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Metallurgy and Ceramics

ULTRASONIC WELDING OF ALUMINUM

by
J. Byron Jones
Carmine F. De Prisco
John G. Thomas

AEROPROJECTS INCORPORATED

West Chester, Pennsylvania

February 1955

Issued By

E. I. du Pont de Nemours & Co.
Explosives Department — Atomic Energy Division
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ABSTRACT

At various stages in the development of the ultrasonic welding process, test coupons of 2S aluminum were prepared to evaluate weld strength, the effect of thermal cycling up to 350°C, and corrosion resistance in an environment of 95°C aerated, distilled water. Substantial improvement in weld strength was obtained during the term of the program, and metallographic examination revealed good solid-phase bonding in isolated areas of the ultrasonically affected zone. Thermal cycling up to about 250°C had no effect on weld strength, although higher temperatures produced an adverse effect; improvement in thermal shock resistance may be possible. No effect of the corrosion environment was observed in five months of exposure. The significance of surface cleaning on weld quality was not clearly established.

Specimen 2S aluminum rib assemblies fabricated with ultrasonic welding techniques established the feasibility of using this joining method for certain end-item configurations. With further development, the process will have substantial merit for application to many AEC end-item assembly problems.

External Distribution according to
TID-4500, 9th Edition

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ULTRASONIC WELDING OF ALUMINUM

INTRODUCTION

This program on the joining of aluminum by means of ultrasonic welding was undertaken to obtain information which could be applied specifically to ribbed aluminum components required for heat transfer purposes.

Earlier research and development effort by Aeroprojects* had demonstrated that solid-phase welding of aluminum could be accomplished by suitable application of elastic vibratory energy--ultrasonics--without the use of heat, solders, of fluxes. The pieces to be joined, such as two lapping sheets, are clamped at low pressure between the tips of two rod-like members called sonotrodes. A brief pulse of ultrasonic energy is introduced into the work pieces through these sonotrodes, which constitute the terminus of the ultrasonic transducer-coupling system. If one of the work pieces is a massive member such as a rod or a plate, it can be suitably clamped and supported in proper location and the second rod-like member can be dispensed with.

With this type of bonding, thickness deformation of aluminum sheet has been found to be less than about 5 per cent. The ultrasonic welding process is therefore different from ordinary pressure welding, which is carried out at very high applied forces and which results in deformations in the range of 60 to 80 per cent.

Development of the ultrasonic welding process was first undertaken in June 1952 by Aeroprojects for the Frankford Arsenal, Department of the Army*. The initial work established the practicability of bonding 2S aluminum in sheet gages up to about 0.020 inch thick. Ultrasonically welded lap specimens were exposed to corrosion environments of aerated distilled water at 95°C and 3 per cent sodium chloride solution at 40°C, with no loss of tensile-shear strength after 5000 hours of exposure. Sealing of lapped wall tubes and pressure specimens was accomplished with overlapping spots which withstood hydraulic pressures in excess of 100 pounds per square inch for seven hours with no evident leakage.

* Aeroprojects Incorporated, "The Application of Ultrasonic Energy to Cold Welding of Metals," Research Report No. 53-77, November 1953. (Contract No. DA-36-034-ORD-1007 for Pitman-Dunn Laboratories, Frankford Arsenal, Department of the Army, Philadelphia, Pennsylvania).

The work reported herein was undertaken to examine the potentialities of the process, with the particular view to determining the feasibility of fabricating ribbed aluminum members.

SUMMARY

This program on the joining of aluminum was undertaken to provide information of significance in the fabrication of ribbed aluminum components employed for heat exchange purposes. The eventual objective was to fabricate, by ultrasonic welding methods, a sound rib-to-tube joint which would provide strength approximating that of the parent metal, withstand a corrosion environment of 95°C aerated distilled water, and withstand thermal cycling over the range of zero to several hundred degrees Centigrade.

For convenience, most of the test specimens were prepared from tab coupons of 2S aluminum, which were overlapped and ultrasonically welded with a single spot. Welds were evaluated by strength tests, and by visual and metallographic examination. The effects on weld strength of five months of exposure in the specified corrosion environment, of thermal cycling to 350°C, and of various precleaning processes, were determined. Specimen rib assemblies, approximating end-item configurations, were fabricated from 2S aluminum using ultrasonic welding techniques.

As a result of this investigation, it was concluded that:

1. The ultrasonic welding process for joining 2S aluminum has been confirmed as a promising method for attaching ribs to tubes.

2. Although marked improvement in ultrasonically welding 2S aluminum was made during the term of this investigation, it is clear that the process remains subject to further improvement.

3. Ultrasonically welded 2S aluminum is unaffected by a 95°C aerated distilled water corrosion environment, at least for exposures up to five or six months.

4. Although the weld strength of thermal-cycled 2S aluminum test specimens was adversely affected when the peak temperature exceeded about 250°C, it is possible that the relatively unclean condition of the specimens prior to welding decreased the resistance of these specimens to thermal shock.

5. The adverse effect of strong cleaning procedures on the strength of ultrasonically welded coupons cannot be accepted as specific, since the strong cleaners used affected the surface finish of the material.

6. Inasmuch as rolled and extruded 2S aluminum of the same gage, when cleaned with strong solutions, exhibited about the same average tensile-shear strengths, there appears to be no difference between the ultrasonic weldability of these two types of materials.

7. The black deposit found adjacent to ultrasonic welds requires further study.

On the basis of these conclusions, it is recommended that the ultrasonic welding process be further developed with the view to welding aluminum components of significance to the Atomic Energy Commission.

DISCUSSION

OBJECTIVES OF THE STUDY

The eventual objective of the project initiated by the investigations herein reported was to fabricate, by ultrasonic welding methods, a sound rib-to-tube joint, which would provide strength approximating that of the parent metal, withstand a corrosive environment of low-conductivity, aerated, distilled water at 95°C, and withstand thermal cycling over the range of zero to several hundred degrees Centigrade.

EXPERIMENTAL PROCEDURES

The program involved the development of ultrasonic welding equipment suitable for the intended purpose, the exploration of welding techniques, and the approximation of satisfactory ultrasonic welding parameters. For convenience, much of the exploratory work was carried out on single-lap specimens of 2S aluminum sheet material. As techniques became established, several types of rib specimens were fabricated and tested. The lap welds were evaluated by strength tests, by corrosion and thermal cycling tests, and by metallographic examination.

Ultrasonic Welding Equipment

The equipment for accomplishing ultrasonic welding consisted essentially of electronic driving equipment, the ultrasonic welding array which was mounted on a drill press stand, and auxiliary control devices.

The driving equipment was an electronic power generating unit incorporating an untuned Class B amplifier with a frequency range of 5 to 100 kilocycles per second, which operated on a 3000-volt d-c power supply and was driven by a stable oscillator unit followed by a buffer amplifier. The output stage consisted of 304TL tubes in push-pull connection, the maximum available power output being in the order of 2400 r-f watts. A pulsing system for controlling the length of the signal input to the Class B amplifier, and thus the welding time, was provided by adopting a condenser-discharge electronic timer of the type used for photographic purposes.

The welding unit itself consisted of two welding tip assemblies or sonotrodes: the upper, a transducer-driven sonotrode for transmitting the vibratory energy into the work piece, and an opposing or reflector sonotrode for preventing transmittance of the elastic energy through and beyond the weld zone. The acoustical geometry of these sonotrodes was repeatedly revised throughout the program as a consequence of the Frankford Arsenal development work devoted to the basic process.

The final ultrasonic welding array is shown in Figure 1. The transducer sonotrode was essentially a metal reed with its axis perpendicular to the plane of the mating surfaces of the pieces to be welded. The transducer-coupling, attached at right angles to and driving the reed, consisted of a metal coupler bar and a laminated-nickel stack transducer which was excited by applied r-f current from the electronic source described above at a nominal frequency of 15 kilocycles per second. The elastic vibratory energy was transmitted through the coupler into the metal reed, which delivered the energy as shear vibration at the face of the pieces.

The lower or reflector sonotrode was a metal member adjusted in length and/or mass so as to be noncompliant at the critical frequency. This member had a flat, massive tip to support the parts being welded. Specially designed support fixtures were used to weld various configurations of parts.

Clamping load was applied to the weldment by means of an air-powered cylinder under the lower sonotrode. After clamping load was applied, the ultrasonic energy cycle was manually triggered, its time duration being controlled by the automatic timer. The complete array of equipment is shown schematically in Figure 2.

Preparation of Specimens

Standard Lap Specimens

During the course of the program, single-lap specimens, each containing a single weld spot, were prepared for several types of determinations: tensile and tensile-shear tests, corrosion tests, and thermal cycling tests.

All lap specimens were of 2S aluminum, either rolled half-hard or extruded, in sheet gages from .005 to .062 inch. The majority of the specimens were made from tabs of rolled material .010 inch thick welded to tabs of rolled material .032 inch thick, since these were the gages which approximated those of one of the contemplated end uses. These standard tabs, 1/2 inch wide by 2 inches long, were assembled with a nominal overlap of 1/2 inch, as shown in Figure 3, after preliminary experiments had established that this overlap provided edge distances adequate to determine weld strength. All specimens were degreased either in acetone, methyl-ethyl ketone, or trichloroethylene prior to further cleaning procedures or welding.

Variation in Welding Parameters

Because of the limitations and capabilities of the various arrays of ultrasonic welding equipment used throughout the program, the welding conditions were varied from time to time. The frequency of operation of the several arrays ranged between 12 and 20 kilocycles per second. In addition, for each separate array, three welding parameters were varied to provide reasonable values for effective welding: (1) clamping load, the static force applied by the sonotrodes to the weldment; (2) ultrasonic exposure time, the length of the ultrasonic pulse; and (3) ultrasonic energy level, the apparent radio-frequency watts as determined by multiplying the plate current of the generator by the plate voltage. Measurements in the transducer circuit with a V.A.W. meter indicate a power factor between the generator and the transducer in the range of 30 to 40 per cent.

It will be noted in the following paragraphs that values of the force, power, and welding time covered ranges of 100 to 250 pounds, 500 to 800 r-f watts, and one to six seconds respectively. As previously mentioned, the equipment and controls were undergoing continuous revision throughout the program. For any group of tests reported, the specific values of force, power, and time were selected on the basis of a few hours' experimentation as those which gave reproducible results at that time.

Strength Test Specimens

With each revision in the welding array, and with approximation of the optimum values of welding parameters for each array, ultrasonic welds were produced in tab specimens of all gages of 2S-H14 aluminum from .005 to .062 inch. These specimens were used to determine the strength of welds produced for each set of conditions. Tabs of extruded 2S aluminum in selected gages were also welded from time to time, and experiments were carried out in welding tabs of .010-inch 2S aluminum to coupons of .032-inch 2S aluminum which had been previously soldered to brass blocks 1 x 2 x 1/4 inch.

After satisfactory welding conditions with the final welding array had been approximated, and after weld strengths had been surveyed in all gages of 2S aluminum, additional groups of tab specimens were prepared from .032- and .040-inch 2S-H14 aluminum sheet for a comprehensive series of shear and tensile tests. These specimens were welded at a clamping load of 250 pounds, 800 apparent r-f watts of energy, and six seconds exposure time.

Corrosion Test Specimens

Specimens for corrosion tests were prepared early in the program at fairly reliable values of the several parameters: 100 pounds clamping load, 550 apparent r-f watts power, and three seconds exposure time. Four hundred lap specimens were made of .010- to .032-inch 2S-H14 aluminum with the standard overlap width of 1/4 inch. An additional 20 specimens were prepared with an overlap of 1/8 inch and with the weld located on the edge of the lap to insure that the corrosive environment would penetrate to the weld zone.

Thermal Cycling Test Specimens

Single-spot lap specimens for thermal cycling tests were prepared from .010- to .032-inch 2S-H14 aluminum, under welding conditions of 150 pounds clamping load, 600 apparent r-f watts, and three seconds exposure time.

Surface Cleanliness Test Specimens

Three separate experiments were made on lap specimens in a preliminary effort to determine the effects on weld properties of precleaning the aluminum sheet. For the first experiment, lap specimens were welded at a clamping load of 150 pounds, power level of 600 apparent r-f watts, and ultrasonic exposure times of 1, 2, and 3 seconds. Prior to welding, one group of .010- and .032-inch aluminum tabs was degreased only in trichloroethylene to serve as controls, while another group was subjected to a rigorous cleaning process. This process involved the following steps:

1. Degrease at room temperature in trichloroethylene.
2. Immerse in 5% sodium hydroxide solution at 80-90°C for three to five minutes.
3. Rinse in distilled water.
4. Immerse in 50% nitric acid solution at room temperature for two minutes.
5. Rinse in distilled water.
6. Immerse in 20% phosphoric acid solution at room temperature for four to five minutes.
7. Rinse in distilled water.
8. Dry in cool air blast or wipe with tissue.

The second cleaning experiment was carried out likewise on tabs of .010- and .032-inch 2S aluminum. Welding was accomplished at a clamping load of 150 pounds, power level of 650 apparent r-f watts, and exposure times of one and three seconds. For each exposure time, one group of specimens was degreased only in trichloroethylene prior to welding; these degreased specimens served as controls. A second group was precleaned by the same process as described on the preceding page, except that the exposure time in sodium hydroxide was reduced to 90 seconds. A third group was precleaned with a hydrofluoric acid dip, using the following procedure:

1. Degrease in trichloroethylene at room temperature.

2. Flash-dip in 30% hydrofluoric acid solution.

3. Rinse in distilled water.

4. Dry in cool air blast.

For the third cleaning experiment, lap specimens were fabricated from .032-inch 2S extruded to .032-inch 2S extruded aluminum, .032-inch 2S-H14 to .032-inch 2S-H14 aluminum, .016-inch 2S-H14 to .032-inch 2S-H14 aluminum, and .016-inch 2S-H14 to .016-inch 2S-H14 aluminum. These specimens were all welded with the final equipment array, using the established optimum welding conditions for this array: 250 pounds clamping load, 800 apparent r-f watts, and six seconds exposure time. The cleaning procedure for these specimens involved cleaning with solutions of "Versene" or nitrogen-triacetic acid, since it was suggested that these materials attack aluminum oxide while leaving the base metal intact. One group of specimens for each of the combinations of aluminum noted above was precleaned with "Versene", in the following manner:

1. Degrease in trichloroethylene at room temperature.

2. Immerse in "Versene" solution at a pH of 9-10 and a temperature of 88°C for approximately 20 seconds, or until gas bubbles are liberated uniformly over the entire surface of the specimens.

3. Rinse twice in distilled water.

4. Dry in cool air blast.

Another group was precleaned in the same manner, but using a solution of nitrogen-triacetic acid rather than the "Versene" solution. For both of these groups, corresponding control specimens were degreased only in trichloroethylene prior to welding.

Bead-Welded and Seam-Welded Specimens

Brief effort was expended in bead welding and seam welding. Welding conditions included a clamping load of 100 pounds and a power level of 600 apparent r-f watts. Using 6-inch-long strips of .005-inch 2S aluminum, continuous seams were produced by drawing the lapped strips between the sonotrodes with ultrasonic power on. Overlapping bead welds were made in similar strips of .005- to .032-inch, .010- to .010-inch, and .010- to .032-inch 2S aluminum sheet. Approximately 20 overlapping welds were produced to the inch, with three to six seconds individual exposure times.

Rib Specimens

In a brief study of one anticipated end-item use, a group of rib specimens was ultrasonically welded for tensile-shear tests. The ribs were made of one-inch-long folded 2S aluminum of the configuration and dimensions shown in Figure 4; these ribs were welded to one-inch squares of .032-inch 2S aluminum. From one to ten welds were made on each sample, with the equipment operating at 150 pounds clamping load, 600 apparent r-f watts, and three seconds exposure time. With an even number of welds (2, 4, 6, 8, or 10), the spots were equally distributed on both sides of the rib; with an odd number of welds, the spots were staggered on either side of the rib.

Other rib specimens were prepared with the same .010-inch rib configuration, 2 inches long, ultrasonically welded to tabs of .032-inch 2S aluminum 2 inches long by 1/2 inch wide. Eight welds were made on each specimen, four of which were equally spaced on each side of the rib. Welding was accomplished at a clamping load of 150 pounds, power level of 600 apparent r-f watts, and exposure time of two seconds. Additional specimens were made with all conditions being the same except that .005-inch material was used in the fabrication of the folded ribs.

Rib-to-channel specimens were welded at 150 pounds clamping load, 500 apparent r-f watts, and three seconds exposure time. Three types of specimens were made: one in which a .010-inch folded rib of the configuration of Figure 4 was welded to a .032-inch channel; one in which a .010-inch machined rib of the configuration shown in Figure 5 was welded to a .032-inch channel; and one in which the .010-inch folded rib of Figure 4 was welded to an aluminum-brass sandwich block. These sandwich blocks were made of 1/4-inch brass 10 inches long by 1 inch wide, on each side of which a plate of .032-inch 2S aluminum had been ultrasonically soldered with 85% tin-15% zinc solder. The welds on each of these types of rib specimens were spaced at three different intervals: single welds at one-inch intervals along both sides of the rib; connecting welds located with the peripheries of adjacent welds touching; and welds overlapped to the extent of about one half of each spot.

Using the final equipment array, groups of .005- and .010-inch 2S aluminum folded ribs and .010-inch 2S extruded ribs were ultrasonically welded to 1/4-inch thick 2S aluminum plate, 6 inches long by 3 inches wide. The extruded ribs, having the configuration shown in Figure 6, were annealed at 340°C for one hour prior to welding; all ribs were precleaned by degreasing in methyl-ethyl ketone. Three 6-inch ribs were welded to each aluminum plate, the weld pattern being a series of consecutive welds with their peripheries touching. With the same equipment array, both folded and machined ribs, of the configurations shown in Figures 4 and 5, were welded to channel sections 6 inches long. The weld spots on these specimens were overlapped, connected, or placed at a one-inch spacing. All of these specimens were produced at 250 pounds clamping load, 750 apparent r-f watts, and five-six seconds exposure time.

Test Equipment and Procedures

Strength Tests

The simplest means for evaluating the quality of ultrasonic welds in single-spot lap specimens was by means of tensile-shear tests. Most of these tests were carried out with the ends of the lap specimens gripped in the jaws of a simple, manually operated, spring-loaded, tension testing device. Where the weld strength exceeded 222 pounds, specimens were tested in the low (0-500 pounds) range of a standard Young hydraulic testing machine equipped with self-aligning jaws. Load was applied at a reasonably constant rate of about 600 pounds per minute until failure occurred, either by separation of the tabs in the weld zone or by pulling out the weld nugget in one of the tabs.

Direct tension tests were made on some of the .032- and .040-inch lap specimens prepared with the final equipment array. For this test, 3/4-inch-diameter brass plugs were ultrasonically soldered to each side of the lap specimen over the weld area in the manner shown in Figure 7; a 92% tin-8% zinc solder was used at a temperature of 260°C, and the ultrasonic exposure time for soldering each side of the specimen was ten seconds. The brass plug extension rods were then clamped in the jaws of the Young testing machine, as shown in Figure 8, and the specimen loaded to failure. In a few instances failure occurred in the soldered joint rather than in the weld; these tests were considered invalid.

In order to compute shear or tensile strength in pounds per square inch, weld areas were determined on some of the fractured lap specimens. The fractured surface was photographed and the film projected on a screen at suitable magnification. The contours of the weld were then traced and the area measured with a planimeter.

Corrosion Tests

The corrosion resistance of a group of ultrasonically welded lap specimens was evaluated by exposure in an environment of low-conductivity, aerated, distilled water maintained at a temperature of 95°C. A total of 70 lap specimens having the standard overlap width of 1/2 inch and 10 lap specimens prepared with the weld on the edge of a 1/8-inch overlap were suspended from glass rods in two glass beakers of distilled water. Air was delivered to the bottom of each beaker through a fritted glass disk fitted to a glass bubbler tube. The protruding end of the tube was connected to an air-pressure reducing valve to maintain the air supply to that beaker. Both beakers were placed in an open, heated vessel filled with water which was maintained at a constant temperature of 95° ± 2°C.

The resistivity of the distilled water in the beakers was monitored continuously by means of a "Serfass" conductance bridge (Industrial Instruments Model No. RC-M15) with a dipping conductivity cell having a cell constant of approximately 1.0. Initial resistivity of the water was 500,000 to 600,000 ohms at room temperature. Whenever the resistivity approached 100,000 ohms at room temperature (or approximately 40,000 ohms at 95°C), fresh distilled water was added or the water in the beakers was completely changed.

Before exposure in the corrosion bath, 40 of the standard 1/2-inch-lap specimens and 10 of the 1/8-inch-lap specimens were tested in tensile-shear as described above. At intervals during the test, which was continued for a total exposure time of 3748 hours, specimens were removed from the bath and tested in tensile-shear.

Thermal Cycling Tests

Two series of thermal cycling tests were carried out on lap specimens. For the first series, one group of .010- to .032-inch specimens served as controls and were given no treatment. The remaining specimens were divided into five groups, each group of which was heated to a different temperature during the cycling test. The specimens were placed in a heated oven for 30 seconds, then removed and immediately dipped into an ice-water bath at 6°C for an additional 30 seconds. This cycle was repeated six times for each group of specimens. Oven temperatures of 315°, 370°, 425°, 480°, and 535°C were maintained for the respective tests; in each instance it was determined that the specimens achieved actual temperatures of 150° to 215°C below the oven air temperature during the 30 seconds of exposure in the oven; i.e., actual specimen temperatures were

120°, 155°, 275°, 300°, and 340°C respectively. At the conclusion of the thermal cycling tests, all treated specimens, as well as all control specimens were given tensile-shear tests.

A second series of thermal cycling tests was carried out, in which the specimens were given 10 and 20 cycles respectively to a temperature of 300°C. For each cycle, the specimens were immersed in boiling water for 10 seconds, maintained at room temperature for 10 seconds, placed in an oven at 300°C for four minutes, and subsequently quenched in water at 4°C before beginning the next cycle. Appropriate control specimens were tested in tensile-shear prior to the thermal cycling treatment. After exposure, the cycled specimens were also fractured in tensile-shear tests.

Metallographic Examination

Periodically during the preparation and test of various groups of lap specimens, some of the specimens were sectioned, mounted, polished, etched, and examined at various magnifications to study the nature of the metallurgical bond produced by welding under given combinations of ultrasonic parameters.

Rib Specimen Examination

Inasmuch as this program was brief, exploratory, and oriented to developing preliminary data only on the properties of ultrasonic welds in 2S aluminum, no great effort was made to obtain data on effects of end-use geometries on either ultrasonic weldability or weld properties. A number of rib-type specimens were prepared for inspection to demonstrate process applicability and for exploratory testing, which was usually accomplished by removing the rib from its opposite member by chiseling or twisting with pliers.

Representative specimens were submitted to du Pont Atomic Energy Division for evaluation. Both folded-rib and machined-rib specimens were evaluated by chiseling, by stud tensile tests, and by metallographic examination.

TEST RESULTS

Ultrasonic Weld Strength

The progressive improvement in ultrasonic welding capability, resulting from revisions in the ultrasonic welding array, improved techniques, etc., was revealed by the tensile-shear strength of lap specimens prepared and tested at various stages throughout the program. These data are summarized in Table I and graphically presented in Chart 1.

Tables II and III give individual results of shear and tensile tests on lap specimens of .032- and .040-inch 2S aluminum. In each instance, the actual load at failure was divided by the area of the weld in square inches to obtain the shear or tensile strength in pounds per square inch.

It should be noted that the weld specimens fabricated for the various tests--corrosion, thermal cycling, and cleaning--were produced at different stages during the program. Thus no valid comparison can be made of the results of the several tests, and each test is meaningful only within itself.

Corrosion Test Results

Results of the corrosion tests are presented in Table IV and Chart 2. No decrease in the strength of the lap specimens was evident after 3748 hours of exposure in the 95°C, low-conductivity, aerated, distilled water environment, either for the standard specimens with 1/2-inch overlap or for the 1/8-inch overlap specimens. Charts 3 and 4 graphically present the resistivity readings taken in the corrosion baths throughout the exposure period.

Thermal Cycling Test Results

Tables V and VI and Charts 5 and 6 summarize the results of the thermal cycling tests on lap specimens. As the maximum temperature to which the specimens were exposed during cycling exceeded about 200°C, a progressive decline in strength is noted (Table VI and Chart 5); at a cycling temperature of 340°C, approximately 20 per cent of the original strength had been lost. Similarly, as the number of cycles to a constant temperature of 300°C was increased, the strength decreased; exposure to 20 cycles at this temperature produced an 18 per cent loss in strength.

Surface Cleanliness Test Results

The results of tests to determine the effect of precleaning the aluminum tabs on weld strength are given in Tables VII, VIII, IX, and X. For each condition, the maximum, minimum, and average fracture loads are given, as well as the coefficient of variation, which is determined by subtracting the minimum from the maximum strength and dividing by the average strength.

Precleaning with sodium hydroxide solution followed by successive immersion in nitric acid and phosphoric acid solutions resulted in decrease in strength over the control specimens, as well as increase in scatter of results as reflected by the coefficient of variation (Tables VII and VIII). Micrometer measurements on the test specimens, made before and after cleaning, indicated a loss of about 15 per cent of the original thickness for those specimens immersed in the caustic solution for three to five minutes; for those immersed for only 90 seconds, this loss in thickness was only about 0.001-inch for both .010- and .032-inch tabs.

Decreased strength also occurred when a hydrofluoric acid dip was used for precleaning (Table VIII). Increasing the welding time of the control specimens and of the specimens precleaned by both of these methods (sodium hydroxide and hydrofluoric acid) increased the strength slightly for all specimens (Charts 7 and 8).

A similar decrease in strength generally occurred when 2S rolled aluminum tab specimens were precleaned with "Versene" or with nitrogen-triacetic acid (Tables IX and X). Those specimens made with extruded material showed increased strength when precleaned with "Versene", but slightly decreased strength when precleaned with nitrogen-triacetic acid.

Metallographic Observations

Figure 9 shows the complete cross section of a typical ultrasonic weld in 2S-H14 aluminum at a magnification of 180X. This particular weld, in .032- to .032-inch material, was taken from the group of welds the strengths of which are presented in Tables II and III. The disruption of the mating surfaces across the entire weld is evident and, in isolated areas, complete solid-phase bonding has taken place.

Rib Specimen Observations

Although little quantitative information was obtained on the quality of welds in rib specimens prepared during the program, observations indicated that these welds compared favorably with the welds produced in lap specimens. Rib specimens prepared with ribs having bases .005-inch thick always failed by tear-out of the nugget from the .005-inch material; those prepared with .010-inch ribs usually failed by tear-out of the .010-inch material. The specimens with 1 to 10 weld spots on each rib, when tested in shear, showed an average failing load of 48.9 pounds for those ribs attached with only one weld; this strength is comparable to that of lap specimens prepared contemporaneously.

Examination of the ribs ultrasonically welded to aluminum-brass sandwich blocks indicated good welds when a good soldered bond had been obtained between the aluminum and the brass in the base plate; if the aluminum and brass were not securely bonded directly below this weld, generally poor strength resulted. Figure 10 shows a typical group of rib specimens in which folded ribs were welded to such sandwich blocks.

Results were available from tests on some of the rib-to-channel specimens submitted to du Pont Atomic Energy Division. The folded ribs were reported to be poorly bonded. Some of the machined ribs were difficult to remove by chiseling. Stud tensile tests showed strengths on seven machined-rib specimens ranging from 0 to 12,800 pounds per square inch of weld area. Metallographic examination of the best bonded ribs revealed an interface similar to that shown in Figure 9.

DISCUSSION OF RESULTS

Ultrasonic Weld Quality

The data of Table I and Chart 1 indicate significant improvement in the quality of ultrasonic welds in 2S aluminum during the course of the eight-month program. This improvement resulted from revisions in the welding equipment, refinements in welding techniques, and enhanced understanding of the mechanism of ultrasonic welding. It will be observed that the results shown for the final equipment array reflect a capacity to utilize greater energy levels than was represented earlier in the program. Initially it was found that three seconds application of 600 apparent r-f watts (1800 watt-seconds) gave the results tabulated and that increased power provided no improvement. However, late in the program, higher energy levels were successfully used to achieve stronger welds as noted.

The increase in weld strength is most significant in the heavier gages of aluminum. In .040- to .040-inch 2S material, for example, welds produced at the beginning of the program failed in tensile-shear at a load of 35 pounds; six months later, single welds in the same material failed at 285 pounds. Similar strength increases were not characteristic of the lighter gages of aluminum, because throughout the program the welds in .005-inch material were stronger than the base metal and failed by tear-out of the weld nugget from one of the tabs. At the outset, such nuggets were occasionally, but not consistently, pulled from .010-inch aluminum. By July 1954, nuggets were regularly pulled from .016-inch material and occasionally from .032-inch gage (note Tables IX and X).

The data of Tables II and III show the area of the ultrasonic welds to be 0.035 to 0.042 square inch, indicating a weld diameter of approximately 0.1 inch. Individual shear strengths of these .032- and .040-inch specimens ranged from 6,000 to 8,000 pounds per square inch of weld area; the shear strength of 2S-H14 aluminum sheet is reported to be about 11,000 psi.

Actual tensile strengths of the welds were not determined, since all tensile specimens failed by shear-out of the nugget. It can only be stated that the weld tensile strength <u>exceeded</u> 6,000 to 9,000 psi, and in one instance it exceeded 11,700 psi. Since 2S-H14 aluminum sheet has a tensile strength of about 18,000 psi, it is likely that the tensile strength of the weld approaches that of the base material. The material was annealed in the soldering operation, and its tensile strength probably was about the same as that of 2S-O aluminum (13,000 psi).

On some of the welded tab specimens, a ring-like, black deposit was observed at the edge of the welds. This discoloration was evident particularly on specimens which had been degreased only, prior to welding. It was observed to a slight degree or not at all on specimens which had been cleaned with the stronger solutions previously described. Certain of the welds on degreased materials also exhibited a somewhat grayer appearance than the welds made in more stringently cleaned material. The nature of this deposit and its effect on weld quality have not been determined; however, some of the deposit was removed and a specimen was given to a representative of the du Pont Atomic Energy Division for analysis.

Corrosion Resistance of Ultrasonic Welds

All information accumulated to date indicates that ultrasonic welds in 2S aluminum are not susceptible to corrosion in the stipulated environment. The corrosion tests on the lap specimens (Table IV and Chart 2) showed no decrease in strength after 3750 hours of exposure to low-conductivity, aerated, distilled water at 95°C. Some of the specimens fabricated with the weld on the edge of a 1/8-inch overlap showed individual low strengths (after 2044 and 2572 hours of exposure), probably resulting from variations in welding, since the weld spot diameter was essentially the same as the width of the lap. But even with these specimens, with the weld zone exposed to the corrosive environment, the welds exposed for 3750 hours were as strong as the control welds which had not been exposed.

These tests confirm the results of prior corrosion investigations on tab specimens of .010- to .010-inch 2S aluminum, which were exposed to aerated distilled water at 95°C and to 3% salt solution at 40°C for more than 5000 hours with no loss in strength. It can thus be safely concluded that ultrasonic welds in 2S aluminum are not susceptible to corrosion in the specified environment, at least during the first five or six months of exposure.

Thermal Cycling Resistance of Ultrasonic Welds

The specimens exposed to thermal cycling showed no strength loss at a maximum cyling temperature of about 200°C (Table V and Chart 5). However, with increasing temperature beyond this figure, progressive strength decline was evident; six cycles to 350°C resulted in about a 20% strength decline.

Likewise an increased number of cycles to 300°C produced progressive decline in strength (Table VI, Chart 6). Twenty cycles at 300°C produced approximately the same strength decline as six cycles at 340°C.

If the black deposit previously mentioned proves to be a completely foreign material, it is possible that its existence in the bond zone will magnify any adverse effect of thermal cycling; the black deposit may result in less firmly bonded areas because of volatility of a component or a presently unforeseen chemical activity at elevated temperatures.

Effect of Surface Condition on Weld Strength

Prior to the initiation of this program, preliminary work had been done to determine the effect of sheet surface condition on weld strength in 2S aluminum. These experiments seemed to indicate that grain orientation was not significant, but a smooth surface was found to be essential to the production of consistent welds. Machined aluminum, having a slightly striated surface, did not provide optimum weld strength unless such surfaces were ground and polished. Best welds in extruded 2S aluminum were produced when the mating surfaces were of rolled finish or made flat and smooth by grinding and polishing. Maximum weld strength on any 2S aluminum was achieved on as-received, half-hard, rolled aluminum sheet which had been degreased only, prior to welding. Welds on abraded, etched, or anodized surfaces showed reduced strength.

In the course of the present investigation, it was suggested that the mechanism of ultrasonic welding is similar to high-pressure welding and is therefore chiefly dependent on a clean surface free from oxide films. Ultrasonic welding would therefore be attributed chiefly to an ultrasonic function which removes the oxide film before bonding the metal. In this event, precleaning of the aluminum should result in welds of improved strength, or welds should be obtained in shorter ultrasonic exposure time.

This hypothesis was not substantiated by the cleaning experiments reported herein. With one exception, the control specimens, which had been degreased only, showed higher strengths than those which had been precleaned with sodium hydroxide, hydrofluoric acid, "Versene", or nitrogen-triacetic acid. That single exception (Table IX) concerned specimens of .032-inch extruded 2S aluminum which had been cleaned in a "Versene" solution; these were stronger than the corresponding control specimens. In view of the presumed effect of surface finish on weld strength, the "Versene" may have imparted a smoother surface to the extruded material, making more secure bonding possible. In all other instances, strength was reduced by the cleaning process, regardless of ultrasonic exposure time.

The data suggest that the cleanliness of the metal surface and its freedom from oxide films make little contribution to the strength of ultrasonic welds in 2S aluminum, but such a conclusion cannot be accepted at this time, because it is by no means certain that all of the variables involved have been recognized and evaluated. The surface film and surface finish factors require differentiation, and more rigorous studies in this direction are indicated.

A number of problems associated with ultrasonic welding of sheet material to sheet material are recognized but have not been explored. To accomplish a weld between two sheets, the transducer sonotrode must drive the upper sheet through the sonotrode-sheet interface; the reflector sonotrode must be largely noncompliant to the movement of the lower sheet through the sheet-to-sheet interface. It is evident that welding between the sheets might be affected by the geometry and surface condition of all members of the system, and particularly by their hardness, their smoothness, and the presence of films; these factors will affect the clamping force and driving power which can be tolerated.

On the other hand, the problems implicit in the system described above are undoubtedly alleviated when the transducer sonotrode is contoured to drive an element of the weldment directly, and when the opposing element of the weldment is massive or can be handily clamped. The surface condition of the work pieces may then affect the welding process in a different manner.

Weld Quality on Rib Specimens

The limited evaluation of rib specimens indicates that ultrasonic welds joining 2S aluminum ribs to 2S sheet or plate are as effective as the welds in comparable gages of tab specimens, which were comprehensively tested. No weakening of welded rib joints can be expected from exposure to a corrosion environment of 95°C, low-conductivity, aerated, distilled water. Similarly no decline in strength is anticipated from exposure to thermal cycles up to a temperature of 200°-250°C. At the present state of the art, higher temperatures will probably result in weaker joints, but further developments in welding techniques may alleviate this effect.

It is noted that the end use of the rib-to-tube joints will not subject them to structural stresses; the major requirement is that the rib joints be strong enough to withstand rough handling. In the light of this investigation, it is concluded that ultrasonic welding is a sound method of attaching 2S aluminum ribs to 2S aluminum components.

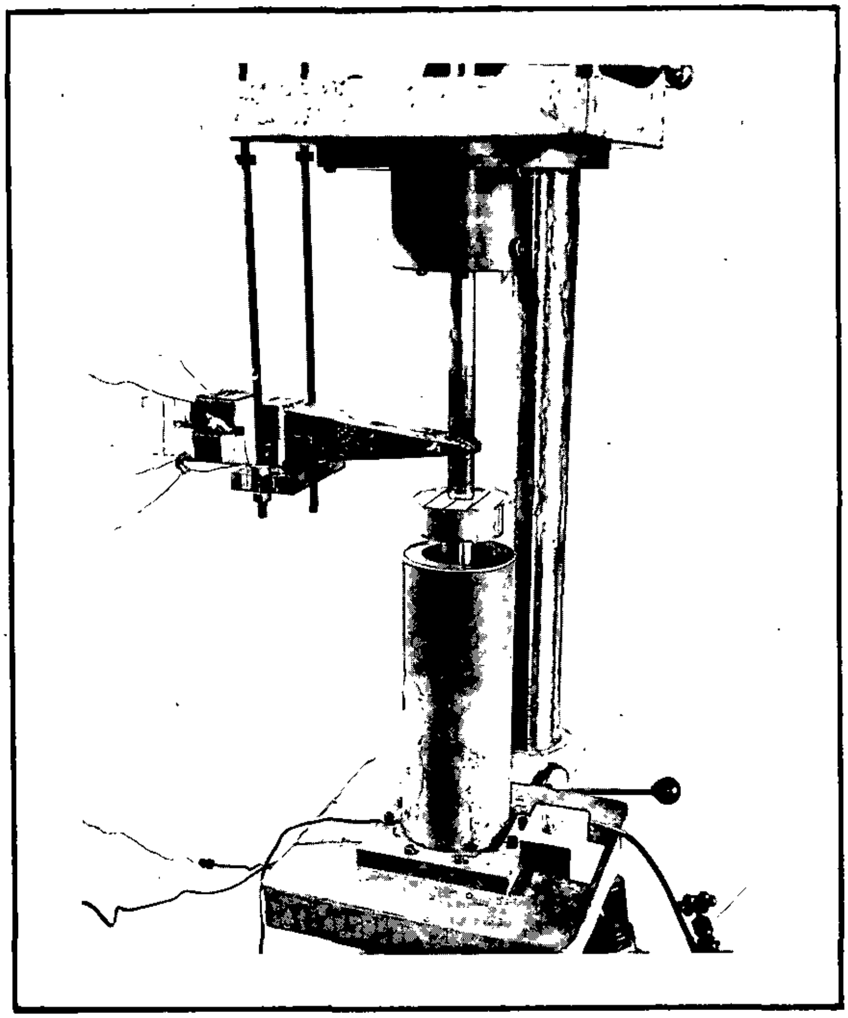


FIGURE 1

ULTRASONIC WELDING ARRAY

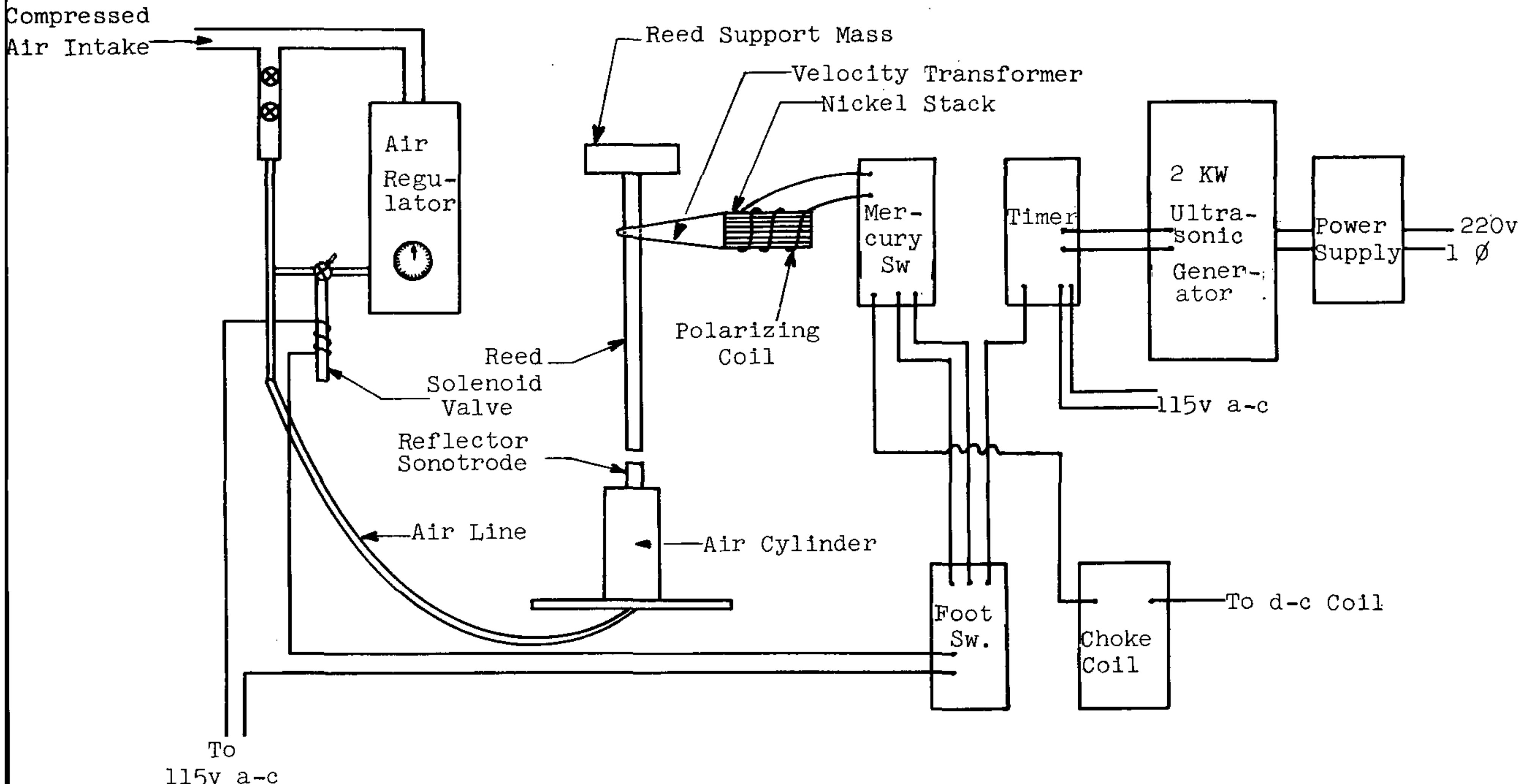


FIGURE 2

SCHEMATIC DIAGRAM OF
ULTRASONIC WELDING ARRAY

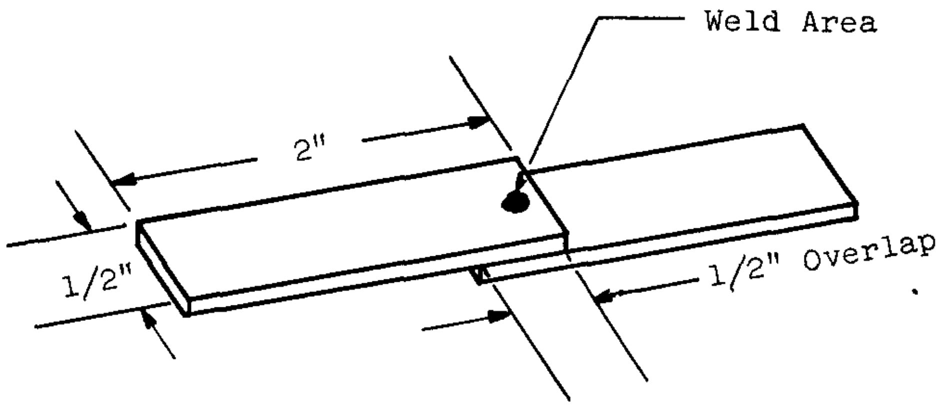


FIGURE 3

STANDARD LAP SPECIMEN

FOR EVALUATION OF ULTRASONIC WELDS

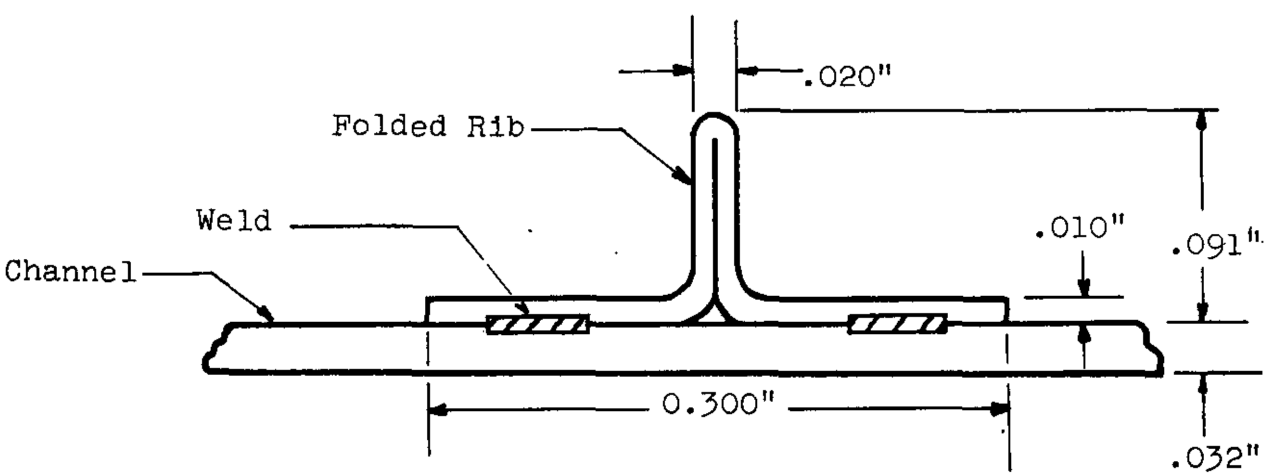


FIGURE 4

FOLDED RIB-CHANNEL CONFIGURATION

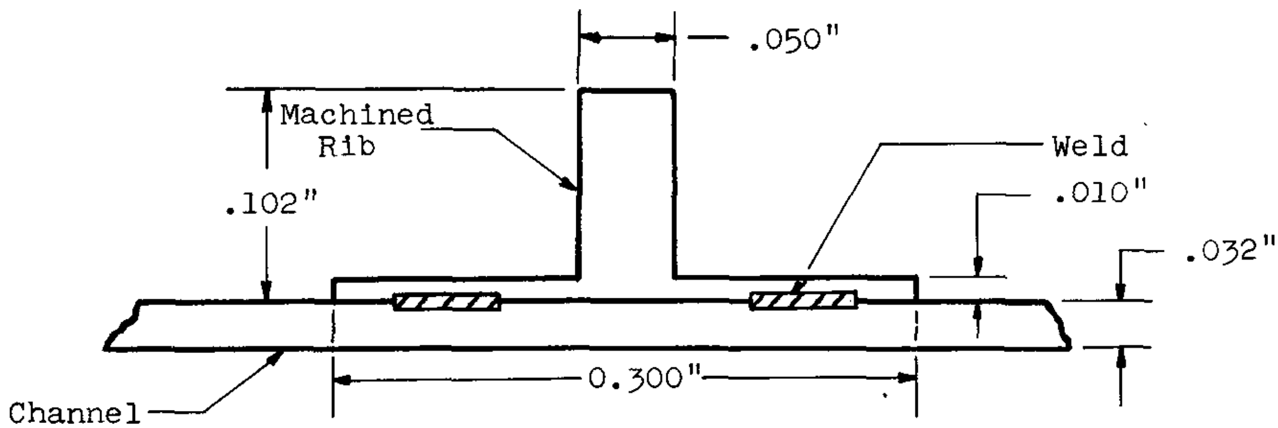


FIGURE 5

MACHINED RIB-CHANNEL CONFIGURATION

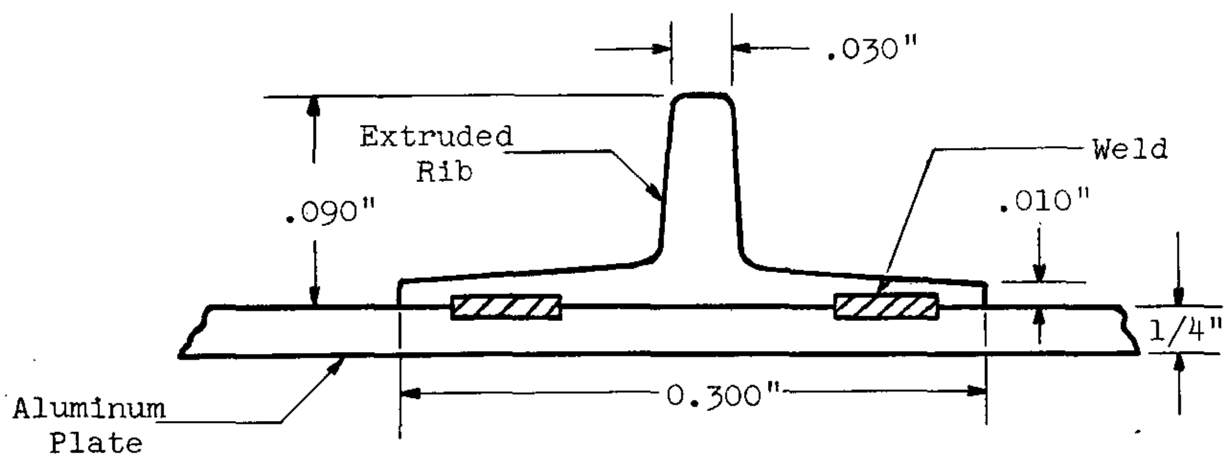
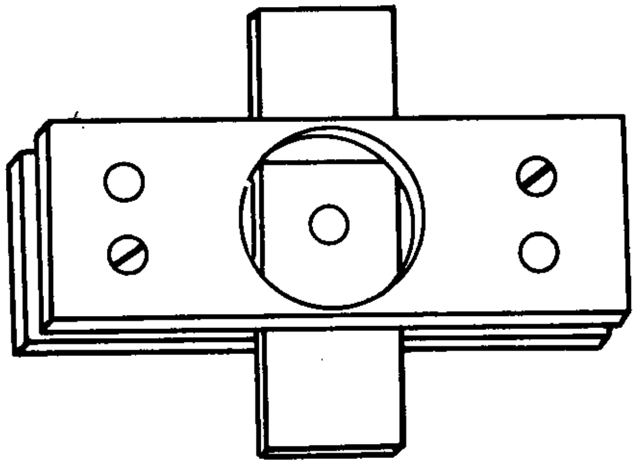
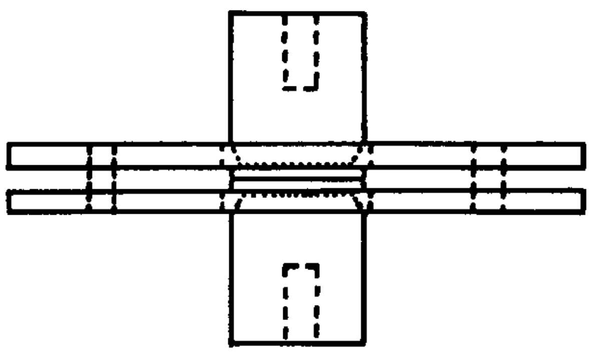


FIGURE 6

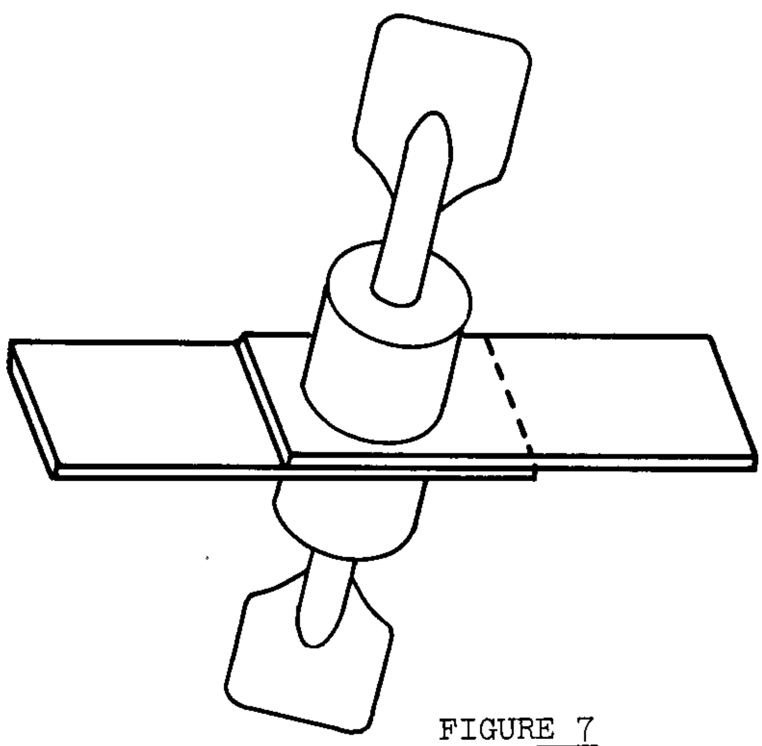
EXTRUDED RIB-SPECIMEN CONFIGURATION



Welded specimen clamped for soldering over weld area



Brass blocks soldered over weld spot



Completed Assembly ready for tensile test

FIGURE 7

PREPARATION OF WELD SPECIMEN FOR TENSILE TESTING

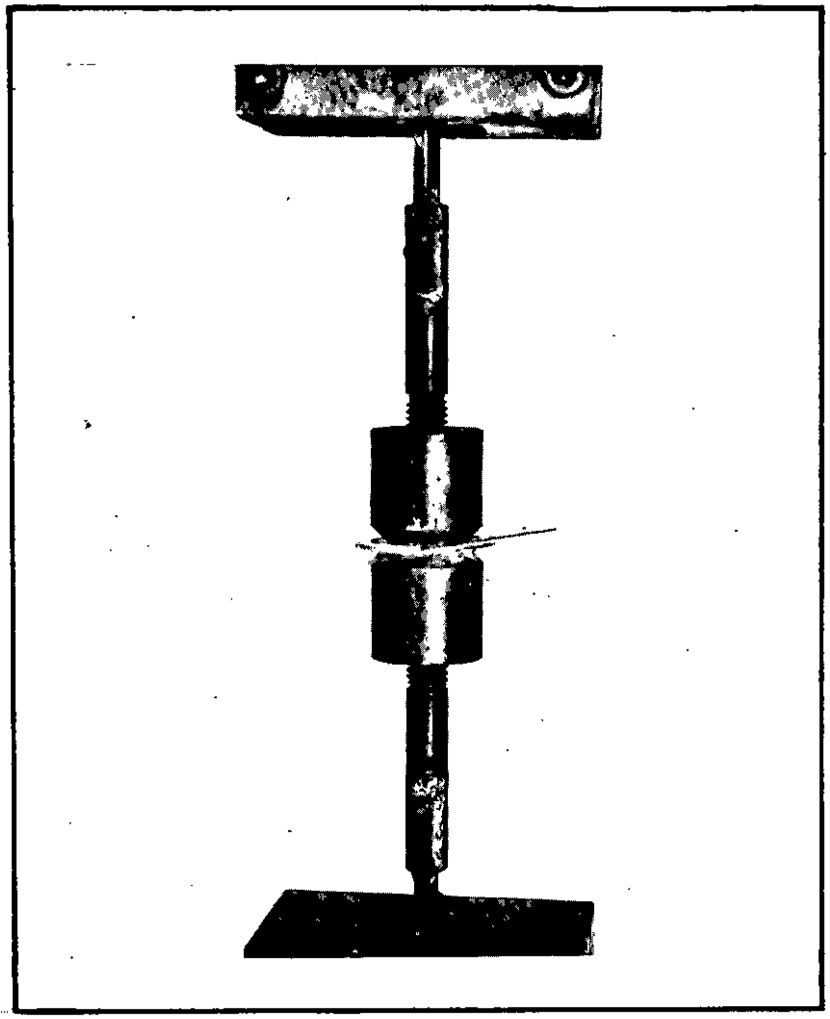


FIGURE 8

ULTRASONICALLY WELDED LAP SPECIMENS
WITH SOLDERED-ON BRASS PLUGS
MOUNTED IN TESTING MACHINE
FOR TENSILE TEST

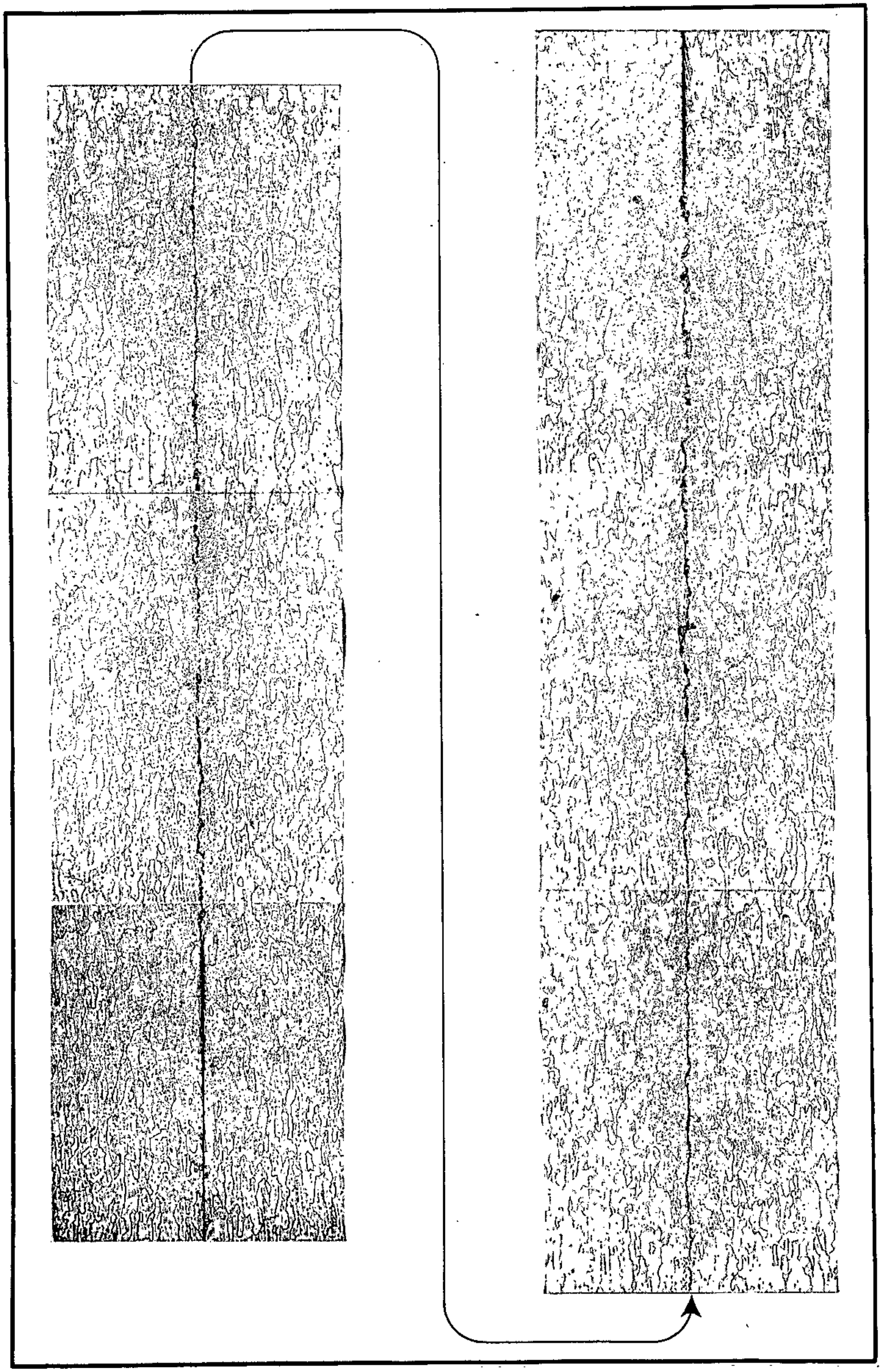


FIGURE 9

PHOTOMICROGRAPH OF ENTIRE CROSS SECTION OF ULTRASONIC WELD IN .032 - .032-INCH 2S ALUMINUM SHEET
(0.5% HF Etch; 180X)

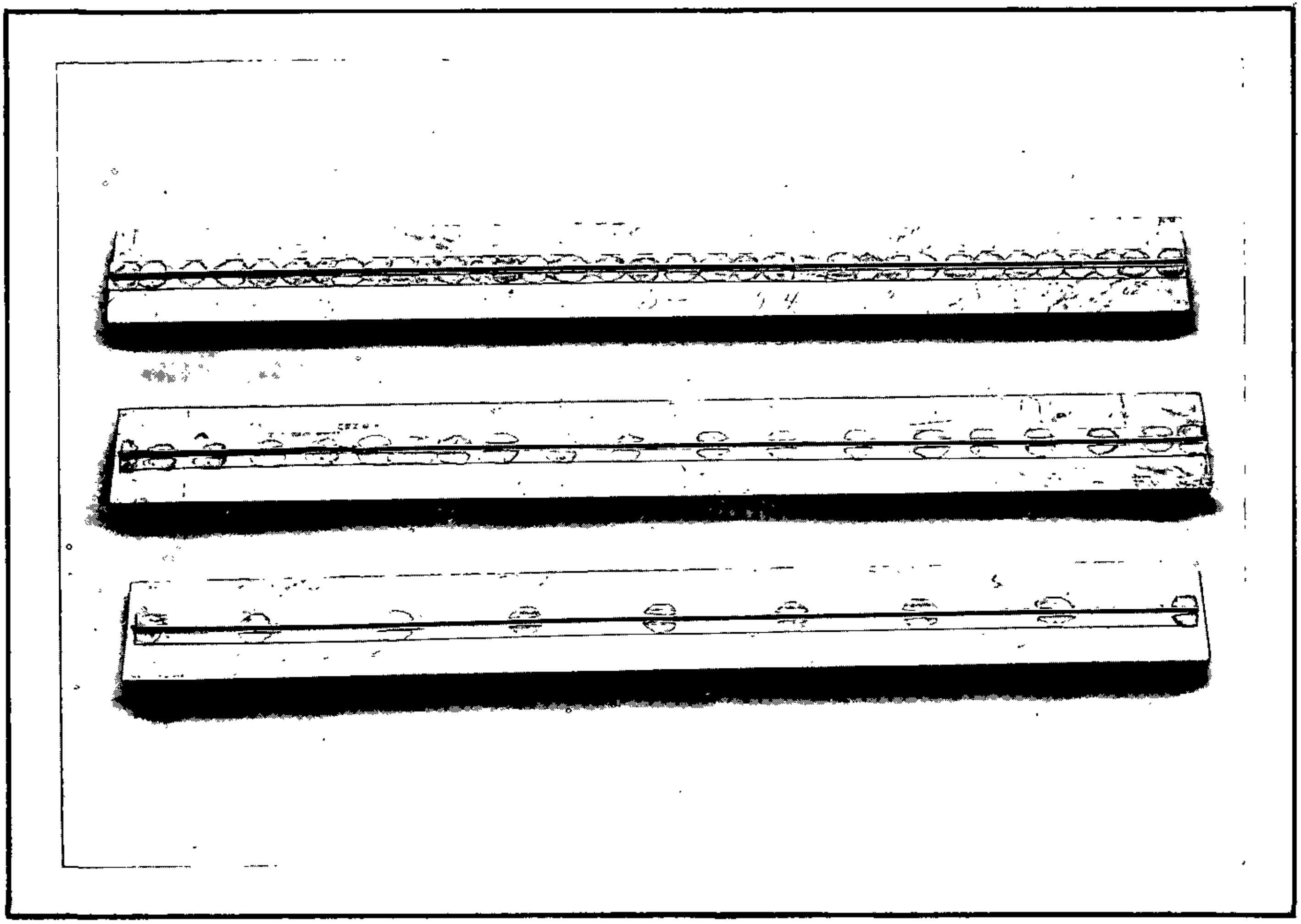


FIGURE 10

FOLDED RIBS ULTRASONICALLY WELDED
TO ALUMINUM-BRASS SANDWICH BLOCKS

TABLE I

IMPROVEMENT IN ULTRASONIC WELDING CAPABILITY AS REVEALED BY RESULTS OF TENSILE-SHEAR TESTS ON 2S-H14 ALUMINUM LAP SPECIMENS

Date	Frequency (kc)	Apparent r-f watt-seconds per weld	Tensile-Shear Load at Failure, Pounds**								
			.005"*	.010"	.016"	.025"	.032"	.040"	.051"	.062"	.010" to .032"
January 1954	15.5	1800	--	49.9	51.2	52.8	33.8	35.3	33.0	44.4	43.7
April 1954	14.95	1800	20+	36.4	34.0	28.4	58.4	59.0	78.6	112.6	63.0
May 1954	12.8	1800	20+	60.2	83.2	99.4	79.8	87.8	79.4	73.0	54.2
May 1954	17.5	1200	35	59.2	82.8	68.2	102.0	121.8	107.8	74.6	67.8
June 1954	20.3	2400	30+	48.0	97.0	85.2	----	----	91.8	105.8	63.8
July 1954	15.35	3750	--	70.0	150.0	195.0	241.0	285.0	----	----	80.0

* All .005-inch specimens pulled nuggets from one tab during test.
** Each strength figure represents the average of at least five test coupons.

TABLE II

SHEAR STRENGTH OF ULTRASONIC WELDS IN 2S-H14 ALUMINUM LAP SPECIMENS

(Welded and Tested in July 1954)

Clamping Load: 250 pounds
Apparent r-f energy: 800 watts
Exposure Time: 6 seconds

Sheet Gage (inches)	Weld No.	Tensile-Shear Load at Failure (lbs)	Weld Area (sq in.)	Shear Strength (psi)
.032-.032	1	260	.0399	6,520
	2	245	.0387	6,330
	3	250	.0392	6,370
	4	235	.0388	6,060
	5	245	.0378	6,490
	6	240	.0357	6,730
	7	230	.0357	6,460
	8	245	.0362	6,770
	9	235	.0364	6,460
	10	225	.0346	6,490
	Average	241	.0373	6,468
.040-.040	1	300	.0420	7,180
	2	290	.0397	7,310
	3	320	.0379	8,020
	4	300	.0395	7,580
	5	260	.0325	7,980
	6	300	.0371	8,060
	7	260	.0377	6,920
	8	275	.0377	7,300
	9	285	.0377	7,670
	10	260	.0354	7,340
	Average	285	.0377	7,536

TABLE III

TENSILE STRENGTH OF ULTRASONIC WELDS IN 2S-H14 ALUMINUM LAP SPECIMENS

(Welded and Tested in July 1954)

Clamping Load: 250 pounds
Apparent r-f energy: 800 watts
Exposure Time: 6 seconds

Sheet Gage (inches)	Weld No.	Load at Failure (lbs)	Nugget Area (sq in.)	Tensile Strength * (psi)
.032-.032	1	380	.0404	9,420
	2	260	.0418	6,230
	3	370	.0412	8,980
	4	340	.0406	8,380
	5	470	.0402	11,700
	6	360	.0407	8,840
	7	200	.0400	5,000
	8	150	.0393	3,820
	Average	316	.0405	7,796
.040-.040	1	210	.0357	5,900
	2	200	.0352	5,680
	3	230	.0377	6,100
	4	265	.0387	6,850
	5	260	.0357	7,280
	6	210	.0360	5,830
	7	240	.0386	6,230
	8	250	.0377	6,380
	9	220	.0363	6,060
	Average	232	.0368	6,257

* All welds failed by tear-out of the weld zone from one sheet; hence, actual tensile strength of the welds exceeds the figures given.

TABLE IV

STRENGTH OF ULTRASONIC WELDS IN 2S-H14 ALUMINUM EXPOSED TO CORROSION ENVIRONMENT OF 95°C, LOW-CONDUCTIVITY, AERATED, DISTILLED WATER

(Welded in January 1954)

Sheet Gage: .010" to .032"

Clamping load: 100 pounds
Apparent r-f energy: 550 watts
Exposure time: 6 seconds

Exposure Time (hours)	No. of Specimens	Tensile-Shear Load at Failure (pounds)		
		Maximum	Minimum	Average
a. Tab specimens with 1/4" overlap				
0	40	54	46	49.7
100	5	51	50	50.2
508	5	50	45	48.0
1012	5	50	48	48.8
1540	5	49	39	44.0
2044	5	52	48	50.0
2572	5	51	44	48.6
3076	5	50	40	45.2
3580	5	53	50	52.2
3748	30	64	43	48.9
b. Tab specimens with 1/8" overlap				
0	10	41	36	39.3
1012	1			31.0
2044	1			27.0
2572	1			22.0
3076	1			39.0
3580	1			39.0
3748	5	44	34	39.4

TABLE V

RESULTS OF THERMAL CYCLING TESTS AT VARIOUS TEMPERATURES ON ULTRASONICALLY WELDED LAP SPECIMENS OF 2S-H14 ALUMINUM

(Welded and Tested in April 1954)

Sheet Gage: .010" to .032"

Clamping Load: 150 pounds
Apparent r-f energy: 600 watts
Exposure time: 3 seconds

Oven Temperature (°C)	Specimen Temperature (°C)	No. of Cycles	No. of Specimens	Tensile-Shear Load at Failure (pounds) Maximum	Minimum	Average	Loss in Strength (%)
Control	---	--	5	64	60	63.0	----
315	120	6	3	64	61	62.6	----
370	155	6	3	68	63	64.6	----
425	275	6	3	62	60	61.0	3.2
480	300	6	3	60	54	57.0	9.5
535	340	6	9	58	48	50.7	19.5

TABLE VI

RESULTS OF THERMAL CYCLING TESTS TO 300°C ON ULTRASONICALLY WELDED LAP SPECIMENS OF 2S-H14 ALUMINUM

(Welded and Tested in April 1954)

Sheet Gage: .010" to .032"

Clamping Load: 150 pounds
Apparent r-f energy: 600 watts
Exposure time: 3 seconds

No. of Cycles	No. of Specimens	Tensile-Shear Load at Failure (pounds) Maximum	Minimum	Average	Loss in Strength (%)
Control	10	63	52	58.1	---
10	5	57	48	52.4	9.8
20	3	49	46	47.6	18.0

TABLE VII

STRENGTH OF ULTRASONIC WELDS IN 2S-H14 ALUMINUM TAB SPECIMENS PRECLEANED WITH THREE TO FIVE MINUTES EXPOSURE IN SODIUM HYDROXIDE

(Welded and Tested in April 1954)

Sheet Gages: .010" to .032"

Clamping Load: 150 pounds
Apparent r-f energy: 600 watts

Welding Time (sec)	Specimen	Number of Welds	Tensile-Shear Load at Failure (pounds) Maximum	Minimum	Average	Coefficient of Variation (%)
1	Control	5	63	48	56.1	26.8
1	Cleaned	5	51	17	30.6	111.1
2	Control	5	59	49	56.2	17.8
2	Cleaned	5	54	25	34.2	84.8
3	Control	5	63	61	61.2	3.3
3	Cleaned	5	56	33	38.4	59.9

TABLE VIII

STRENGTH OF ULTRASONIC WELDS IN 2S-H14 ALUMINUM TAB SPECIMENS PRECLEANED BY VARIOUS PROCESSES

(Welded and Tested in May 1954)

Sheet Gages: .010" to .032"

Clamping Load: 150 pounds
Apparent r-f energy: 650 watts

Welding Time (sec)	Specimen	Number of Welds	Tensile-Shear Load at Failure (pounds) Maximum	Minimum	Average	Coefficient of Variation (%)
1	Control	5	72	66	69.4	8.7
1	NaOH (90 sec)	10	59	54	57.1	8.8
1	30% HF Flash-dip	5	68	62	66.0	9.1
3	Control	10	79	66	71.4	18.2
3	NaOH (90 sec)	10	65	56	60.5	14.9
3	30% HF Flash-dip	10	71	58	66.6	19.5

TABLE IX

EFFECT OF PRECLEANING WITH "VERSENE"
ON STRENGTH OF ULTRASONIC WELDS IN 2S ALUMINUM TAB SPECIMENS

(Welded and Tested in July 1954)

Clamping Load: 250 pounds
Apparent r-f energy: 800 watts
Exposure time: 6 seconds

Material	Sheet Gage (inches)	Specimen	Number of Welds	Nuggets	Tensile-Shear Load at Failure (pounds)			Coefficient of Variation (%)
					Maximum	Minimum	Average	
Extruded	.032-.032	Control	10	None	140	81	120.2	49.1
		Cleaned	10	None	218	122	150.6	63.7
Rolled	.032-.032	Control	5	Partial	250	240	245.0	4.1
		Cleaned	5	Partial	173	160	167.2	7.8
Rolled	.032-.016	Control	5	All	200	190	191.6	5.2
		Cleaned	5	All	185	178	181.6	3.9
Rolled	.016-.016	Control	5	All	174	168	171.0	3.5
		Cleaned	5	All	174	168	171.0	3.5

TABLE X

EFFECT OF PRECLEANING WITH NITROGEN-TRIACETIC ACID
ON STRENGTH OF ULTRASONIC WELDS IN 2S ALUMINUM TAB SPECIMENS

(Welded and Tested in July 1954)

Clamping Load: 250 pounds
Apparent r-f Energy: 800 watts
Exposure time: 6 seconds

Material	Sheet Gage (inches)	Specimen	Number of Welds	Nuggets	Tensile-Shear Load at Failure (pounds) Maximum	Minimum	Average	Coefficient of Variation (%)
Extruded	.032-.032	Control	10	None	214	134	169.0	47.3
		Cleaned	10	None	204	112	158.3	58.1
Rolled	.032-.032	Control	10	Partial	320	240	282.5	28.3
		Cleaned	10	Partial	210	150	185.0	32.4
Rolled	.032-.016	Control	10	All	195	190	193.5	2.6
		Cleaned	10	All	195	175	186.0	10.8
Rolled	.016-.016	Control	10	All	190	185	189.0	2.6
		Cleaned	10	Partial	185	135	166.0	30.1

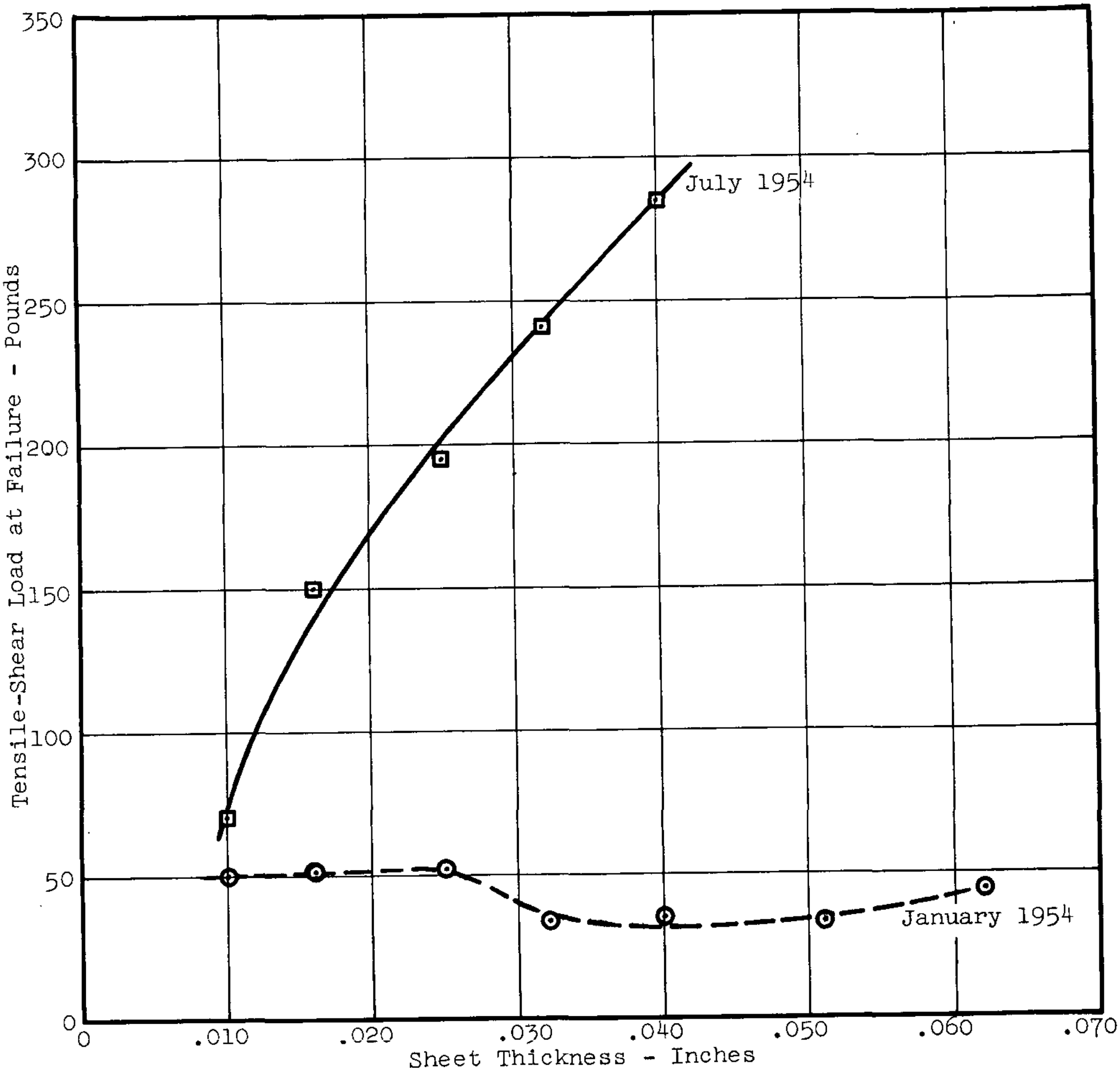


CHART 1

IMPROVEMENT IN ULTRASONIC WELDING CAPABILITIES AS REVEALED BY TESTS ON SINGLE-WELD LAP SPECIMENS OF VARIOUS GAGES OF 2S ALUMINUM

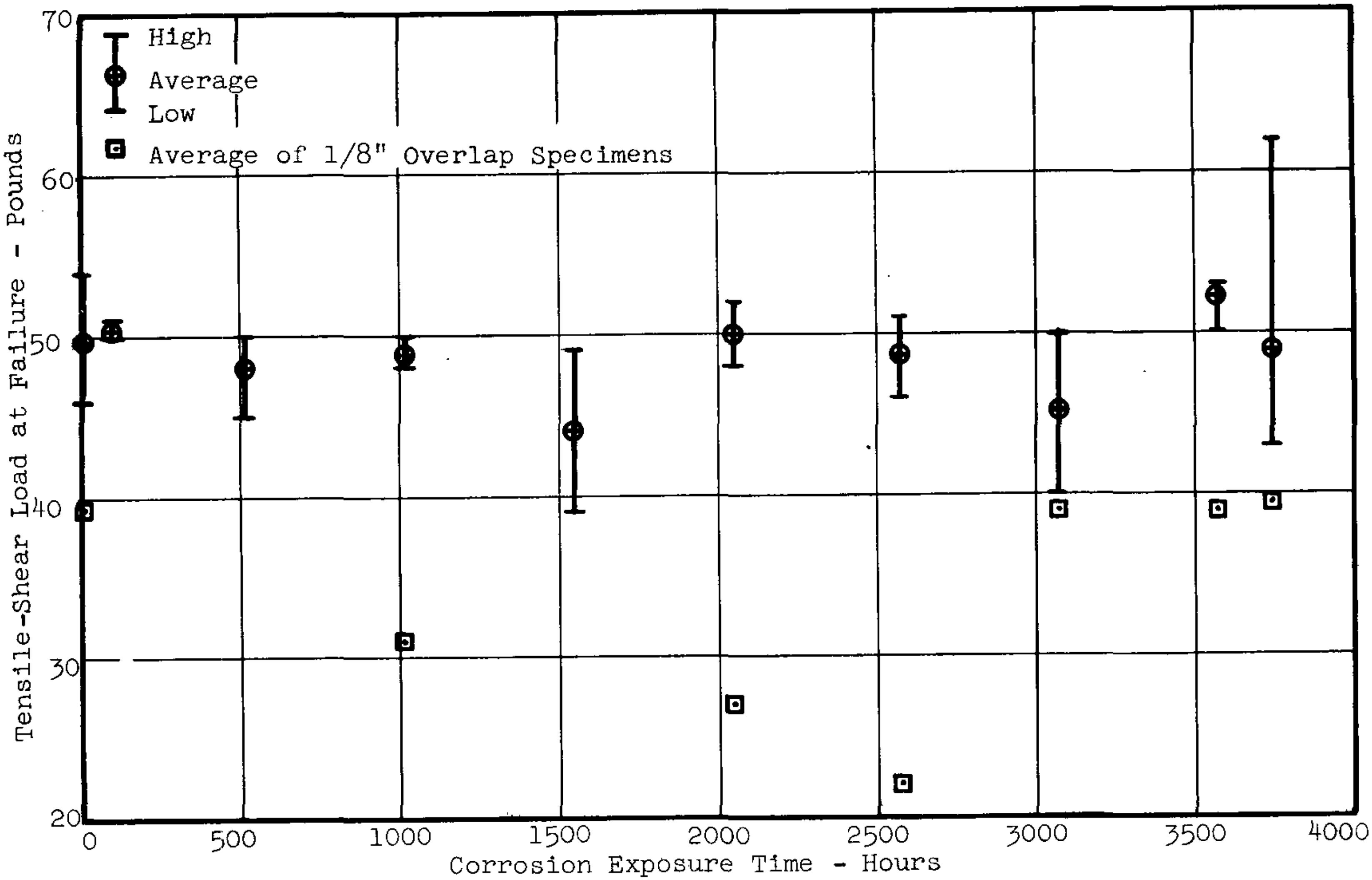


CHART 2

CORROSION RESISTANCE OF ULTRASONIC WELDS IN 2S ALUMINUM LAP SPECIMENS

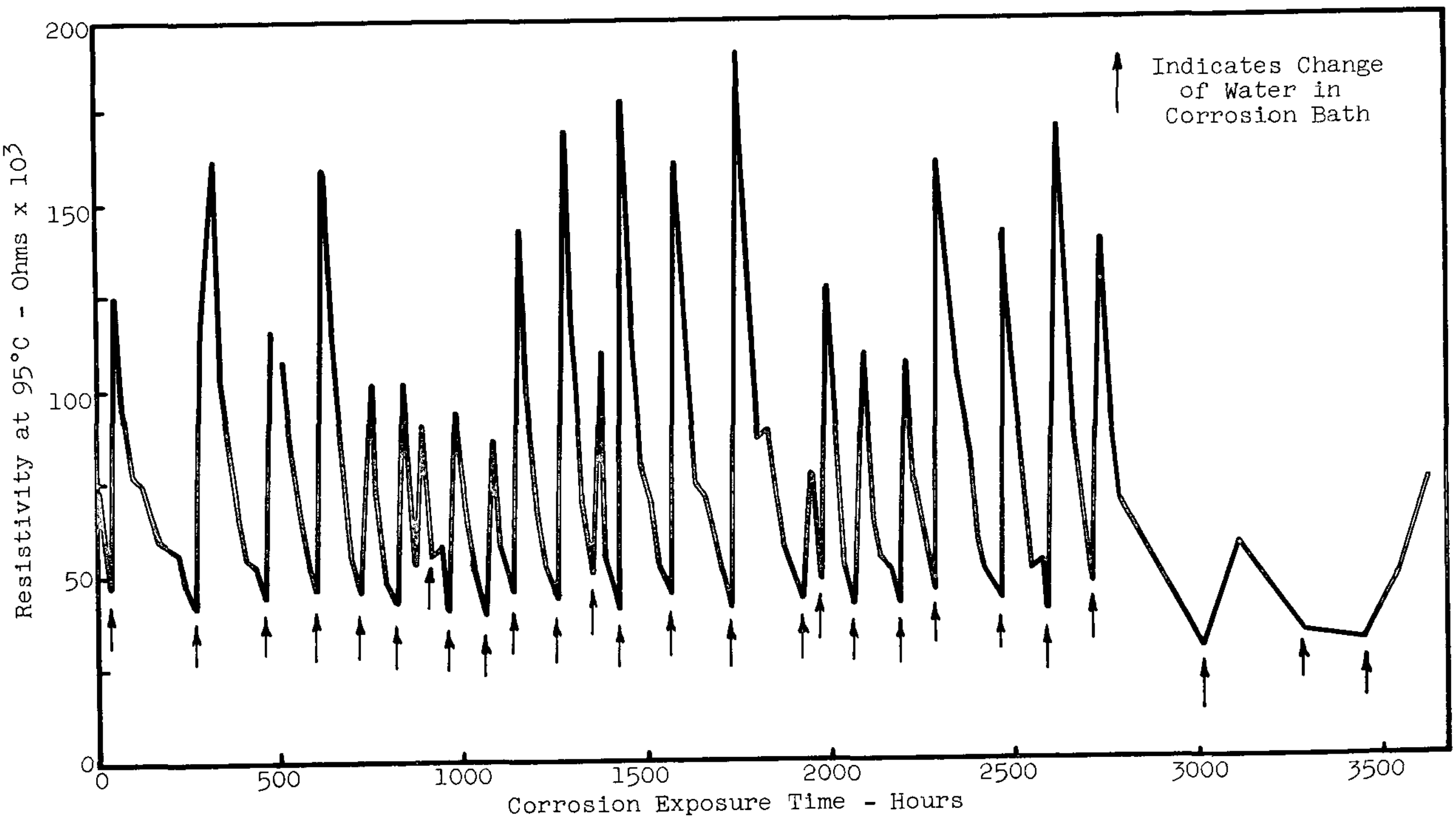


CHART 3

RESISTIVITY OF CORROSION BATH NO. 1
FOR ULTRASONICALLY WELDED LAP SPECIMENS OF 2S ALUMINUM

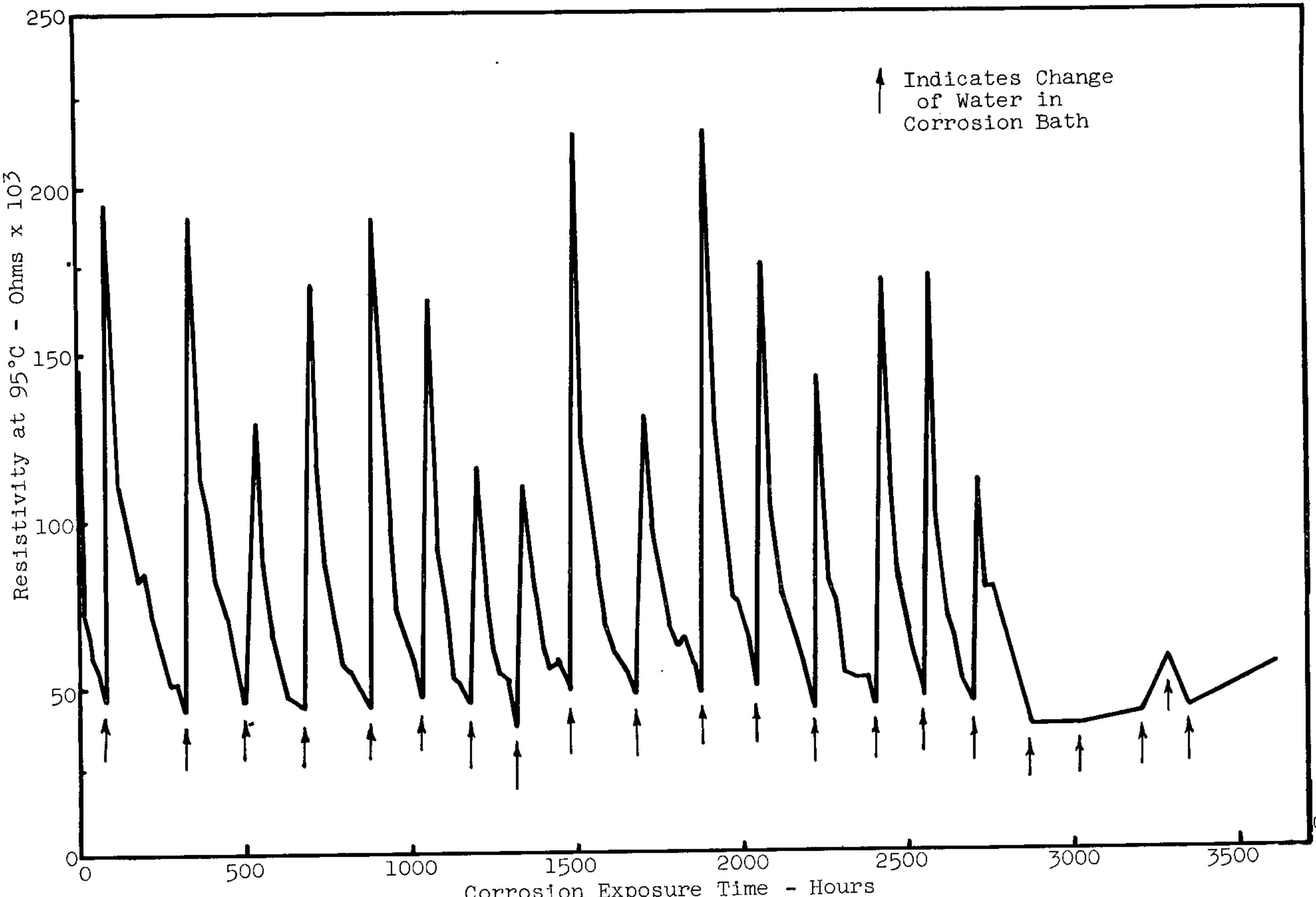


CHART 4

RESISTIVITY OF CORROSION BATH NO. 2
FOR ULTRASONICALLY WELDED LAP SPECIMENS OF 2S ALUMINUM

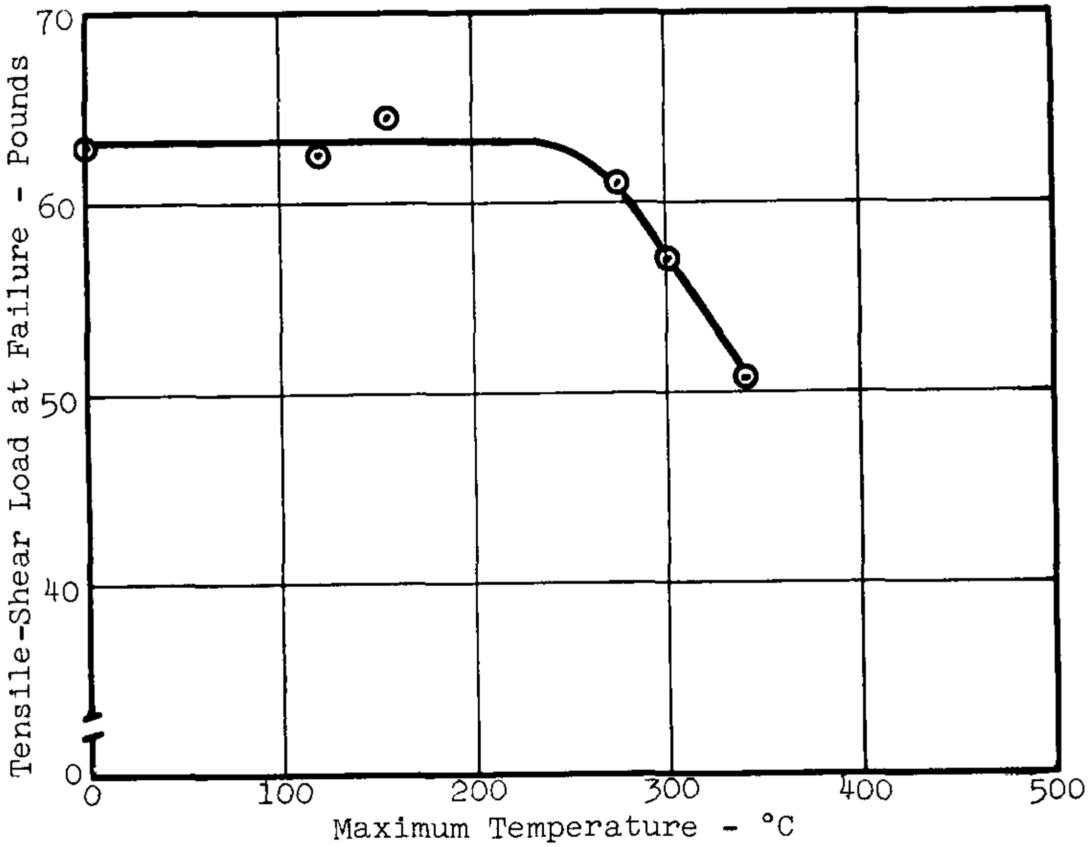


CHART 5

EFFECT OF REPEATED THERMAL CYCLING ON STRENGTH OF ULTRASONIC WELDS IN .010- TO .032-INCH 2S ALUMINUM

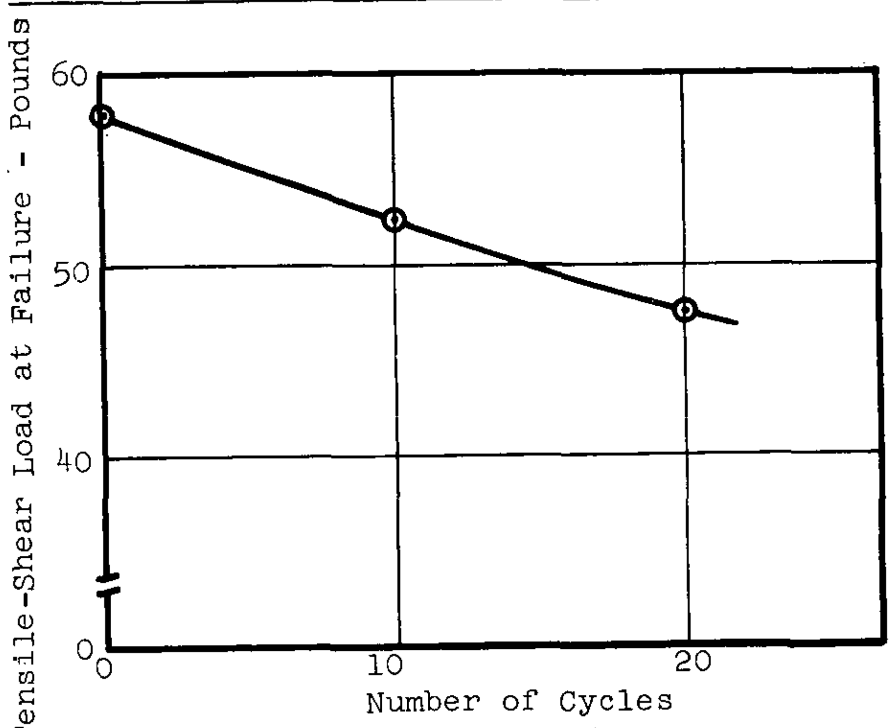


CHART 6

EFFECT OF REPEATED THERMAL CYCLING AT 300°C ON STRENGTH OF ULTRASONIC WELDS IN .010- TO .032-INCH 2S ALUMINUM

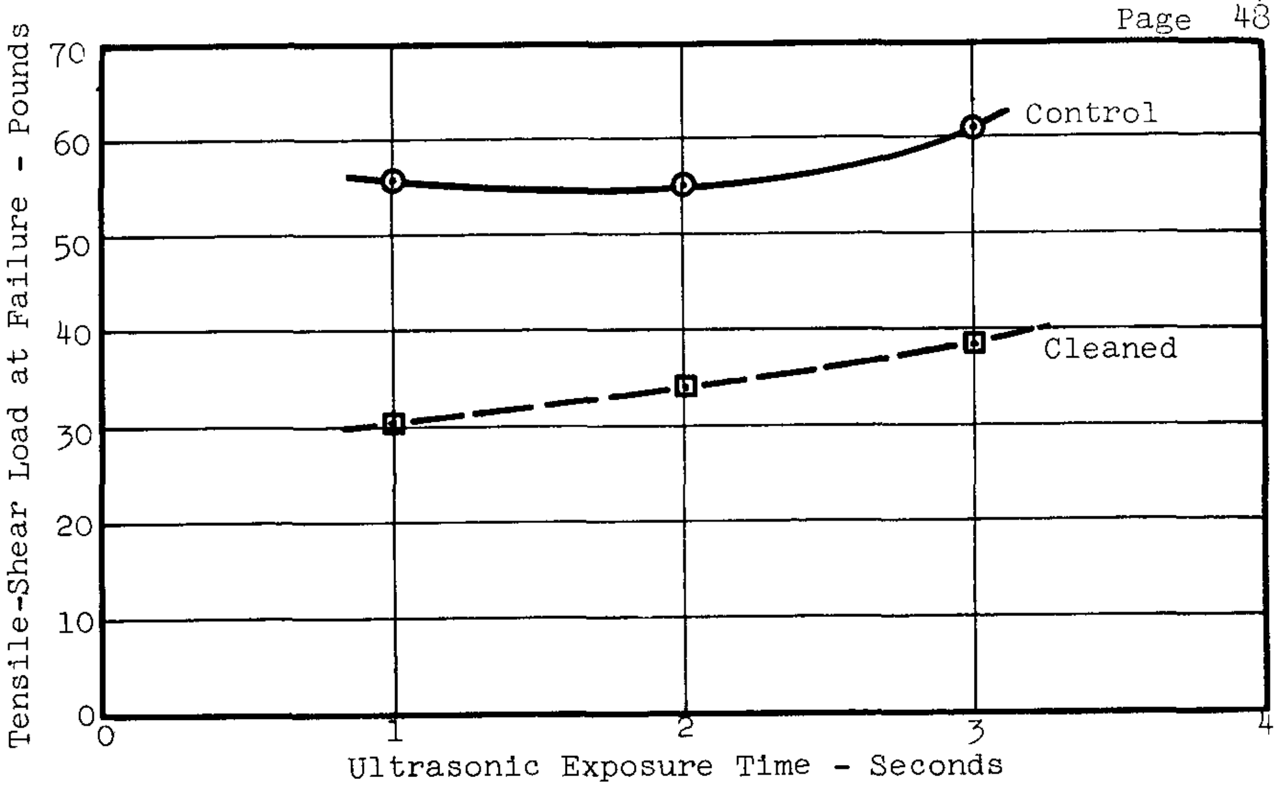


CHART 7

EFFECT OF PRECLEANING WITH SODIUM HYDROXIDE ON STRENGTH OF ULTRASONIC WELDS IN .010- TO .032-INCH 2S ALUMINUM

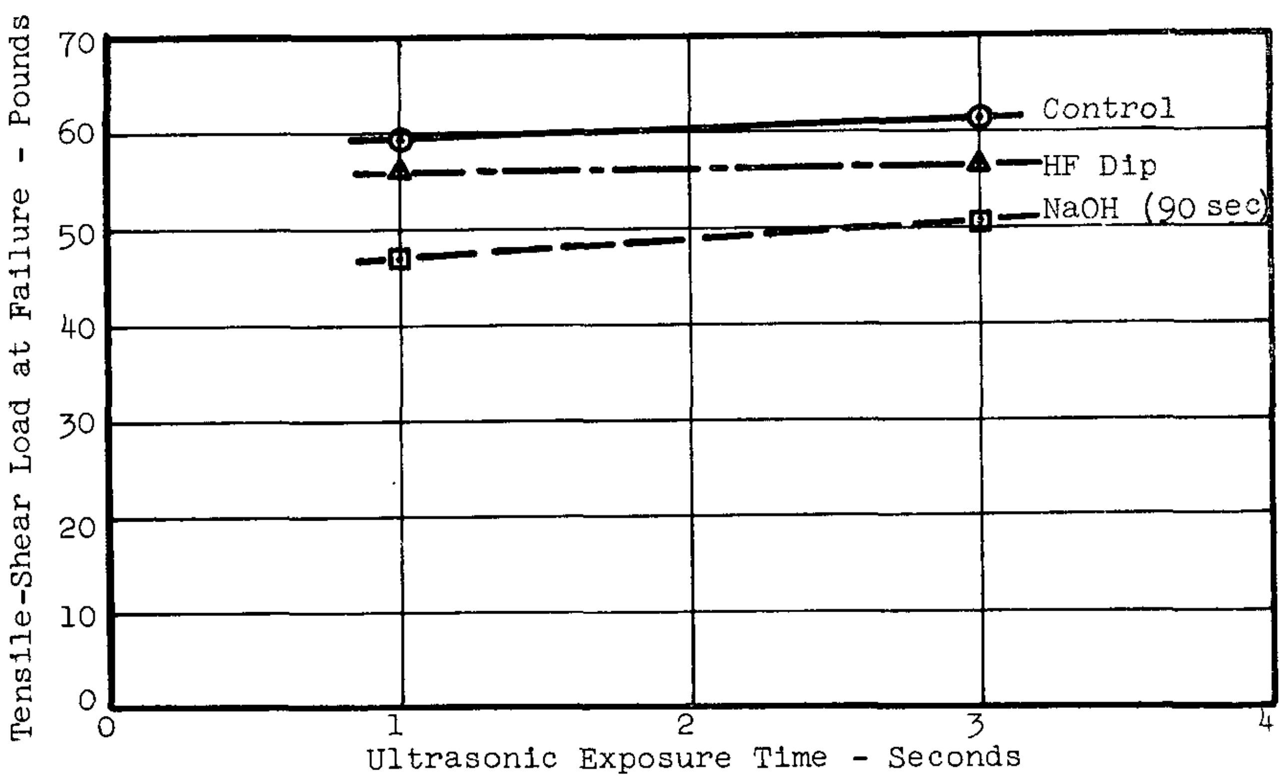


CHART 8

EFFECT OF PRECLEANING WITH SODIUM HYDROXIDE AND HYDROFLUORIC ACID ON STRENGTH OF ULTRASONIC WELDS IN .010- TO .032-INCH 2S ALUMINUM