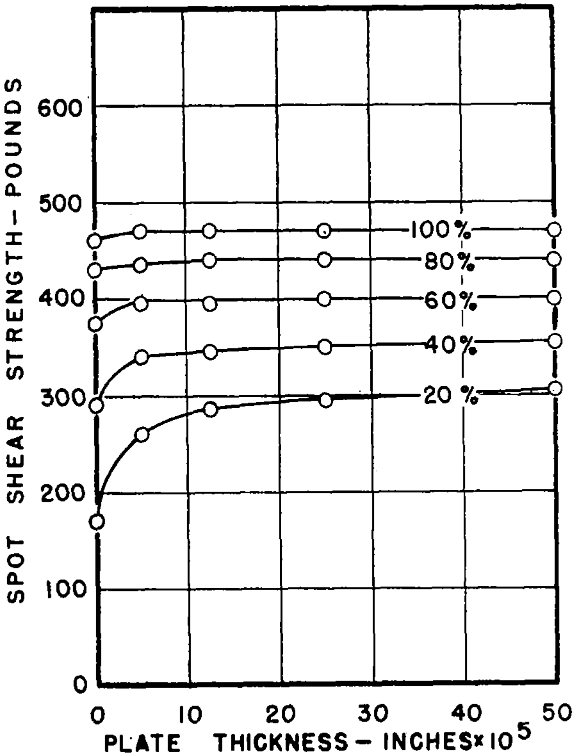


FIG. 12

EFFECT OF SILVER THICKNESS ON WELD PROPERTIES

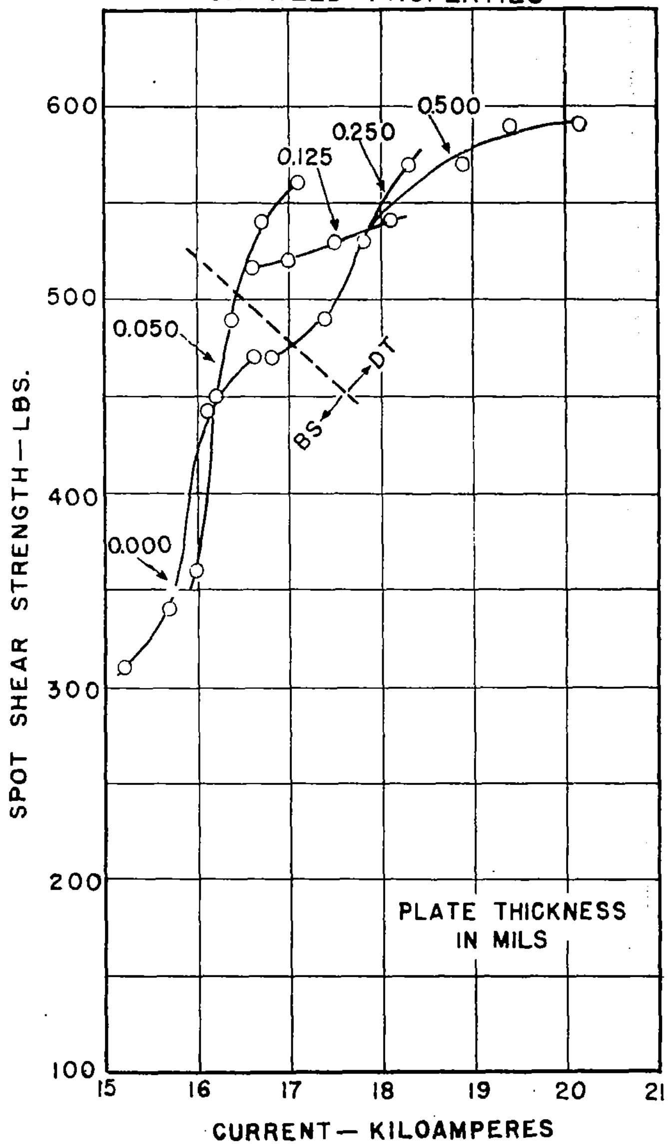


FIG. 13

EFFECT OF SILVER PLATE THICKNESS ON SHEAR STRENGTH FOR VARIOUS NUGGET PENETRATIONS

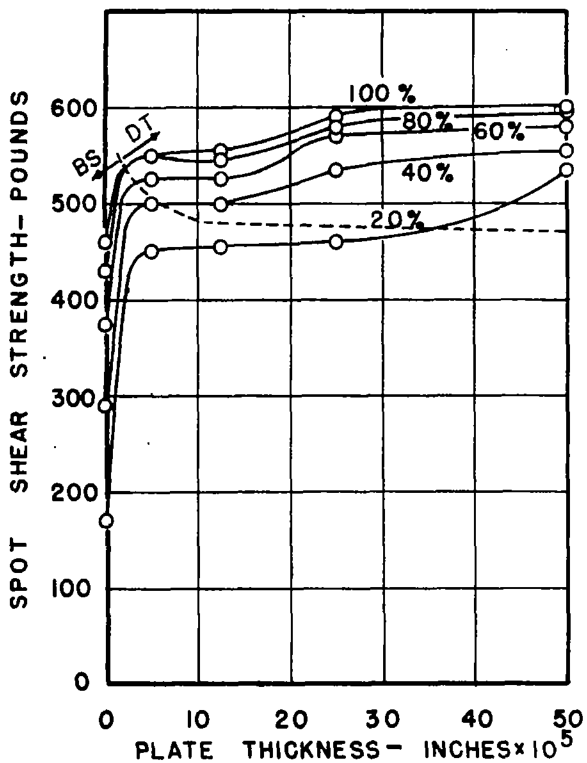


FIG. 14

EFFECT OF COPPER THICKNESS ON WELD PROPERTIES

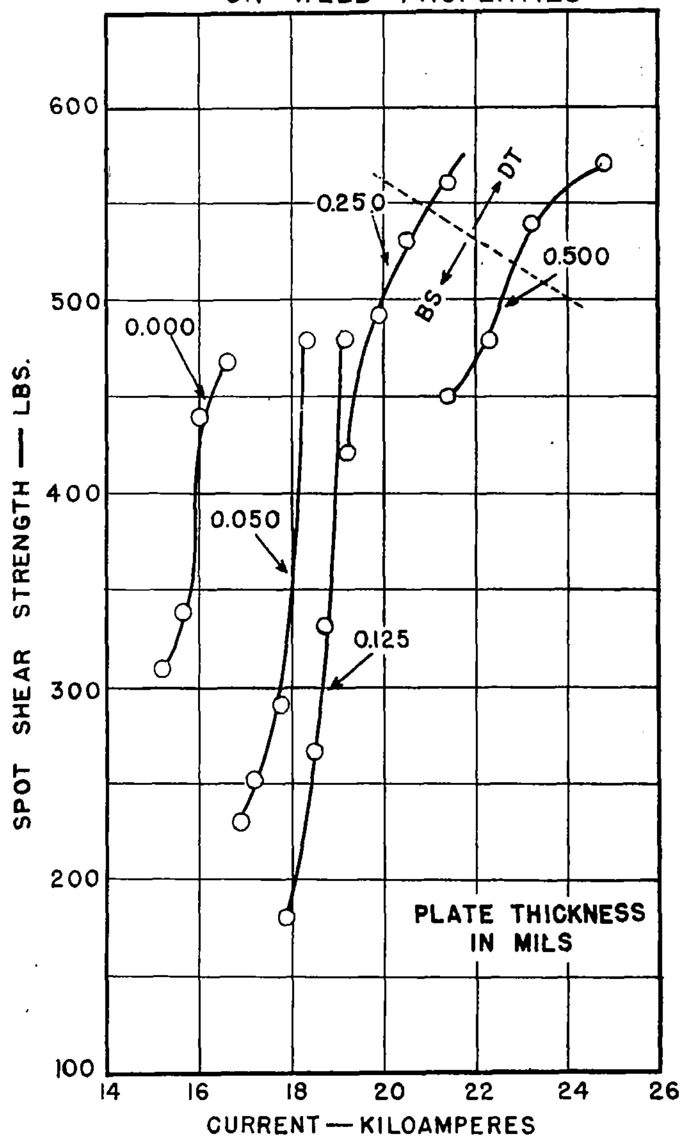


FIG. 16

EFFECT OF COPPER PLATE THICKNESS ON SHEAR STRENGTH FOR VARIOUS NUGGET PENETRATIONS

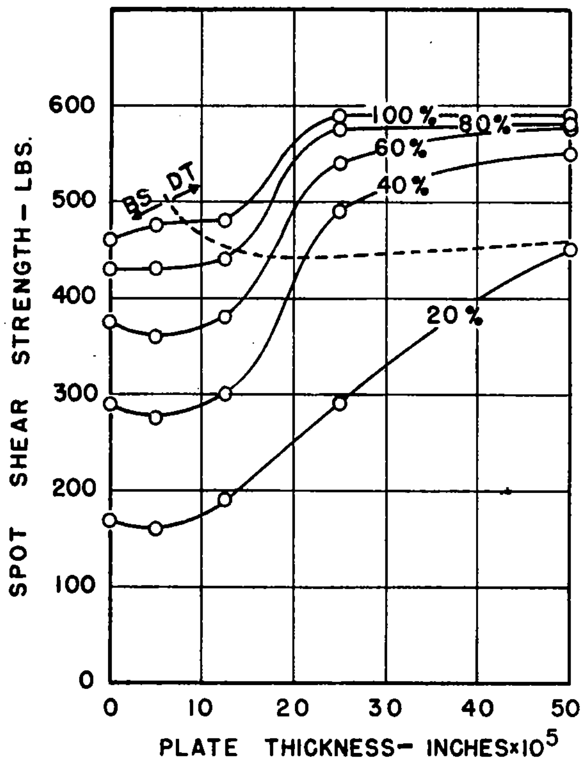


FIG. 17

EFFECT OF NICKEL THICKNESS ON WELD PROPERTIES

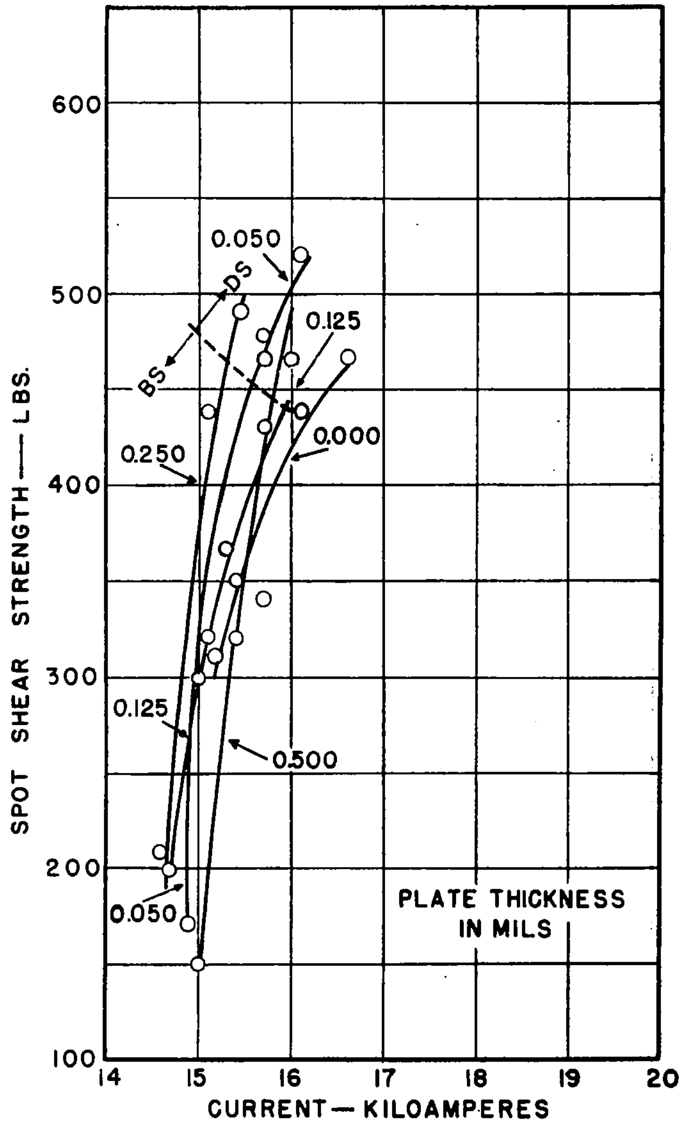


FIG. 18

EFFECT OF NICKEL PLATE THICKNESS ON SHEAR STRENGTH FOR VARIOUS NUGGET PENETRATIONS

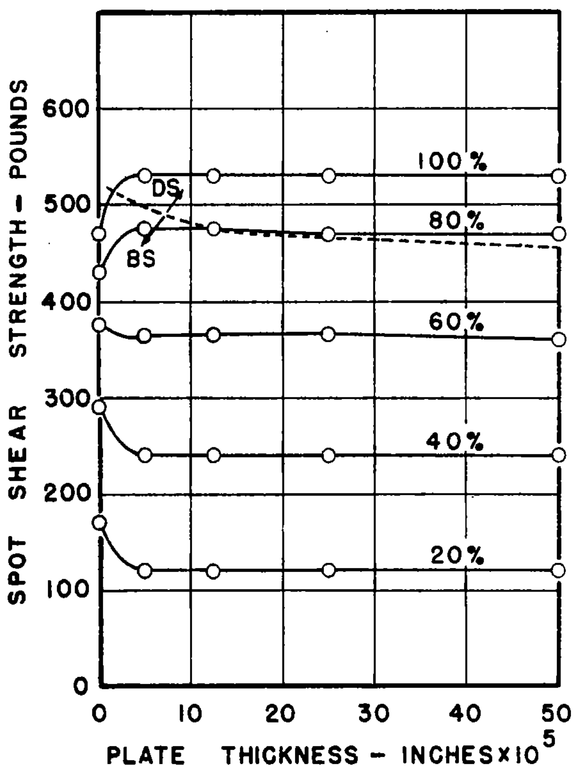


FIG. 19

EFFECT OF CHROMIUM THICKNESS ON WELD PROPERTIES

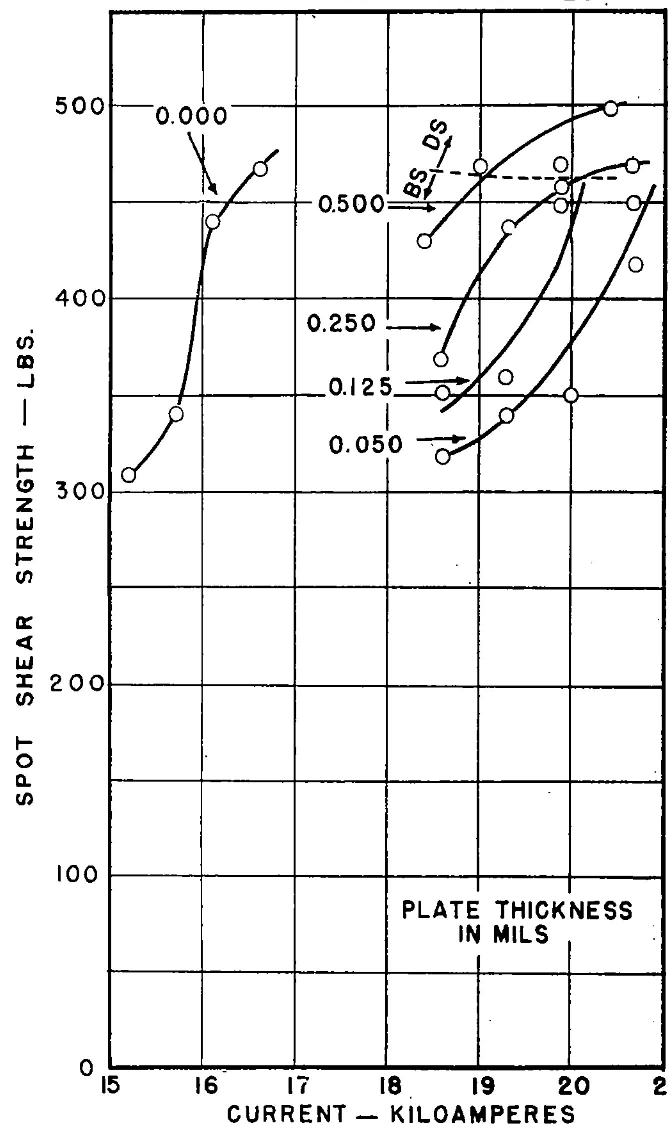


FIG. 20

EFFECT OF CHROMIUM PLATE THICKNESS ON SHEAR STRENGTH FOR VARIOUS NUGGET PENETRATIONS

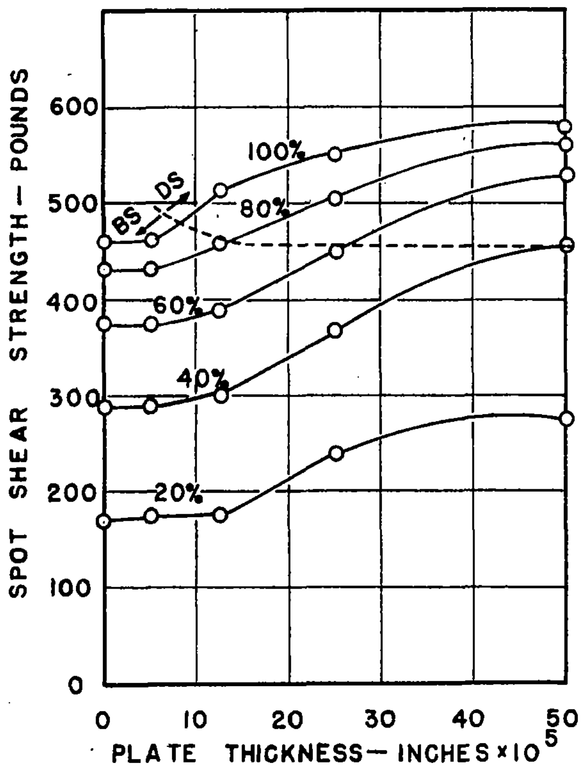


FIG. 21

EFFECT OF CADMIUM THICKNESS ON WELD PROPERTIES

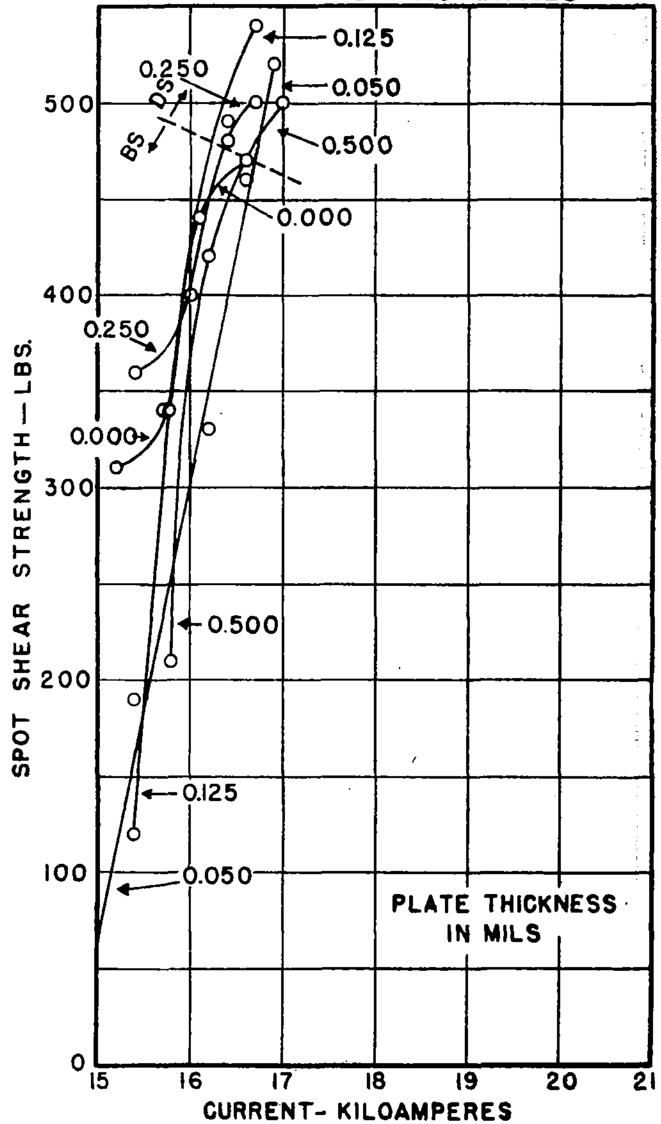


FIG. 22

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Figs. 21,22

EFFECT OF CADMIUM PLATE THICKNESS ON SHEAR STRENGTH FOR VARIOUS NUGGET PENETRATIONS

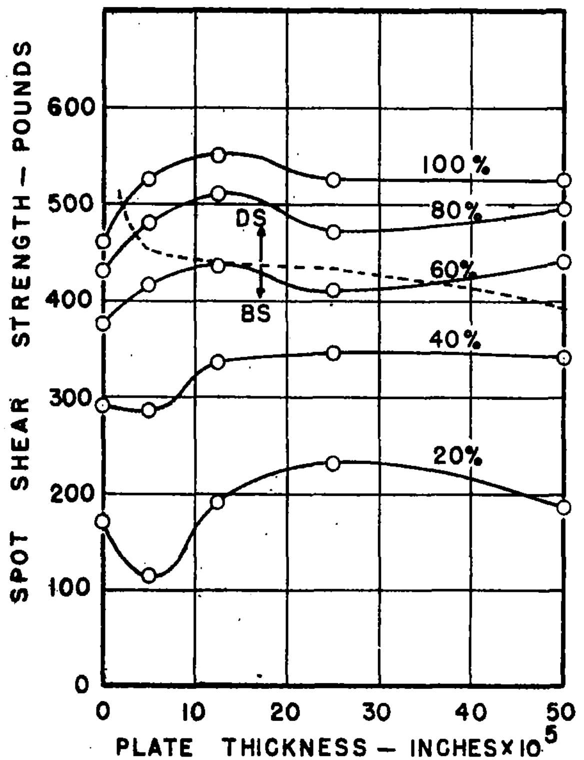


FIG. 23

CONTACT RESISTANCE MEASUREMENTS

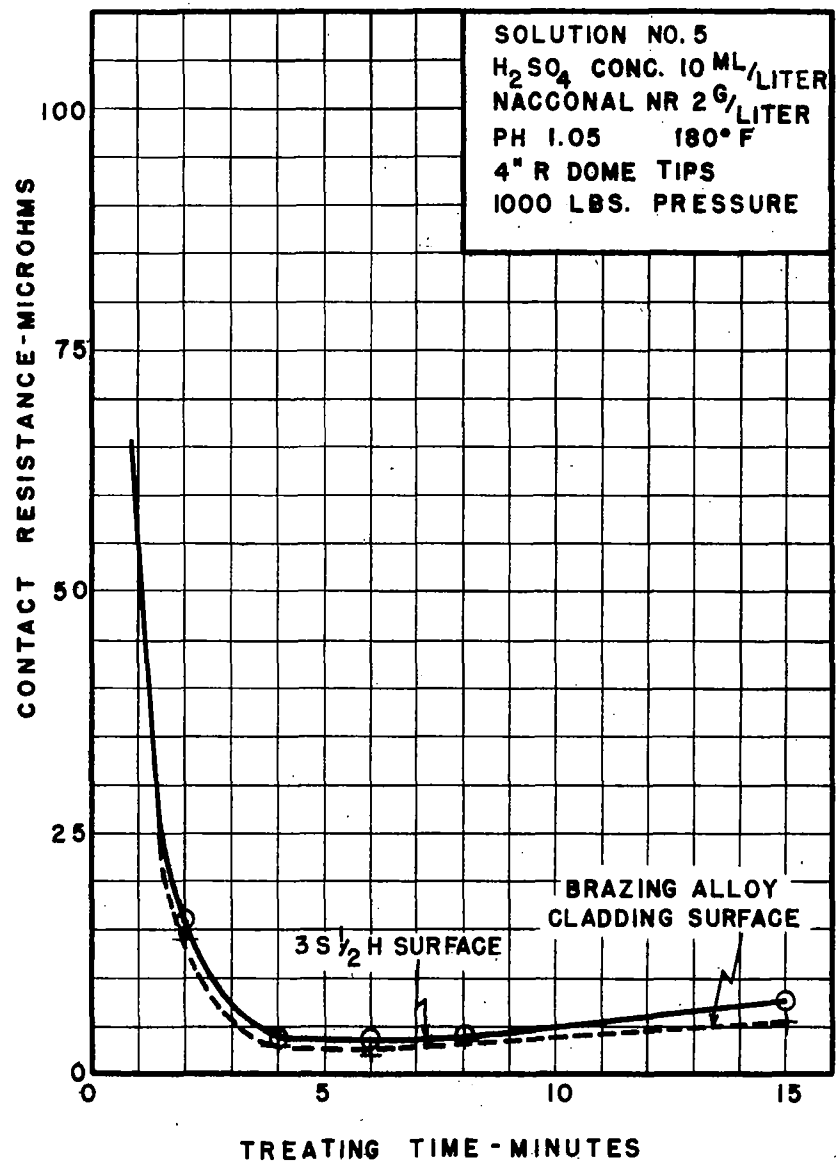


FIG. 24

"S" CURVE FOR S.A.E. 4140

TRANSFORMATION OF AUSTENITE AT CONSTANT SUB-CRITICAL TEMPERATURE

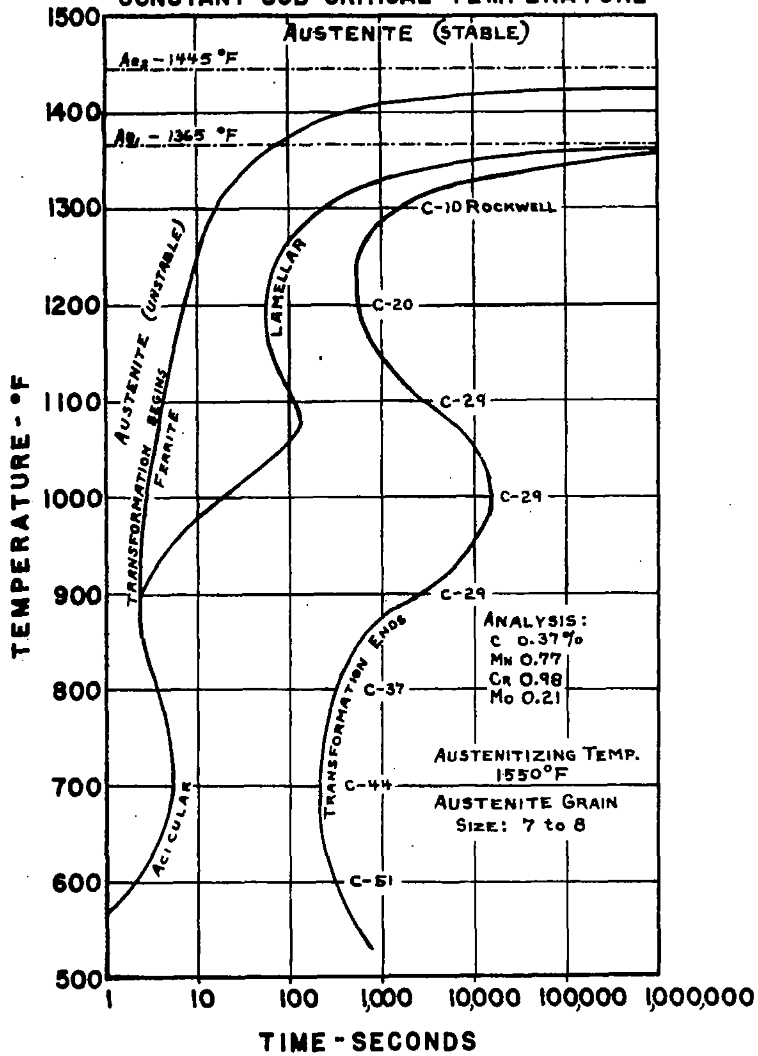


FIG. 25

METHOD FOR CONCENTRATING HEAT AT ALUMINUM-SILVER INTERFACE

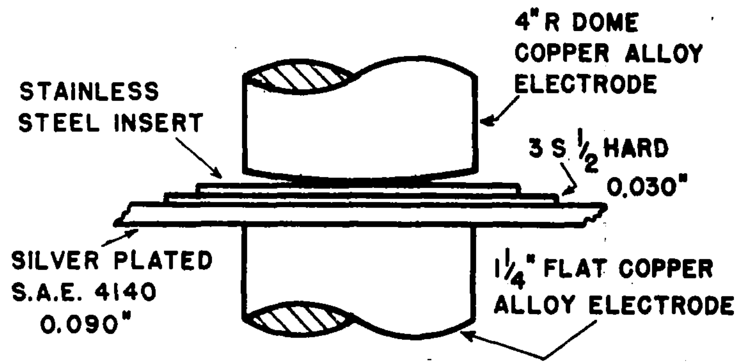
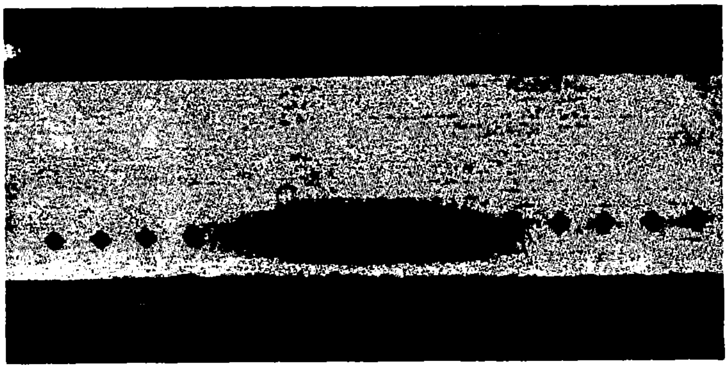


FIG. 26

MARTENSITIC FORMATION
IN S.A.E. 4140 - 12X
ETCHED WITH 2% NITAL



HARDNESS SURVEY OF ABOVE SPECIMEN

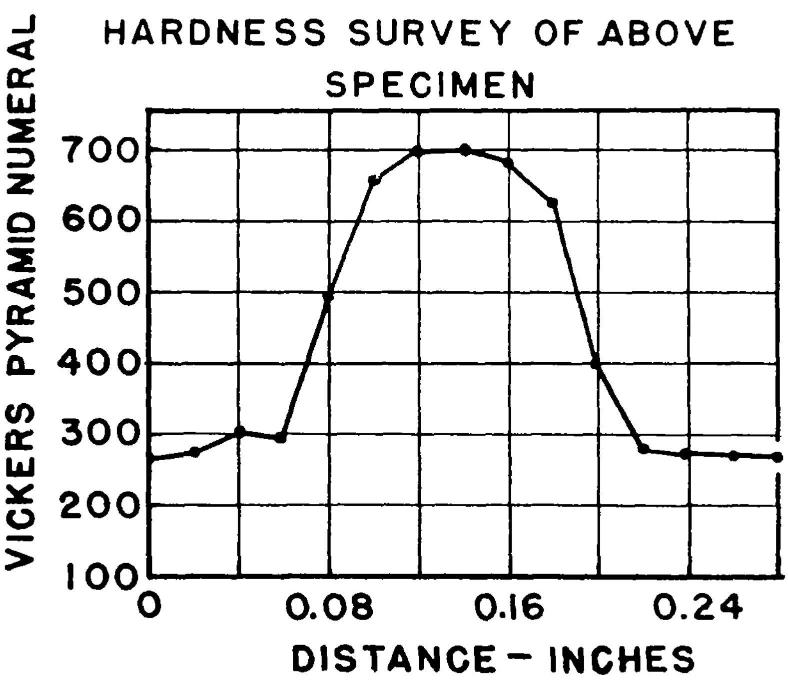


FIG. 27

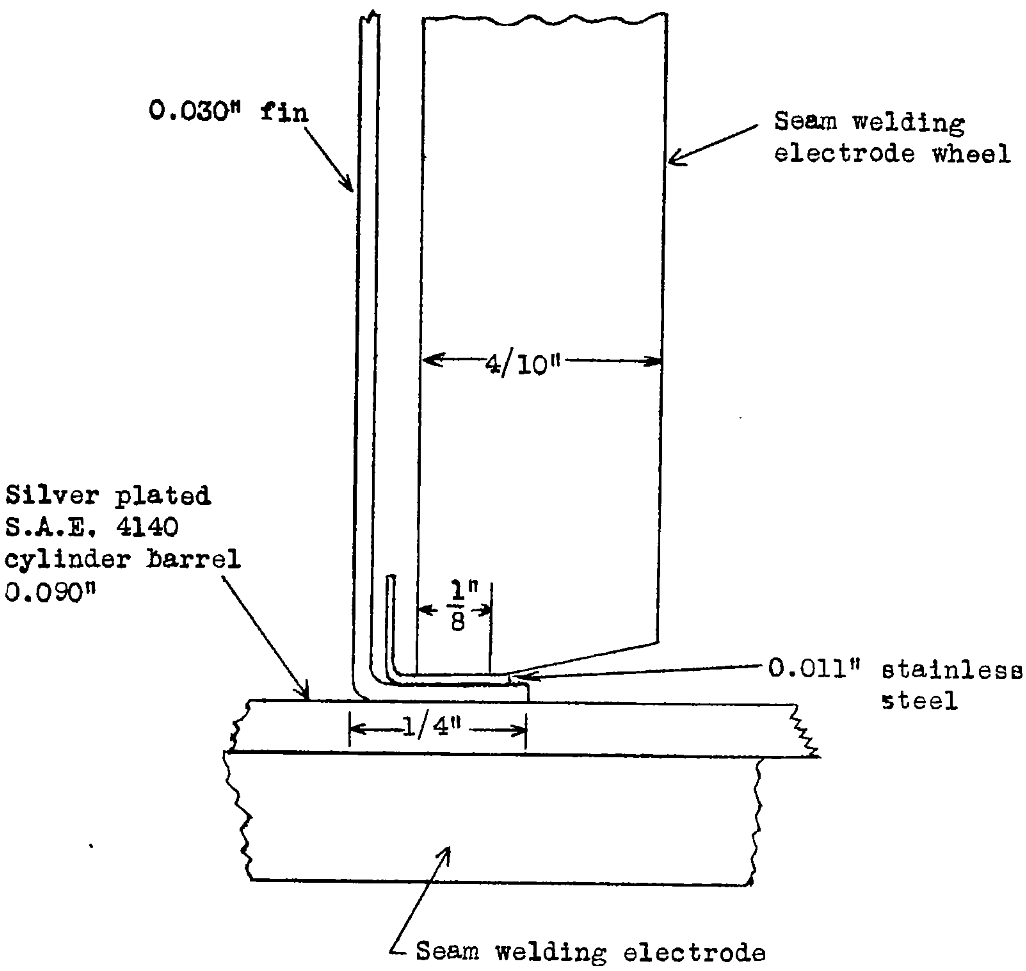


Figure 28.- Seam welding of fins to S.A.E. 4140 cylinder barrel.

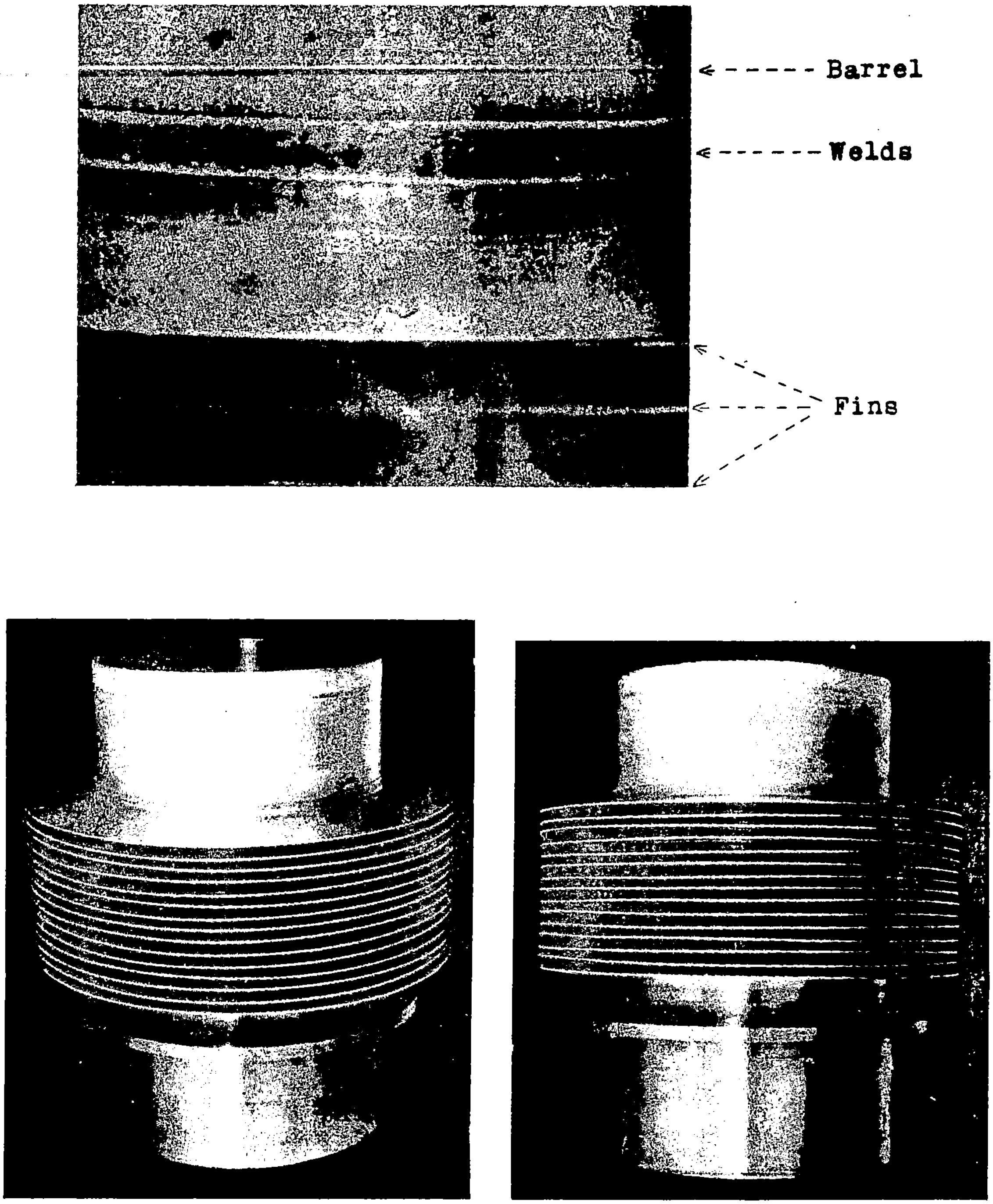


Figure 29.- Photographs of seam welded cylinder barrel.

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	REVISION (None)
AUTHOR(S) : Hess, W. F.; Nippes, E. F., Jr.	**ORIG. AGENCY NO.** ARR-4A01
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ABSTRACT:

Investigation studies variety of metals used as intermediates between aluminum and steel for purpose of securing bond having strength and thermal conductivity. Satisfactory bond between aluminum and steel formed by electroplating steel with layer of silver. Welding equipment completes bond between aluminum and silver plating. It was found desirable to secure heat balance using high resistance insert between electrode and aluminum. Electroplating procedures studied, and optimum conditions developed for plating bonds of maximum strength upon steel.

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