FINAL REPORT

on

FEASIBILITY STUDY OF RESISTANCE WELDING OF ALUMINUM ALLOYS, STAINLESS STEEL, AND TITANIUM IN A HARD VACUUM

(June 27, 1967 to February 29, 1968)

to

GEORGE C. MARSHALL SPACE FLIGHT CENTER
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February 29, 1968

by

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TABLE OF CONTENTS

SUMMARY

An investigation was made of the feasibility of resistance spot welding 2014 aluminum, 304 stainless steel, and Ti-6Al-4V alloy in a hard vacuum (5×10^{-6} torr). The program was carried out in four phases. Phase I consisted of planning the experimental program and physical equipment. Phase II consisted of making weldments both in air and in vacuum using conventional resistance welding techniques. Weldment quality was evaluated by inspection of X-ray films and weld cross sections. In Phase III, the tensile shear strength of the welds was determined. In addition, the data were analysed to show in what ways welds made in air differed from those made in a vacuum. The resulting graphs provide guidelines for determining welding conditions in space once the welding conditions in air are known. A final analysis of the program results was performed in Phase IV to determine what function and capabilities would be required for spot welding in space. A discussion of desirable features and recommendation of guidelines for equipment design was also included. The data from the program provided criteria for the design of portable spot-welding equipment to be used in joining materials in space.

Spot welding is judged to be an excellent candidate process for welding in space, suitable tensile shear strengths can be obtained with low electrode forces and longer welding times (up to 0.85 second). Provision for these longer welding times could decrease welding current requirements. Titanium and possibly aluminum may require increased welding currents after prolonged exposure to a vacuum environment.

Recommendations are made for additional studies of resistance spot welding in a vacuum to determine surface preparation techniques, effects of prolonged exposure to a vacuum, and the effect of ambient temperature.

BACKGROUND

The planned placement of space stations in orbit for use as intermediate stops on deep space flights requires techniques for joining assemblies in space. Many of the present welding processes are not applicable for use in space. One problem encountered in joining is containment of the weld metal since the weld pool produced by most welding processes would be dispersed beyond the joint in the absence of gravitational forces. Another problem is the difficulty of precise manual manipulation of equipment in space. Resistance spot welding is a good candidate process because the molten weld pool is surrounded with solid metal, it requires little manual dexterity, and it only requires power for very short periods of time.

A general search of the available literature revealed only two instances where spot welds had been made in a vacuum. Battelle[(a)] spot welded molybdenum, zirconium, and uranium in a vacuum when welds made in air were found to have low and inconsistent strength. Hughes Aircraft Company[(b)] reported that they could make resistance spot welds in nickel and titanium alloys in a vacuum. Neither of these programs investigated the differences between the welding parameters required to make optimum welds in a vacuum as compared to air.

The following report describes research conducted to show whether resistance spot welds made in a vacuum have different characteristics or quality from welds made in air. In addition, the report describes data obtained to aid in the design of a portable resistance spot welder for use in space.

MATERIALS

The materials selected for study were 2014-T651 aluminum alloy 0.032 inch thick, 304 stainless steel 0.063 inch thick, and Ti-6Al-4V alloy 0.063 inch thick. The chemical analysis of the titanium alloy ingot was obtained and appears below:

Element	Composition, percent*
Carbon	0.03
Iron	0.10
Aluminum	6.5
Vanadium	4.4
Nitrogen	0.015
Oxygen	0.110
Hydrogen	99 ppm

* Except hydrogen, which is given in parts per million.

To minimize material variations, only one lot of each alloy was used.

(a) "A Metallurgical Study of Molybdenum", Fourteenth Quarterly Report; December, 1952; Battelle Memorial Institute, Columbus, Ohio, Office of Naval Research Contract Number N9onr 82101

(b) Enquist, R. D. and Nord, D. B.; "Study of Space Environment Fabrication and Repair Techniques", Final Report; December 1966; Hughes Aircraft Company, Culver City, California; NASA Contract NAS9-4548

EQUIPMENT

Welding was conducted using single-phase a-c welders with ignitron electronic contactors. Figure 1 shows the principal equipment used. A stainless steel vacuum chamber was placed within the throat of the welders. The upper welding electrode was allowed to move within the chamber through a sliding vacuum seal in the chamber wall. The chamber fixture held four specimens, which could be positioned between the electrodes by moving a shaft connected to the fixture and protruding from the left side of the chamber. The chamber was connected to a 6-inch-diameter diffusion pumping system equipped with a chevron-type liquid-nitrogen cooled trap. Figure 2 shows two specimens held in the fixture with one specimen positioned for welding.

The titanium and stainless steel specimens were welded using the Precision 50 kva welder shown in Figure 1. The aluminum specimens required a welder with a higher current capacity because of the throat opening needed to accomodate the chamber. Aluminum specimens were welded with a Taylor-Winfield 150 kva welder.

A Duffers Model 276 C current analyzer was calibrated and used to determine the rms welding current and to verify the welding time.

PROCEDURES

The following sections describe procedures used for specimen preparation, welding, and testing. The procedures were designed to insure consistent results and accurate comparison between air and vacuum welding.

Specimen Preparation

The sheet used during this investigation was sheared into 1 by 5-inch strips. The strips were degreased to remove gross contaminants such as oil or marking inks. Aluminum and stainless steel specimens were degreased in acetone, but methyl ethyl ketone was used for titanium strips since it removed the marking ink more readily. The degreased strips were stored in a clean air environment and finally cleaned just prior to welding.

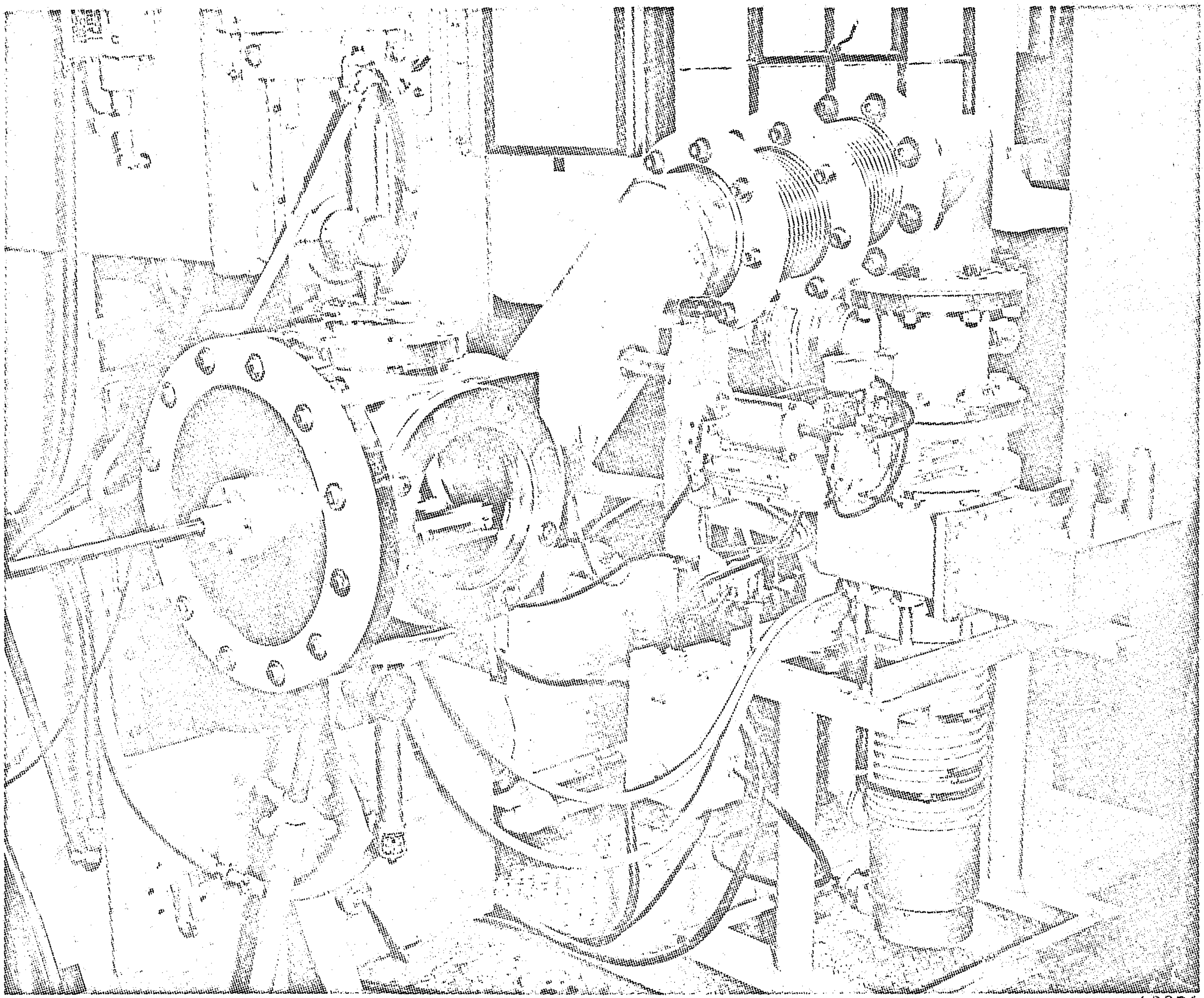

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FIGURE 1. WELDING CHAMBER MOUNTED ON SPOT WELDER

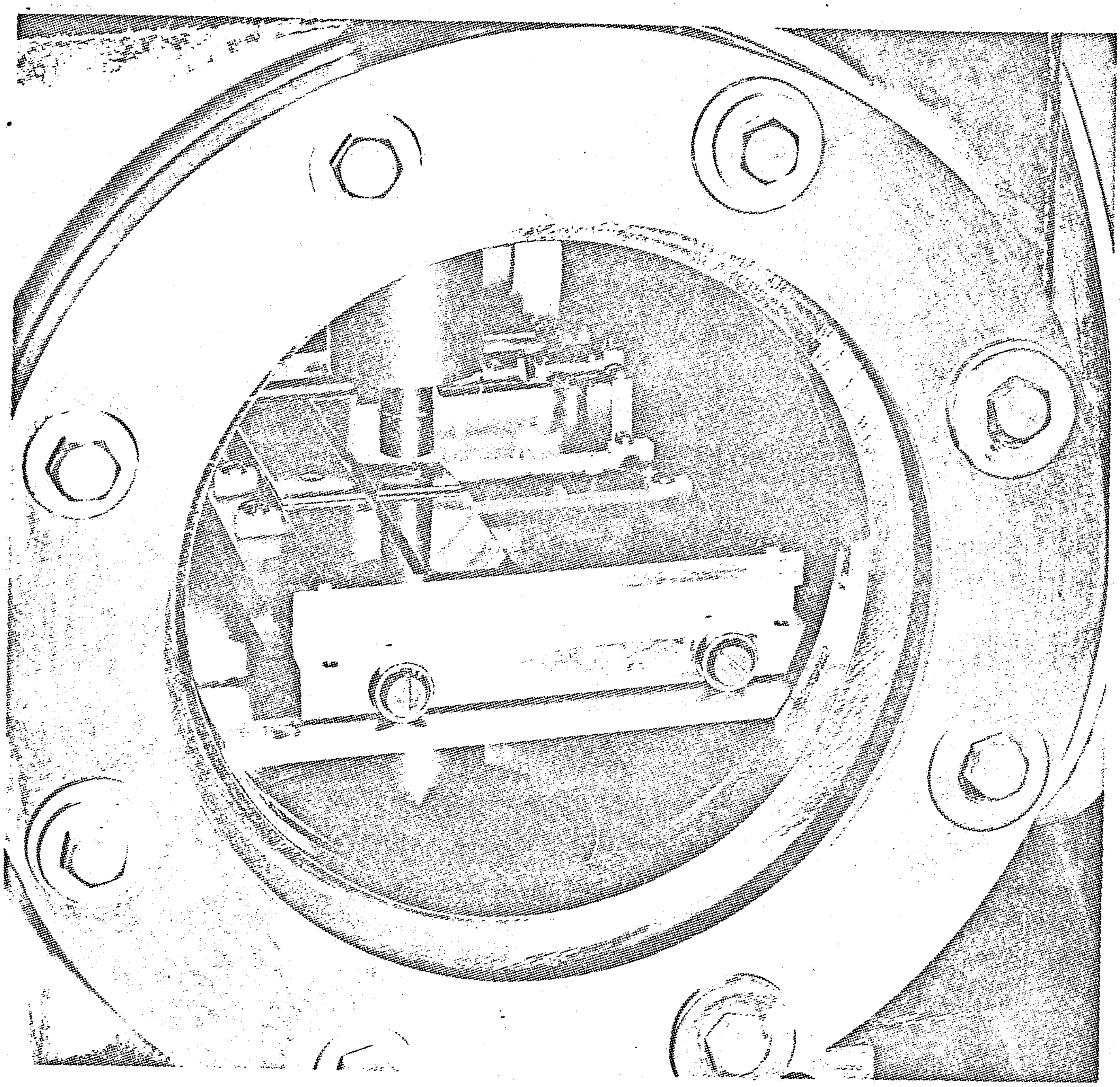

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FIGURE 2. CHAMBER INTERIOR WITH TWO SPECIMENS IN TRAVEL FIXTURE

Cleaning Prior to Welding

Specimens were cleaned within two hours of welding with the exception of several aluminum specimens. These aluminum specimens were cleaned and then stored in a vacuum-evacuated container to minimize surface oxidation and oxide hydration. Prior to welding, they were reexposed to air for at least 30 minutes.

The cleaning procedures used are given in Table 1. They were designed to provide uniform surfaces with a minimum amount of surface reaction products. The stainless steel surfaces were already sufficiently uniform and were only degreased. After cleaning, the specimens were inspected for any visible discontinuities such as gouges or stains on the surface. Specimens containing visible imperfections were discarded.

TABLE 1. CLEANING PROCEDURES PRIOR TO WELDING

A. 2014 Aluminum Alloy
   1. Degrease in c.p. acetone and wipe dry
   2. Etch in sodium hydroxide (40 grams NaOH per liter) at 160 F for 30 seconds
   3. Rinse in running water with agitation of specimen
   4. Brighten in nitric acid (50 percent by volume) at room temperature for 15 seconds
   5. Rinse in running tap water with agitation of specimen
   6. Air dry
   7. Inspect for water marks and repeat process if any stain is visible.

B. 304 Stainless Steel Alloy
   1. Degrease in c.p. acetone
   2. Air dry

C. Ti-6Al-4V Alloy
   1. Degrease in c.p. acetone
   2. Etch in acid solution (2 HF, 10 HNO_3, 88 H_2O) at room temperature
   3. Rinse in running tap water
   4. Air dry

Welding

As indicated previously, the stainless steel and titanium specimens were welded on the Precision 50 kva spot welder shown in Figure 1. The aluminum alloy welds were made with a 150 kva Taylor-Winfield spot welder using the same vacuum equipment. All welding, regardless of atmosphere, was performed in the chamber utilizing the locating mechanism shown. There were, therefore, no differences in the external magnetic field and no resultant differences in the secondary circuit impedance for the welds made in air and the welds made in a vacuum.

The cleaned specimens were handled by their edges away from the weld area when placed in the locating fixture. The lower specimen was supported on teflon insulators at three points while the upper specimen was supported by the lower specimen at one end and teflon at the other end. The tooling provided little restraint and allowed the specimens to bend easily during welding. This flexibility assured that the lower specimen rested firmly on the lower electrode during welding.

Electrodes

The water-cooled electrodes extended through a sliding seal into the chamber and were carefully aligned prior to welding. The electrode tips were made of a copper alloy meeting the specification for RWMA Class 2. The tip diameter was 5/8 inch and tip radius as follows:

Alloy	Spherical Radius of Tip, inches
2014 Aluminum	2
304 Stainless Steel	3
Ti-6Al-4V	3

The tips were changed before wear became apparent, generally after every 60 welds.

Welding Variables

The variables selected for study were welding current, welding time, and electrode force during welding. The welding current was controlled by the adjustable secondary tap settings of the welder. The welding time was regulated electronically by the adjustable settings of the welder controls. The electrode force was adjusted by varying the air pressure in the pneumatic cylinder that activated the upper electrode.

Welding Cycle

A simple welding cycle was used with downslope employed for only a few aluminum welds. All welds were made at the 100 percent heat setting. Pulsing was not used and a single electrode force was applied throughout the cycle. The value of the electrode force was determined by correlating the air pressure activating the air cylinder and the force between the electrodes as measured with a calibrated load cell. The values reported for electrode force have a probable $\pm$ 25-pound variation.

The welding current was determined by a current analyzer. The current values reported are rms values. The same current analyzer determined the welding time in half cycles on a 60 cycle per second base. On several occasions, the current analyzer indicated that actual welding time was less than what the welding machine was set for. This occurred with both welders and indicates the necessity for monitoring spot welders. In these cases, the specimen was discarded and a new weld made with the proper welding time. The welding current fluctuated $\pm$ 5 percent at most tap settings due to variations in the output of the welder with extended use. Current fluctuation were also suspected to be caused by local differences at the weld interface. Repeat welds were made if the current readings were erratic. There was no attempt made to change current to minimize these variations by using other tap or heat settings since the intent of the program was to determine how the welding values varied at the same machine setting for welding in a vacuum as compared to welding in air.

Vacuum Welding

Procedures for welding in air and in a vacuum were the same except that time was required to establish a hard vacuum. Pumping time ranged from 20 to 30 minutes. This was determined by the rate of pressure rise measured when the chamber was closed off from the pumping system for three minutes. The maximum rate of pressure rise allowed was 6×10^{-4} torr over the three-minute period. If the chamber pressure rise was greater than this, the chamber was pumped for an additional time until the pressure rise was acceptable. Measurement of the rate of pressure rise eliminates the possibility of excessive amounts of contaminants, due to outgassing and leaks, being pumped past the specimens during welding and contaminating the weld. Rate of pressure rise measurements are therefore a better indication of the surface cleanliness than the ultimate vacuum. The pressure rise over a period of three minutes was typically 3×10^{-4} torr. The ultimate vacuum was typically 2×10^{-6} torr but varied from 8×10^{-7} torr. When the upper electrode moved through the vacuum seal during the welding cycle the pressure in the chamber was observed to increase to about 6×10^{-5} torr and then drop back to the 10^{-6} torr range.

Four welds were made consecutively after each pumpdown. After all four specimens were welded, the chamber was backfilled and specimens for the next four welds were placed in the fixture. The chamber was pumped down and the welding process repeated. Figure 3 shows the dimensions of the welded specimens. The specimens is similar but not completely identical to the standard AWS* specimen for testing single spot welds in these sheet thicknesses.

Tensile Testing

After welding, the specimens were first X-rayed and then tested in tensile shear. The specimens were gripped securely by clamps on either end and loaded at a rate of approximately 150 pounds per minute for the 2014 aluminum specimens and 1500 pounds per minute for the titanium and stainless steel specimens. The maxiumum load applied during the test to failure was determined by a calibrated dynamometer. The maximum load was recorded and is reported as the tensile shear load of the weld.

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* See "Recommended Practices for Resistance Welding (C1. 1-66), American Welding Society

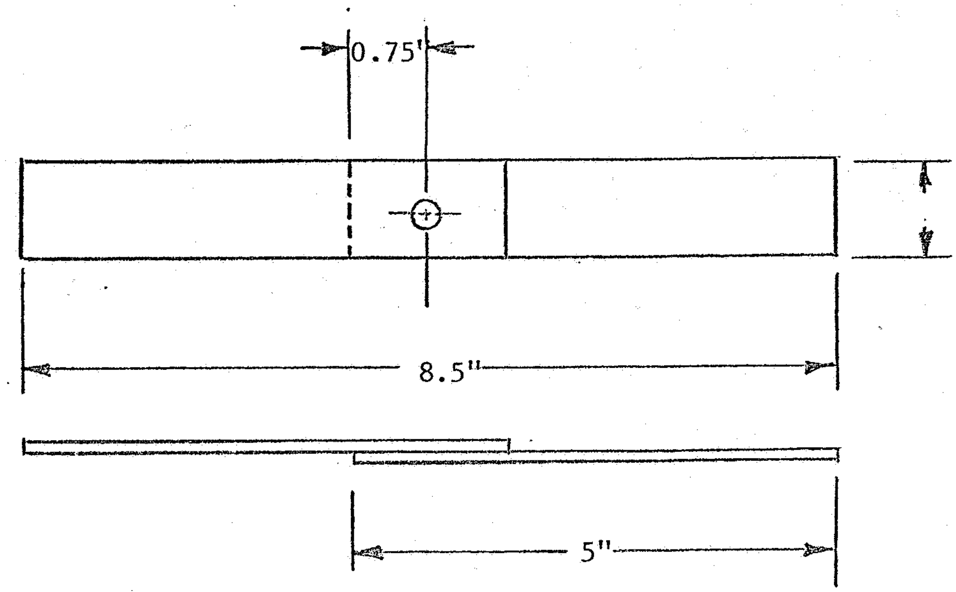

FIGURE 3. DIMENSIONS OF RESISTANCE SPOT WELDED SPECIMENS

There were no problems with the specimens slipping in the clamps and the effects of any misalignment were slight. The manner in which the specimen failed was observed and recorded by the operator. None of the specimens failed from cracks propagating from the sheared edges of the specimens.

X-Radiography and Metallography

After welding, X-rays were prepared of each specimen using fine-grained film. The X-ray films had good contrast and high sensitivity. These X-rays were inspected and any discontinuities found were recorded.

In addition, a total of 20 stainless steel welds were prepared and then cut and polished through the weld center to show the weld structure.

RESULTS

The most significant difference between the quality and characteristics of welds made in air and welds made at the same welding machine setting in a vacuum was shown by the tensile shear strength data. The following sections present the results obtained and other significant observations.

Effect of Variables on Tensile Shear Strength

Initially, a brief analysis was made using computer-aided statistical analysis of the results to provide a quantitative expression of the relationships between welding parameters and also to make maximum use of the results obtained. The statistical analysis gave limited, but interesting results that are reported below.

Statistical Analysis

A preliminary analysis was made of the data obtained from welding stainless steel in air. Data were obtained for three welding-current settings, three welding-time settings, and three electrode-force settings. Three replications were made at each of the 27 combinations of welding conditions. The first problem encountered in the analysis was the variation in measured current between successive welds made at the same tap settings. The current variation made it necessary to use the tap setting rather than the actual weld current as input in the computed relationships. The computer program utilized performed a regression and variance analysis on the data. The results showed that weld tensile shear strength was most significantly affected by weld current, followed in order of significance by time, and a combination factor of current multiplied by electrode force. Interestingly, current multiplied by time was one of the least significant factors studied.

The value of R^2, the coefficient of determination, for this analysis was 0.99, indicating an excellent correlation between the data and the calculated equation linking the significant factors to weld strength. The value of R^2 also indicated consistent results from the experimental work.

Despite the good fit between the computed equation linking weld strength with welding parameters, statistical analysis had some drawbacks. The limited range of experimental variations that could be studied at one time by statistical analysis, the difficulty of obtaining reproducible weld currents, and the ease with which large numbers of specimens could be welded and tensile tested all made the use of computer-aided statistical analysis impractical. The results presented in this program were analyzed qualitatively. The consistency of the results obtained, as shown by the statistical analysis, made it possible to draw curves through plotted points to present the results graphically.

Qualitative Analysis

Generally, the data obtained were consistent and easy to analyze qualitatively. The most valuable presentation of data was found to be plots of weld tensile shear strength versus the welding current. These plots are presented and discussed in the following sections for each alloy.

2014 Aluminum Alloy. The data for the aluminum alloy welds were the least consistent obtained. Errors may have been caused by the 150 kva welder, since this equipment maintained less consistent welding times and electrode forces than the Precision welder used for the other materials.

Figures 4, 5, and 6 show the scatter in data. Recommended* conditions for welding 0.032-inch-thick aluminum alloys are 26,000 amperes for six cycles with 500 pounds welding force. The tensile shear strength of welds made at these conditions is stated to be about 350 pounds. The tensile shear strengths obtained during this program therefore compare well with welds made by accepted practices.

For all three welding times, the tensile shear strength was significantly higher for welds made with 300 pounds electrode force. At the same welding current and electrode force, there was no basic difference in tensile shear strength between the welds made in air and the welds made in a vacuum. Changes in welding time changed the tensile shear strength of aluminum welds less than that obtained with the other alloys. The welds made at 30 cycles in a vacuum that had no shear strength are believed anomalous; there is no good reason why a weld could be made at this same conditions at 15 cycles but not at 30 cycles.

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* Resistance Welding Manual, Volume 1, 3rd Edition (1956)

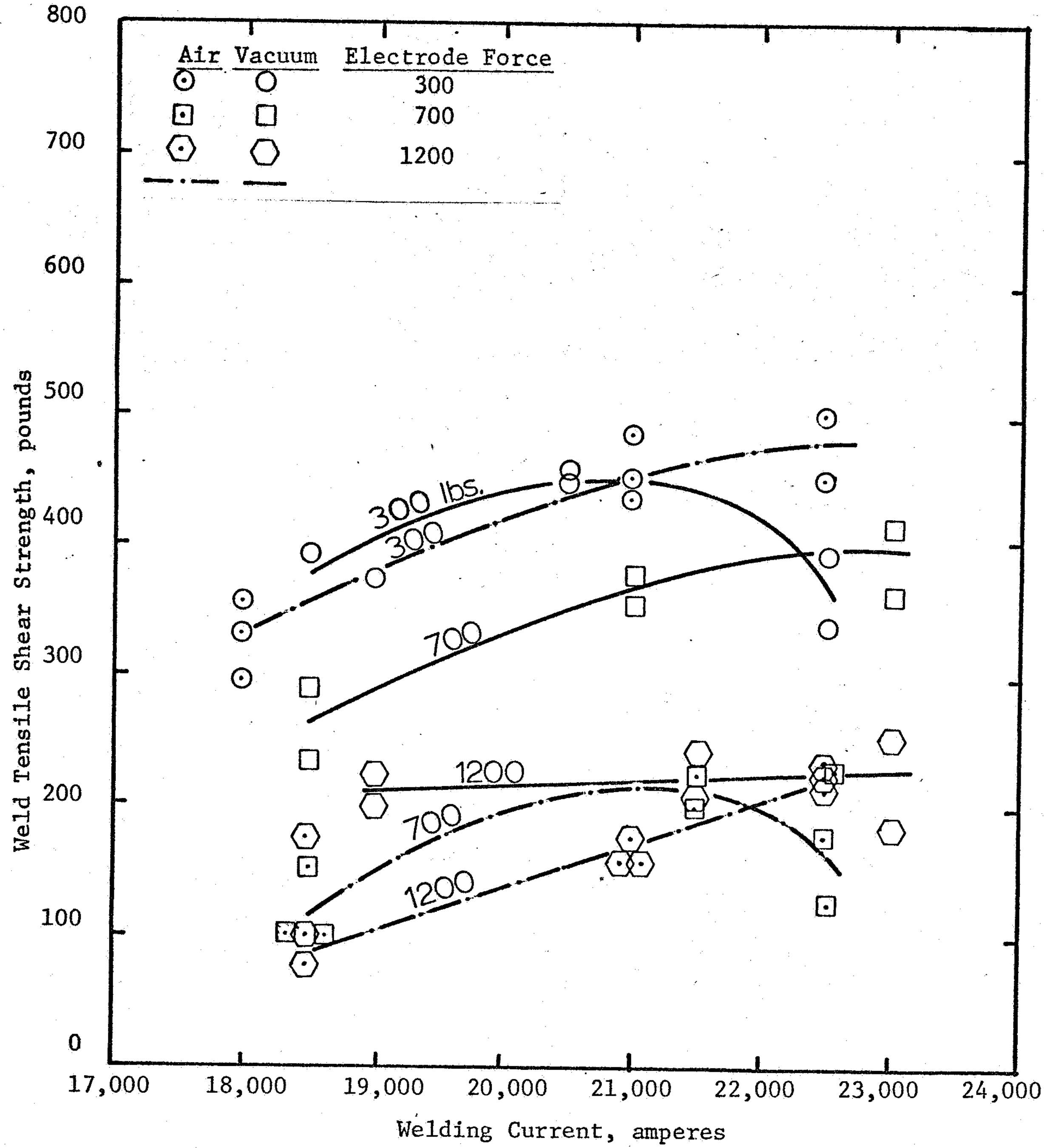

FIGURE 4. TENSILE SHEAR STRENGTH OF 2014 ALUMINUM SPOT WELDS MADE AT 5 CYCLES

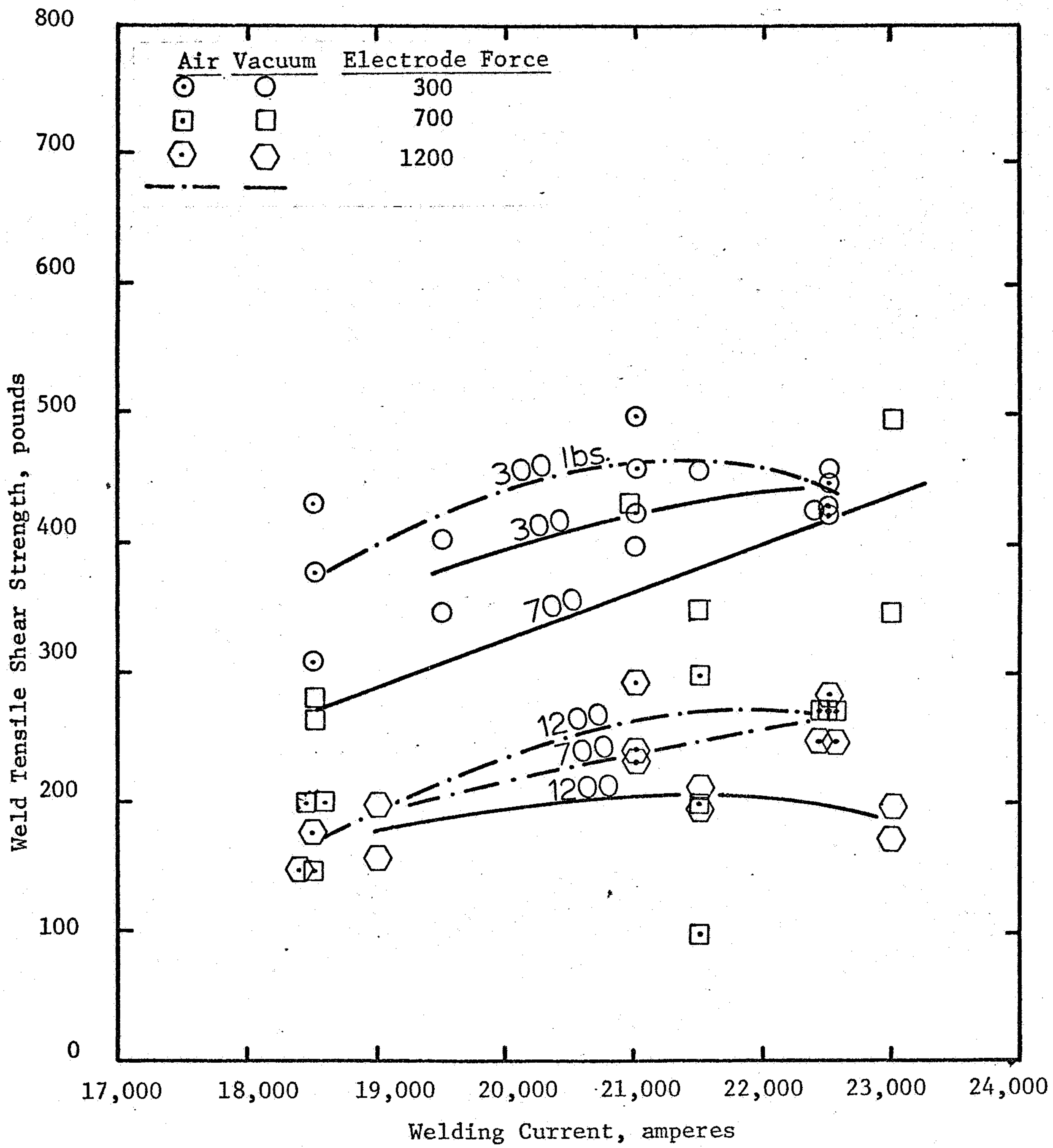

FIGURE 5. TENSILE SHEAR STRENGTH OF 2014 ALUMINUM SPOT WELDS MADE AT 15 CYCLES

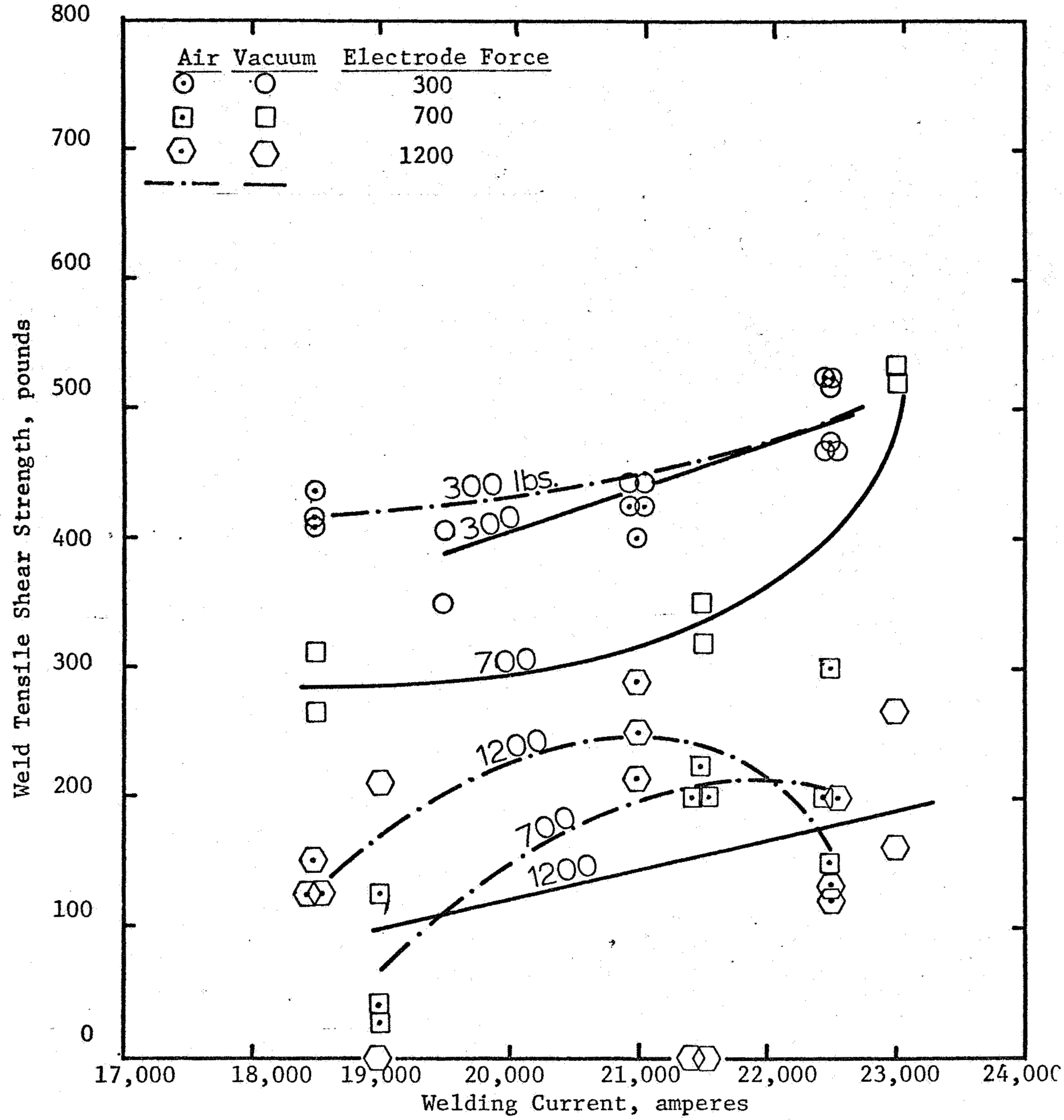

FIGURE 6. TENSILE SHEAR STRENGTH OF 2014 ALUMINUM SPOT WELDS MADE AT 30 CYCLES

304 Stainless Steel Alloy. The stainless steel welding data were the most consistent, possibly because the surface was degreased rather than chemically cleaned prior to welding. As a result, the surface was uniformly oxidized and was not affected by differences in time between cleaning and welding.

Figures 7, 8, and 9 plot the results obtained with stainless steel. No data were obtained for welding stainless steel in a vacuum at 50 cycles, since the results in air showed only marginal benefits from increasing welding time above 30 cycles. Recommended* conditions for welding 0.062-inch-thick stainless are 11,000 amperes for 10 cycles with 1500 pounds welding force. Tensile shear strengths of 2400 to 2900 pounds are expected at these conditions. The tensile shear strengths obtained for stainless steel during this program compare well with these figures.

Below 7000 amperes, higher tensile shear strengths were obtained with lower electrode forces. At currents above 8000 amperes, increasing the electrode force from 300 to 1440 pounds did not result in an appreciable change in tensile shear strength. Unlike the aluminum welds, increasing the cycle time from 10 to 30 to 50 cycles resulted in significant increases in weld tensile strength. The tensile shear strength at any given current increased at least 500 pounds when the welding time was increased from 10 to 30 cycles. A general increase in shear strength of 200 pounds at any given current was noted when the welding time was changed from 30 to 50 cycles.

There was no significant difference in tensile shear strength between welds made in air or in a vacuum at the same welding current, welding time, and electrode force. The curves shown in Figures 7, 8, and 9 are strikingly similar.

Ti-6Al-4V Alloy. The data for the titanium alloy welds showed some scatter but variations were not as great as for the aluminum welds. Figures 10, 11, and 12 plot shear strength versus weld current at 10, 30, and 50-cycle welding times. Conditions recommended** for Ti-6Al-4V alloys are 10,600 amperes for 10 cycles with 1500 pounds welding force. Tensile shear strengths of 5000 pounds are expected at these conditions. Titanium welds made in air, using the above conditions, during this program had tensile shear strengths ranging from 3900 to 4200 psi. The cause of variation was not determined, but is most likely due to current variations. Welds with tensile shear strengths slightly over 5000 pounds were made during the program using slightly different welding conditions.

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* Resistance Welding Manual, Volume I, 3rd Edition (1956)

** Nolen, R. K., Rudy, J. F., Schwartzbart, H., and Kessler, H. D., "Spot Welding of Ti-6Al-4V", Welding Journal Research Supplement, 37 (4) 129s-137s (April, 1958).

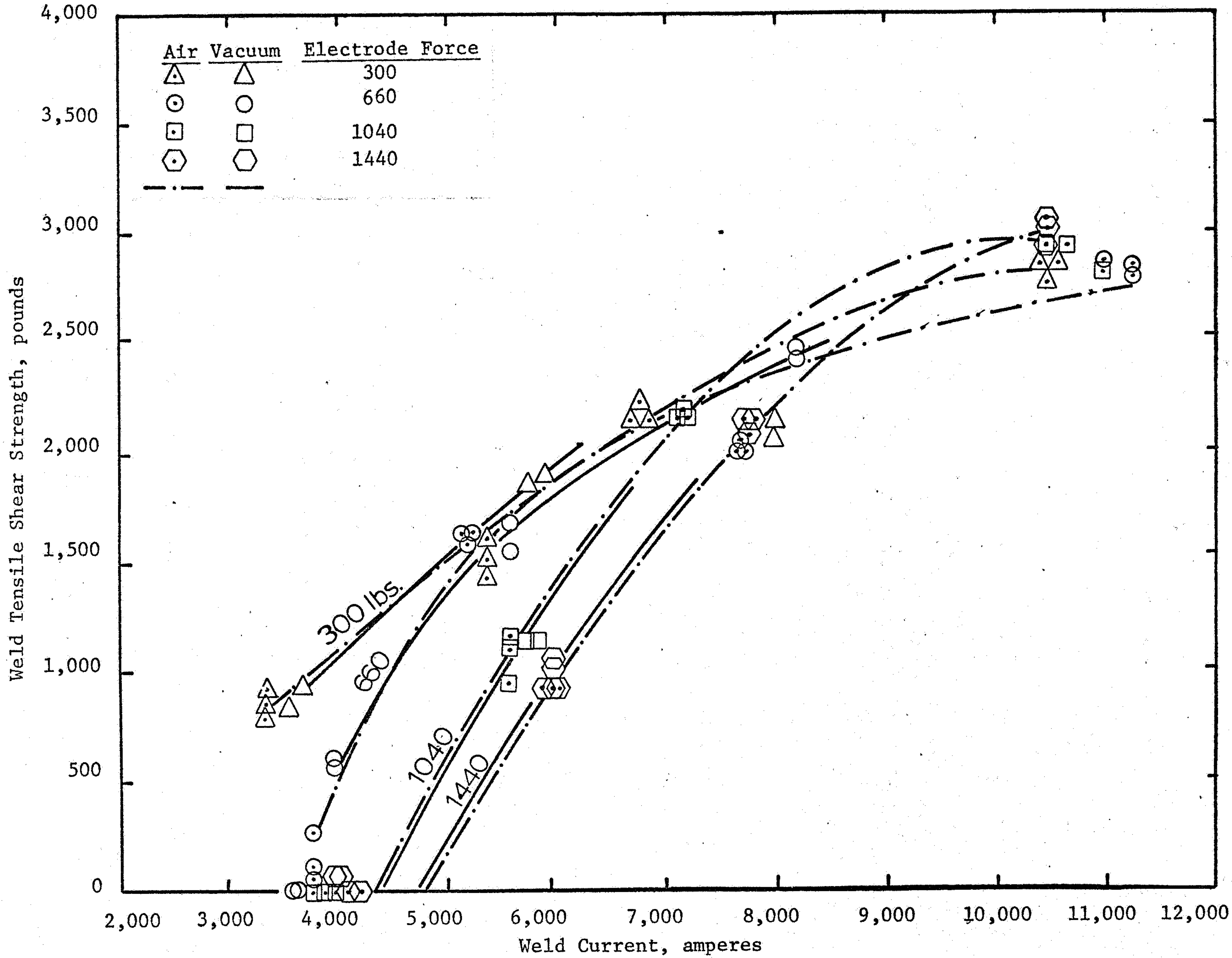


FIGURE 7. TENSILE SHEAR STRENGTH OF 304 STAINLESS STEEL WELDS MADE AT 10 CYCLES

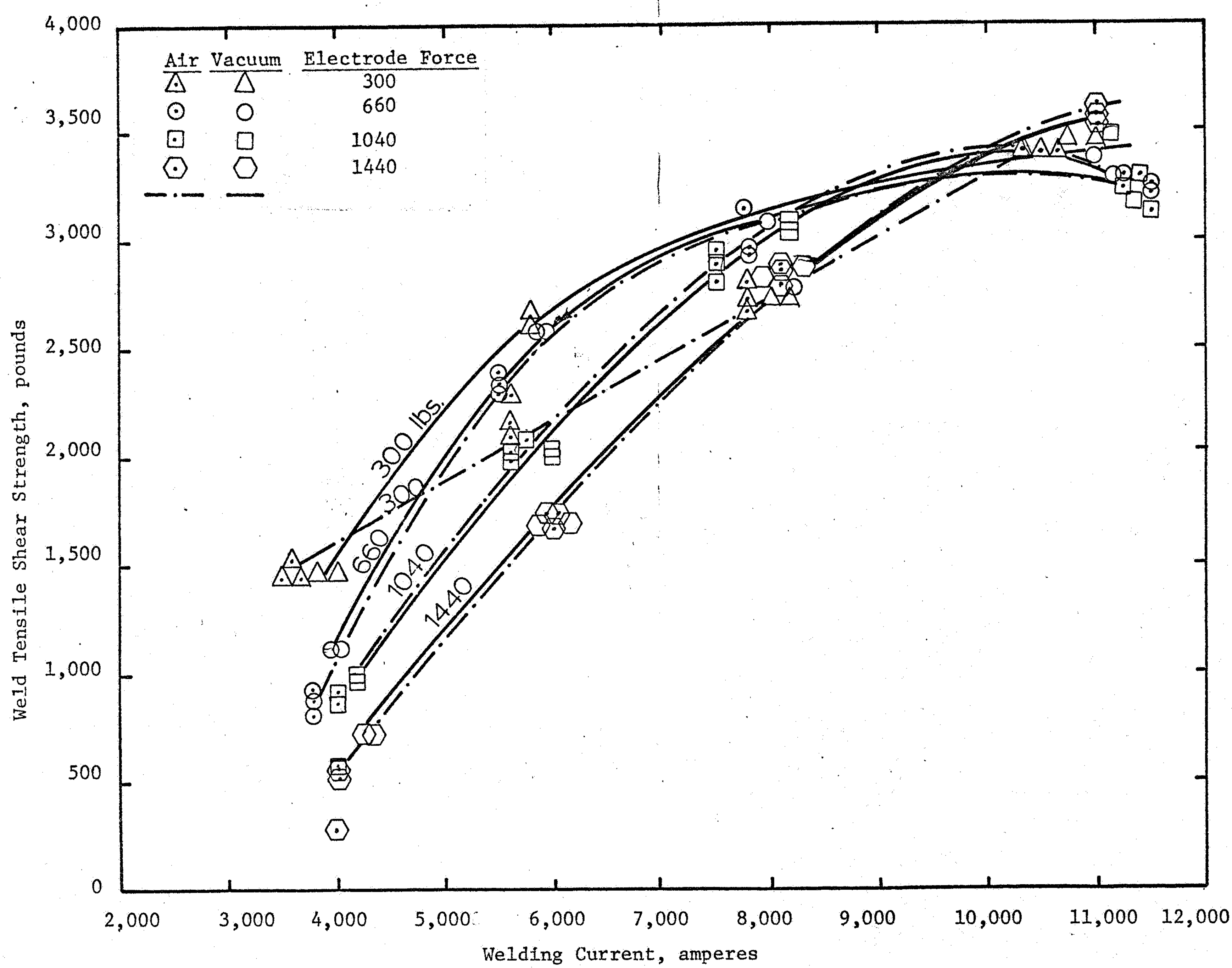


FIGURE 8. TENSILE SHEAR STRENGTH OF 304 STAINLESS STEEL WELDS MADE AT 30 CYCLES

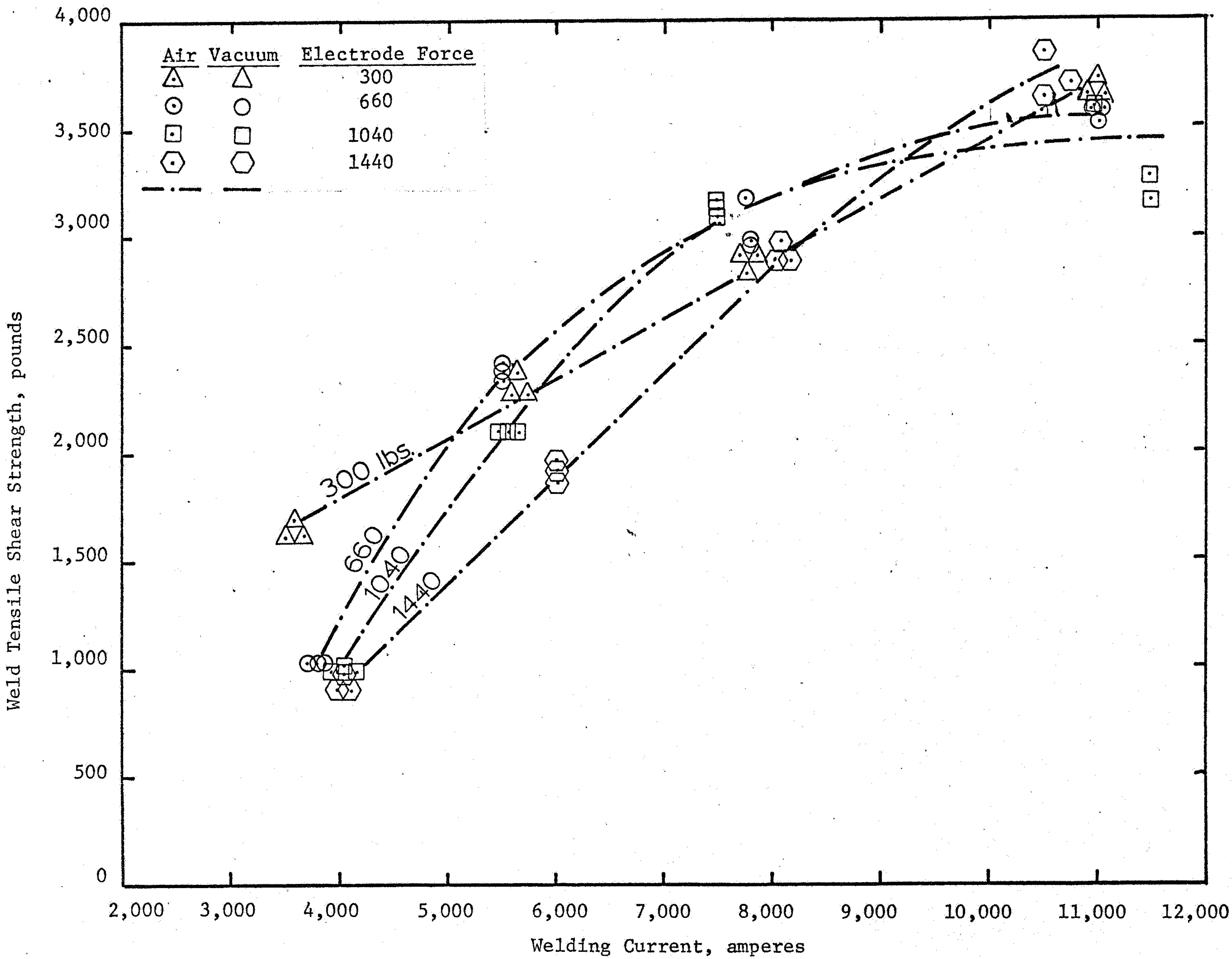


FIGURE 9. TENSILE SHEAR STRENGTH OF 304 STAINLESS STEEL WELDS MADE IN AIR AT 50 CYCLES

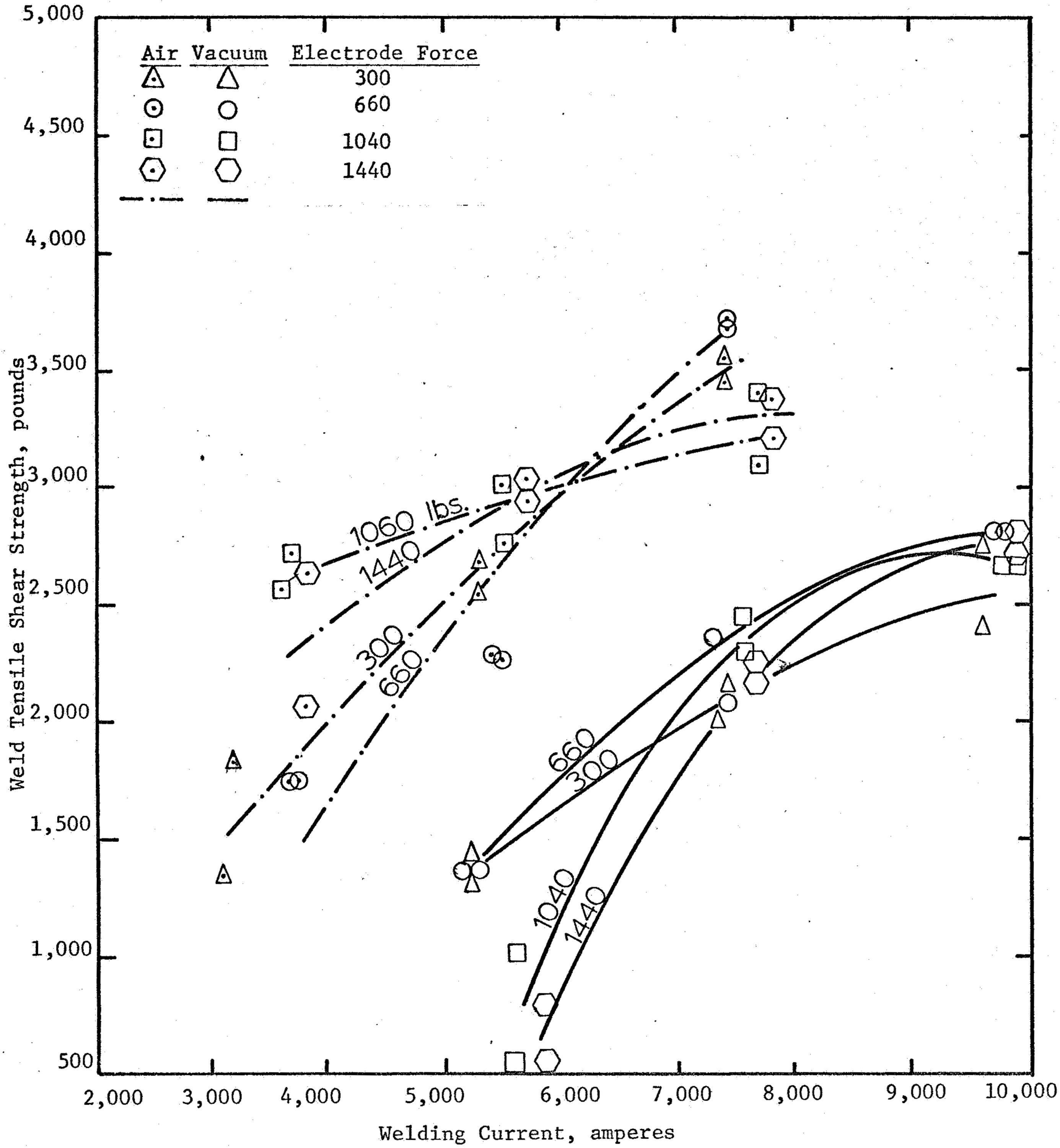


FIGURE 10. TENSILE SHEAR STRENGTH OF Ti-6Al-4V ALLOY WELDS MADE AT 10 CYCLES

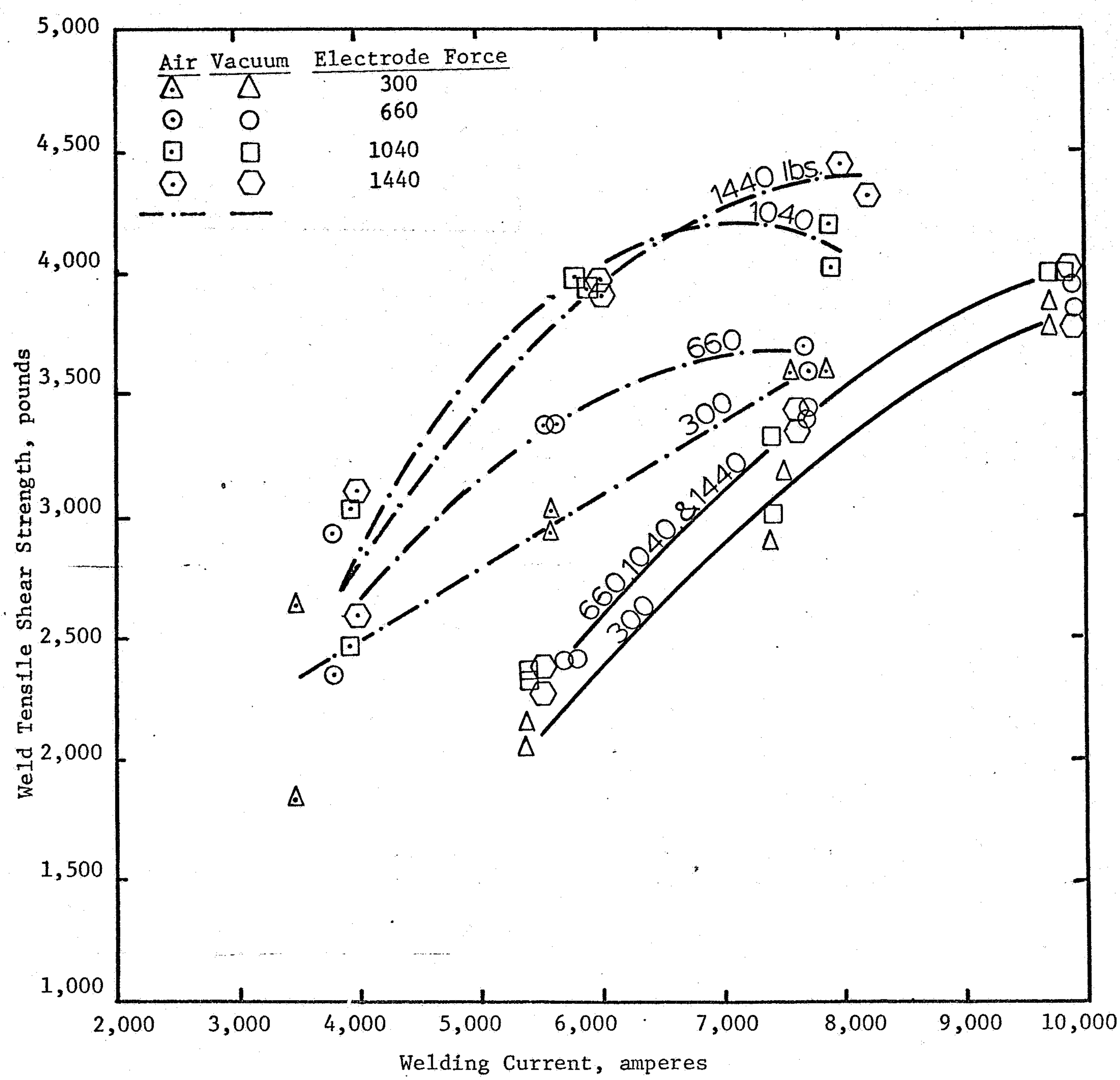


FIGURE 11. TENSILE SHEAR STRENGTH OF Ti-6Al-4V ALLOY WLEDS MADE AT 30 CYCLES

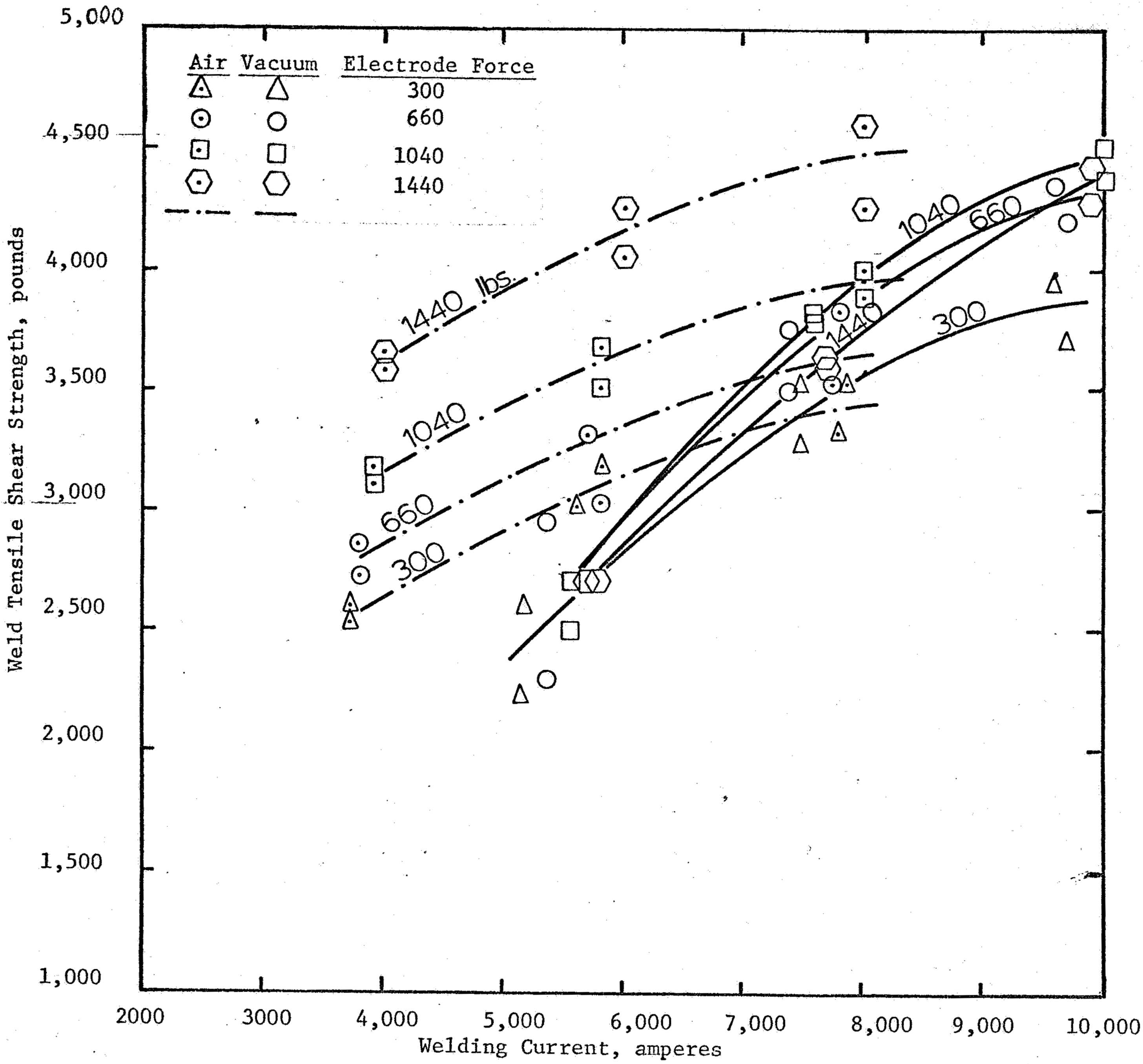


FIGURE 12. TENSILE SHEAR STRENGTH OF Ti-6Al-4V ALLOY WELDS MADE AT 50 CYCLES

The titanium welds showed the most significant variation between welds made in air and in a vacuum. As Figures 10, 11, and 12 show, the current obtained at the same machine settings was 1500 to 2000 amperes greater for welds made in a vacuum. The welds made in a vacuum had lower tensile shear strengths than the welds made in air except when the welding time was 50 cycles. At welding times of 10 and 30 cycles, the effect of changing the electrode force was slight. However, at 50 cycles, the welds made in air showed a definite increase in strength (approximately 1300 pounds as the electrode force increased from 300 to 1440 pounds). Also, at 50 cycles, the tensile shear strengths of the welds made in a vacuum were closest to the strength of welds made in air.

Weld Expulsion

Weld expulsion is often regarded as undesirable in spot welding operations where high reliability is desired. Expulsion can be avoided by using high electrode forces or low welding currents. If the only criterion by which welds are judged is the spot shear strength, expulsion is of little concern. Expulsion was found to be associated with aluminum welds in air only when the electrode force was 300 pounds (the lowest force studied) and when the current was 21,000 amperes or above. As shown in Figures 4, 5, and 6, the highest weld strengths were achieved at those conditions where expulsion occurred. The weldments made in a vacuum contained expulsion only when welded with 300 pounds electrode force.

The stainless steel welds in air showed expulsion at the higher currents at all electrode forces except 1440 pounds. At 300 pounds. expulsion began at 3600 amperes, 50 cycles. At 660 pounds, expulsion began at 7700 amperes, 10 cycles. At 1040 pounds, expulsion began at 5600 amperes, 30 cycles. The stainless steel weldments made in vacuum showed expulsion only at electrode forces of 660 pounds and below.

The titanium weldments showed no expulsion at any of the conditions studied.

Weld Quality

The weld quality was evaluated by radiography and inspection of polished weld sections. The initial stainless steel weld sections did not provide much additional data. Therefore, sectioning was discontinued.

Radiography

Radiography did not reveal any detectable discontinuities in either aluminum or titanium welds.

The stainless steel welds generally contained voids in the center of the weld ranging from 0.008 to 0.25 inch in length or diameter. The only welds consistently free of voids were made with an electrode force of 1440 pounds. The void size increased when weld current at any cycle time was increased. For example, the welds made in air at 1040 pounds electrode force showed the following voids:

TABLE 2. RELATIONSHIP OF VOID SIZE TO WELDING CONDITIONS

Current	Cycles Setting, cycles 10	30	50
4,000	No voids (no weld)	No voids	No voids
5,600	1/64-in. circle	1/32-in. circle	1/16-in. ellipse

The circular voids were found to have a maximum diameter of 1/16 inch. The elliptical voids were as short as 1/32 inch and as long as 1/4 inch.

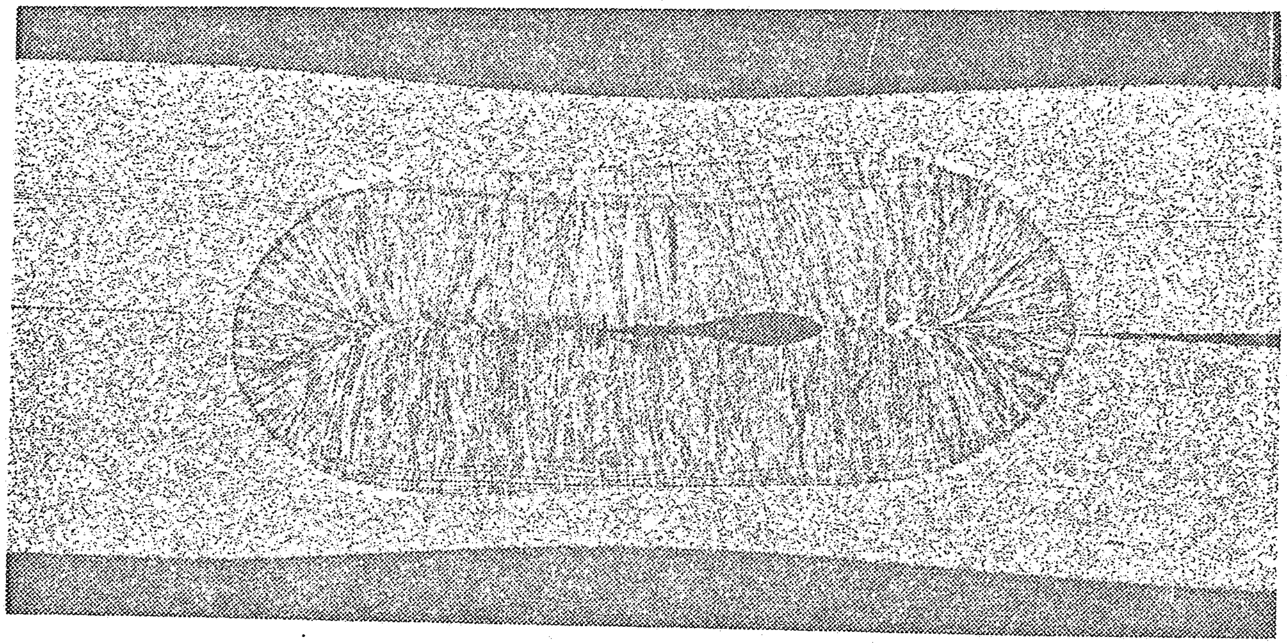
The stainless steel welds made in a vacuum contained radiographically visible voids in almost every weld. Even at an electrode force of 1440 pounds, most of the welds contained small voids. Void formation was erratic. At one set of conditions, only the welds made at the highest and lowest currents were void free. The voids were typically 1/16 to 1/32-inch-diameter circles.

Microscopic Examination

A microscopic study of 20 stainless steel spot-weld sections gave such limited results that sectioning was stopped. Instead, additional effort was spent preparing and testing welds. No difference could be detected between welds made in air or in a vacuum when the welding conditions were similar, as shown in Figures 13 and 14. The voids shown in these specimens are larger than the average void size found by radiography in stainless steel welds. There is no evidence that the welding atmosphere affected the amount of weld expulsion or the size of internal weld voids. The welds show a "ghost" outline on the top and bottom. This was attributed to the design of the electrode cooling system in which water flowed only when the welding began. The weld cycles were sufficiently great that the nugget formed initially was quite thick. As cooler water flowed through the electrodes, a portion of the nugget was solidified (even while the current flowed) due to the increase in heat sink provided by the electrodes. Figure 15 shows one of the welds made in air. The enlarged view of one end of the weld illustrates the typical columnar structure of the weld, the partially melted grains at the fusion-zone boundary, and the enlarged grains in the weld heat-affected zone. However, the weld contained a considerable number of microscopic voids at the nugget center as Figure 16 shows. The interdendritic voids ranged in size from irregular voids as long as 0.002 inch to small rounded voids approximately 0.00003 inch in diameter.

Mode of Specimen Failure

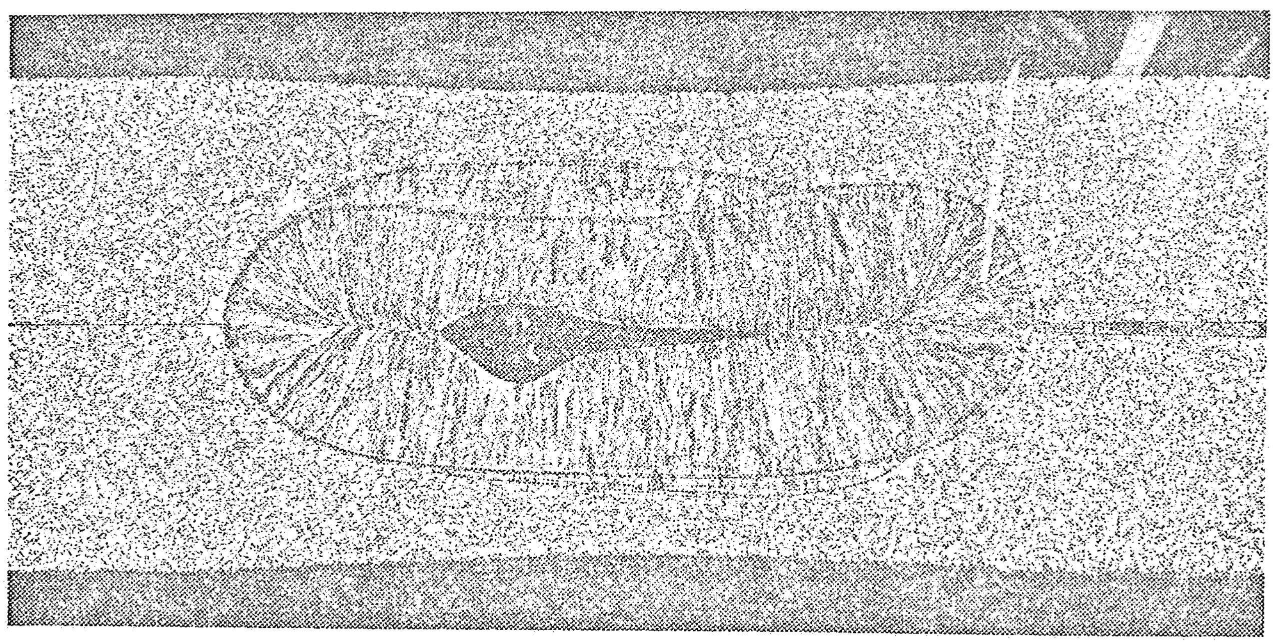
The majority of the weld specimens failed during testing by shear at the original interface between the two pieces of sheet. This type of failure is described in Figure 17a.



20X 98 HCl, $3HNO_3$, $1/2CuCl_2$ 5C234

(a) Weld Made in Air

(2700 amperes, 30 cycles, 300 pounds)

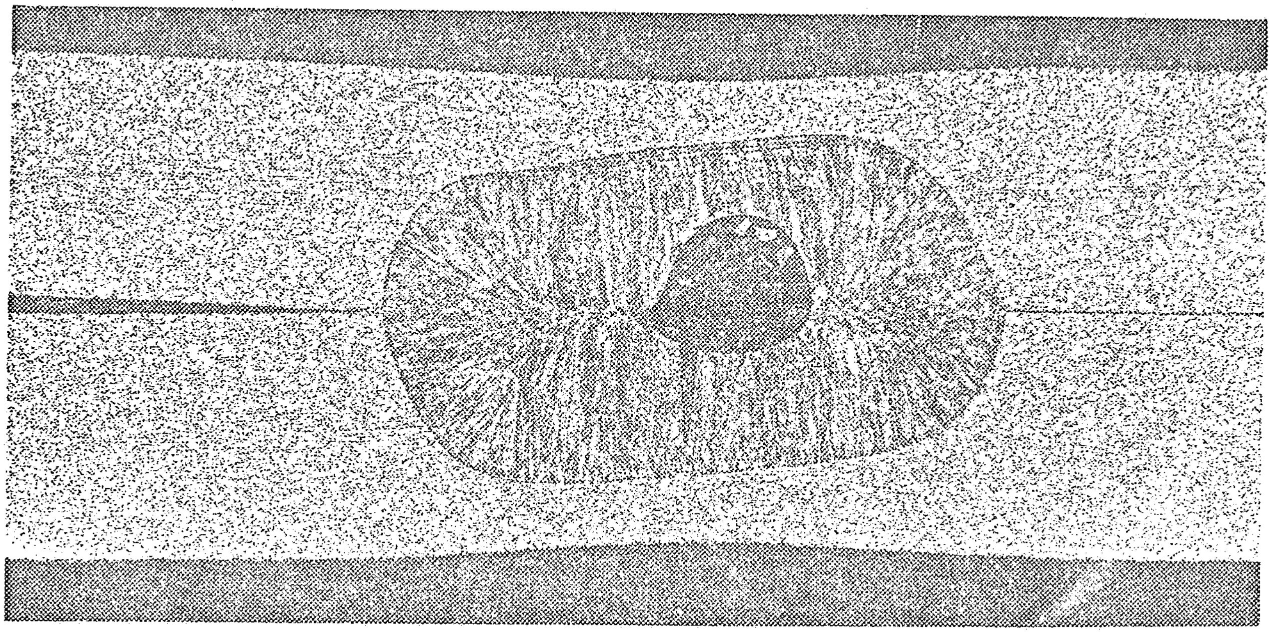


20X 98HCl, $3HNO_3$, $1/2CuCl_2$ 5C244

(b) Weld Made in Vacuum

(5900 amperes, 30 cycles, 300 pounds)

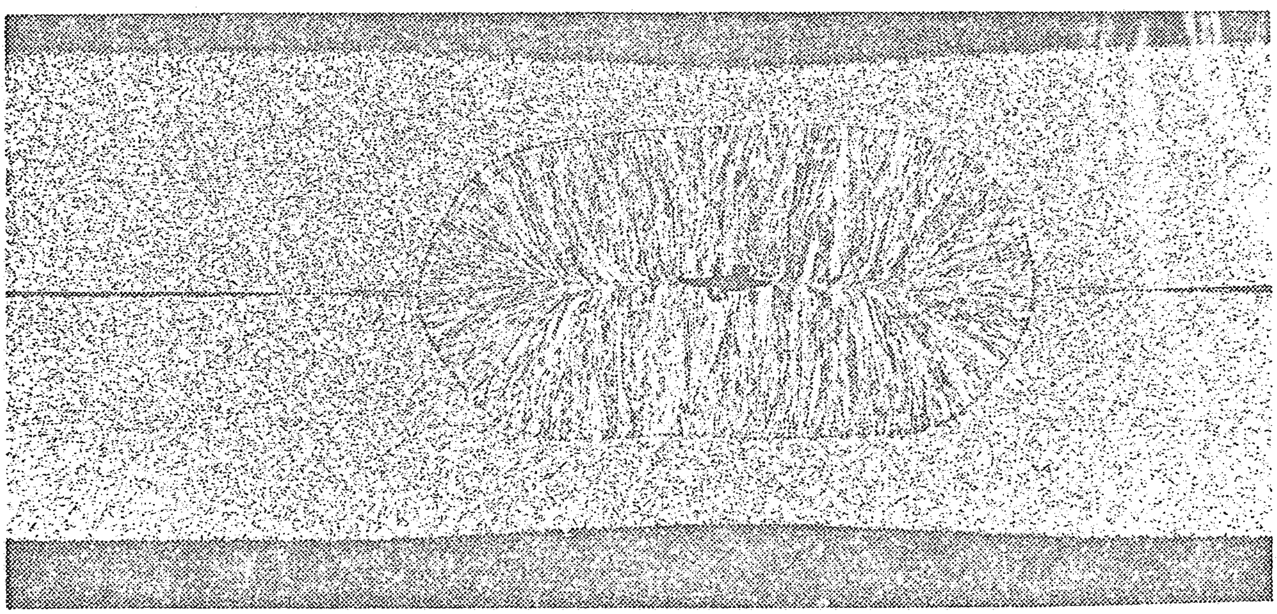
FIGURE 13. ILLUSTRATION OF THE SIMILARITY BETWEEN STAINLESS STEEL WELDS MADE IN AIR AND IN VACUUM AT THE SAME CONDITIONS



20X $98HCl$, $2HNO_3$, $1/2CuCl_2$ 5C231

(a) Weld Made in Air

(5600 amperes, 10 cycles, 300 pounds)

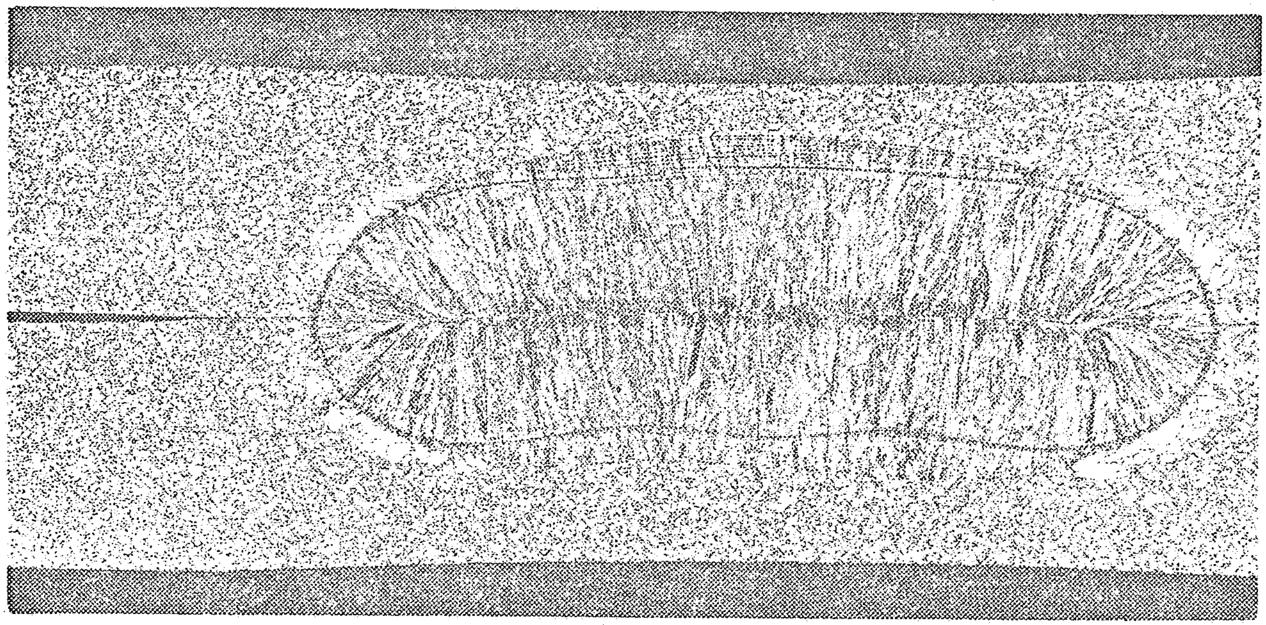


20X $98HCl$, $2HNO_3$, $1/2CuCl_2$ 5C241

(b) Weld Made in Vacuum

(6000 amperes, 10 cycles, 300 pounds)

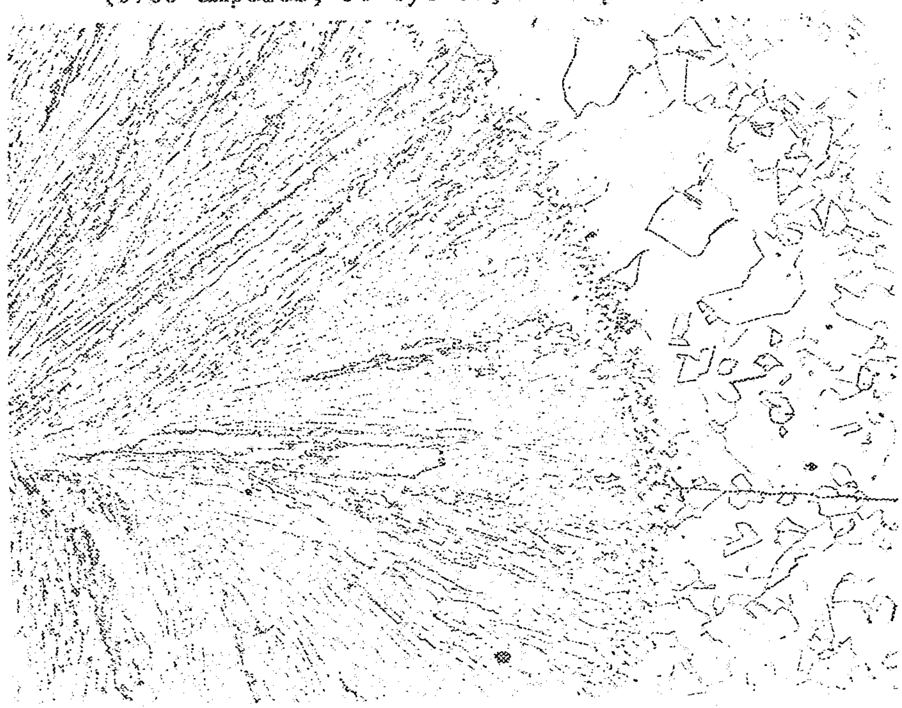
FIGURE 14. ILLUSTRATION OF THE SIMILARITY BETWEEN STAINLESS STEEL WELDS MADE IN AIR AND WELDS MADE IN VACUUM AT THE SAME CONDITIONS



20X $98HCL, 2HNO_3, 1/2CuCl_2$ 5C238

(a) Overall View of Weld

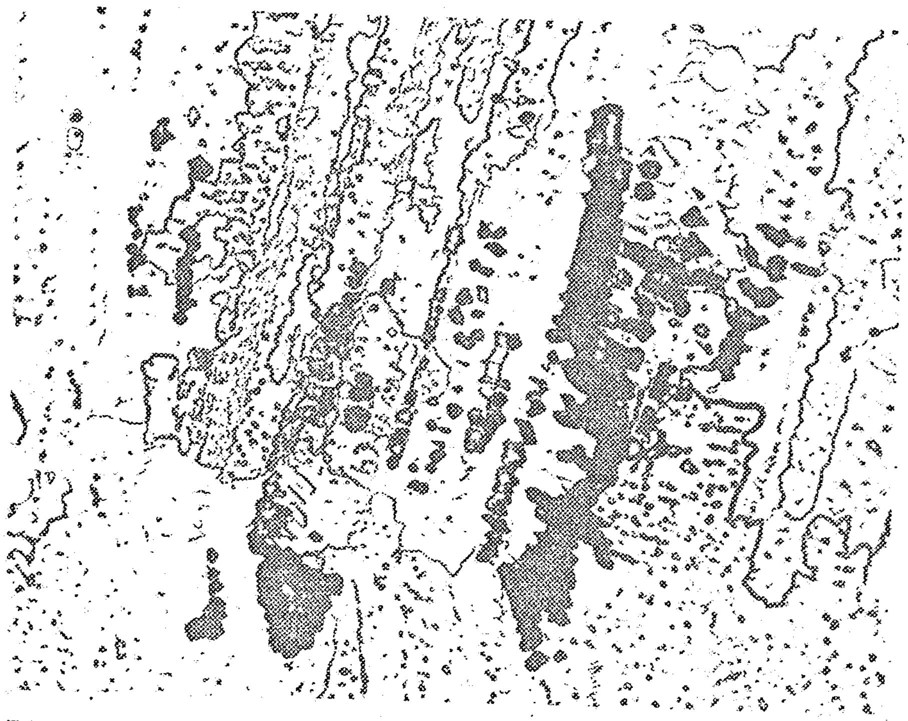
(6700 amperes, 50 cycles, 1040 pounds)



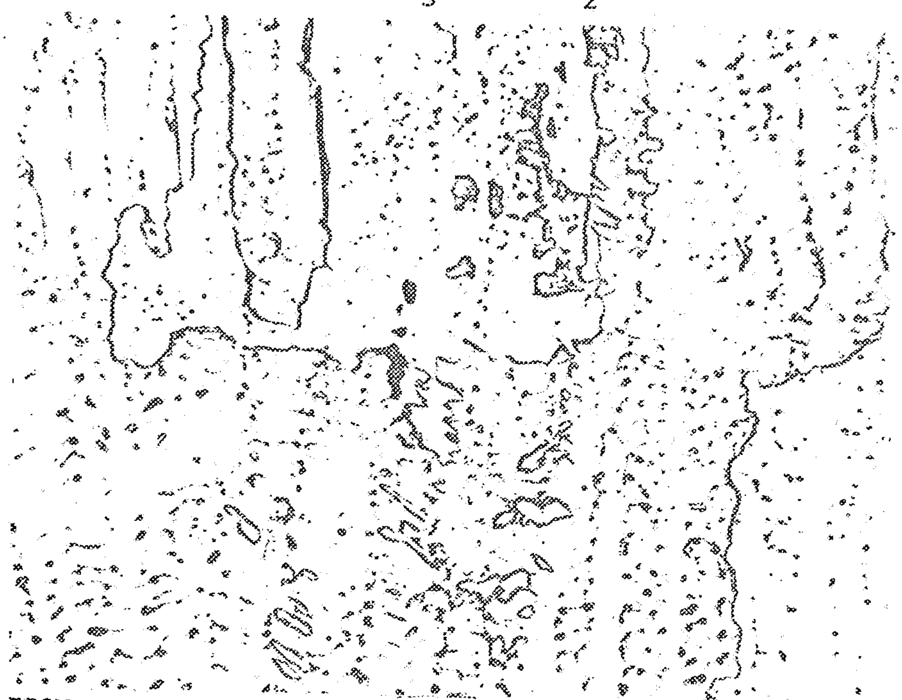
100X $98HCl, 3HNO_3, 1/2CuCl_2$ 5C227

(b) Right Side of Weld

FIGURE 15. WELD MADE IN AIR CONTAINING INTERDENDRITIC VOIDS AT NUGGET CENTER

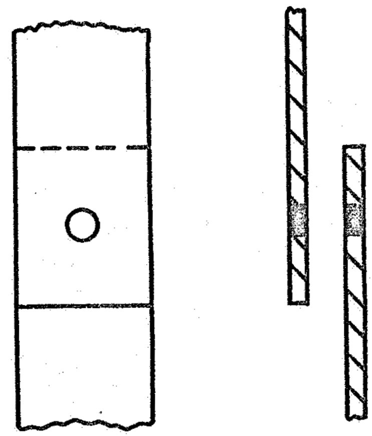


750X 98HCl, 2HNO$_3$, 1/2CuCl$_2$ 5C228

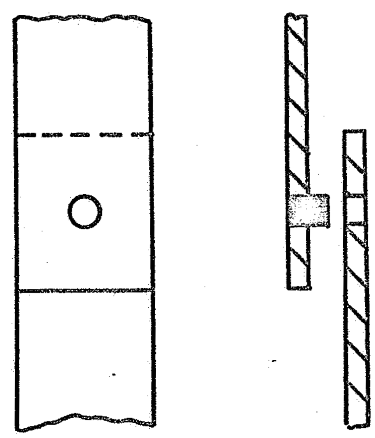


750X 98HCl, 2HNO$_3$, 1/2CuCl$_2$ 5C229

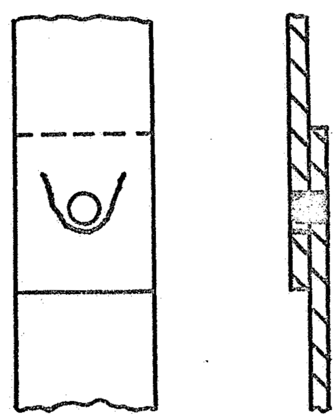
FIGURE 16. VARIATIONS IN SIZE AND SHAPE OF INTERDENDRITIC VOIDS WITHIN THE WELD SHOWN IN FIGURE 15.



(a) Interface Failure



(b) Weld Button



(c) Partial Button

FIGURE 17. MODES OF FAILURE FOR ALUMINUM AND STAINLESS STEEL WELDS

The aluminum welds made in air did form "buttons" or "partial buttons" when the highest strength specimens failed. "Buttons" were formed when a crack first occurred in the heat-affected zone of the weld and then encircled the weld button completely as shown in Figure 17b. "Partial buttons" occurred when a crack in the heat-affected zone grew to form a three-cornered type tear, as shown in Figure 17c. The welds made in a vacuum at 300 and 700 pounds electrode force formed buttons also.

The stainless steel welds formed buttons during tensile testing only if they were welded at currents of 7500 amperes and above and with welding times of 30 cycles or greater. All of the welds made at 10,500 amperes formed weld buttons.

The titanium welds failed in an entirely different manner, as shown in Figure 18. The type of failure shown in Figure 18b was typical of welds made in air and vacuum at currents of at least 5600 amperes and at 30 cycles welding time.

Effect of Pumping Time

A limited number of specimens were prepared and placed in the welding chamber for extended pumping prior to welding. The intent of this work was to determine whether welding conditions changed with prolonged exposure to a vacuum. The results are shown in Figure 19. The variation in the measured welding current for each material was slight except for titanium where the welding current was 7300 to 7400 amperes initially and 7500 to 7800 amperes for the last welds. The welds were all made at the lower electrode forces.

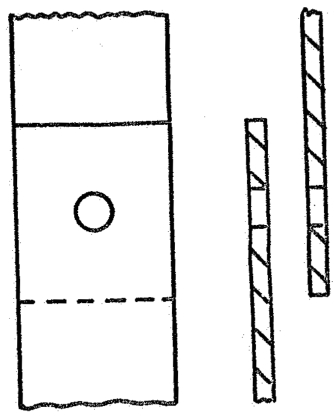
Other Results

Measurements were made of the sheet separation and the thickness of the spot weld at the indentation. Analysis of these data showed little difference in these measurements between welds made in air and in vacuum. However, for the aluminum welds, there was an indication that the sheet separation was greater in a vacuum.

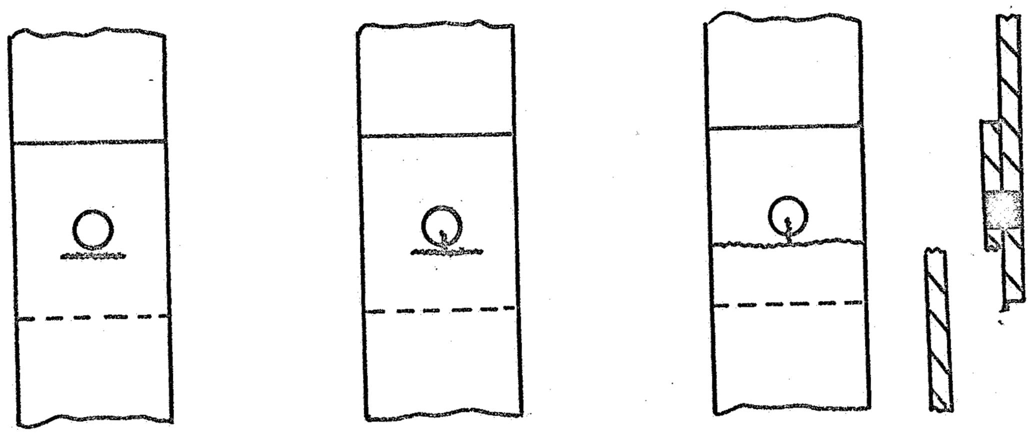
The indentation was found to be dependent on the weld current only at lower values of electrode force. The sheet separation was measured by feeler gauges at the edge of the specimen. The separation seemed to be independent of the welding variables and was not a means of consistently indicating whether weld expulsion had occurred.

Slope Control

A limited number of welds were made in aluminum using downslope. Table 3 presents data from these welds and compares the effect of slope on the tensile shear strength. There was no significant difference between welds made with or without slope.



(a) Interface Failure



Stage 1

Crack in Heat-
Affected Zone

Stage 2

Crack Extended
Into Weld

Stage 3

Crack Extended
Across Specimen

(b) Sheet and Weld Failure

FIGURE 18. MODES OF FAILURE FOR Ti-6Al-4V WELDS

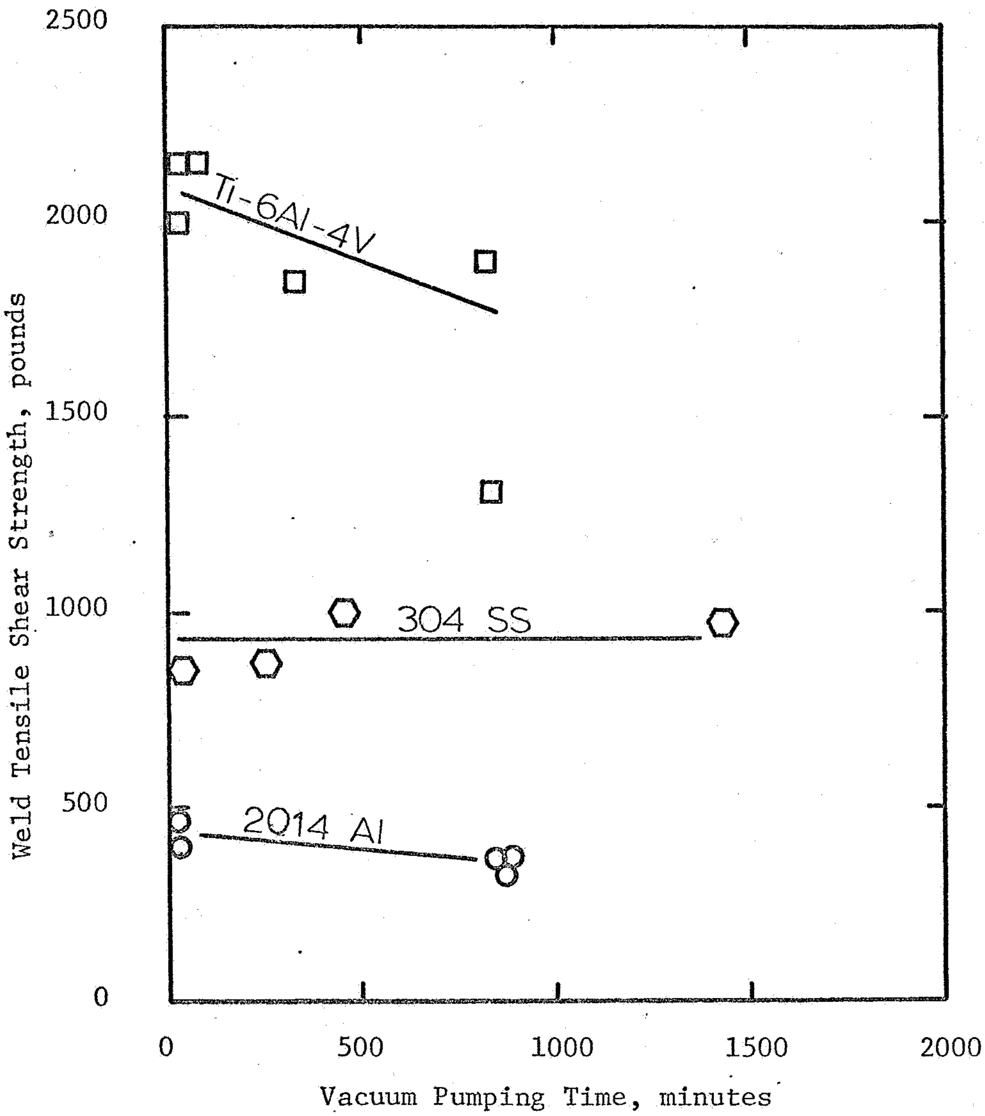


FIGURE 19. EFFECT OF EXPOSURE TO A VACUUM ON WELD TENSILE SHEAR STRENGTH

TABLE 3. STUDY OF USE OF DOWNSLOPE WITH ALUMINUM WELDS

	Welding Conditions					Tensile Shear Strength	
Atmosphere	Current, amperes	Total Time 1/60 second	Electrode Force, pounds	Downslope Time, 1/60 second	Downslope Heat, percent	Welded with Downslope, pounds	Welded at Same Conditions But no Downslope, pounds
Air	18,500	15	300	4	50	255	310 to
Air	18,500	15	300	4	50	340	430
Air	21,500	15	300	4	50	380	425 to
Air	21,500	15	300	4	50	325	500
Air	22,500	15	300	4	50	400	425 to
Air	22,500	15	300	4	50	400	450
Air	23,000	15	700	4	50	320	275
Air	23,000	15	700	4	50	330	
Vacuum	19,000	15	300	4	50	350	350
Vacuum	18,500	15	300	4	50	340	405
Vacuum	21,500	15	300	4	50	380	400
Vacuum	21,000	15	300	4	50	500	460
Vacuum	22,500	15	300	4	50	350	425
Vacuum	23,000	15	300	4	50	390	460
Vacuum	23,000	15	700	4	50	380	350
Vacuum	23,000	15	700	4	50	370	500

DISCUSSION OF RESULTS

The following sections discuss the significance of the results of this program in providing information to determine the feasibility of resistance spot welding in space.

Effect of Vacuum Environment

The effect of the vacuum environment varied depending upon the alloy. For aluminum alloys, there were no significant differences in tensile shear strength for welds made with the same conditions in air and in vacuum. The aluminum alloy welds made in vacuum tended to promote expulsion at slightly lower currents than did those made in air. The effect of prolonged pumping time was not determined with certainty, but it would appear that aluminum specimens welded after extended exposure to vacuum might possibly have lower tensile strengths than specimens welded after only a short exposure to a vacuum.

The stainless steel welds showed a possible slight increase in tensile shear strength at the same machine settings when welded in vacuum. Expulsion and X-ray discontinuities were about the same in both environments. Vacuum pumping time did not affect weld strength.

The titanium welds showed a definite decrease in weld tensile shear strength when welds were made in a vacuum. Also, the welding current obtained at the same machine setting increased as much as 3000 amperes when the welds were made in a vacuum. Comparison of curves drawn in Figures 10, 11, and 12 shows that welds made in a vacuum had a tensile shear strength about 200 to 500 pounds less than the welds made in air at the same machine settings, except at 50 cycles welding time. At 50 cycles, welds made at 6500 amperes in a vacuum were as strong or stronger than welds made at the same machine settings in air. The titanium welds with the highest tensile shear loads were made in a vacuum at 50 cycles. The fact that none of the titanium welds exhibited expulsion or radiographically detectable discontinuities is encouraging.

Factors Affecting Weld Strength

In analyzing these results, it must be remembered that the tensile shear strengths are reported in terms of total pounds, not pounds per square inch of the weld cross sectional area in shear. Most of the results reflect an increasing tensile shear strength for increasing current because the weld area was larger, not because the weld metal failed at a higher stress. The only definite method for determining cross sectional area would have been to section each weld. However, since the designer of structures is more concerned with the strength he can obtain per weld, the shear stresses were not of great interest in this program.

In general, it does not seem that the absence of gases at the weld interface improves the quality or the strength of welds in materials such as aluminum and titanium. The possibility that prolonged exposure to a vacuum actually decreases the spot weld strength indicates that the presence of gases during spot welding may even be helpful. For example, data has been compiled[(a)] for a titanium alloy showing that the contact resistance increased with exposure to air. The conclusion reached was that air and humidity had combined to form a surface oxide. It is possible that exposure to a vacuum is sufficient to decrease the amount of oxide hydration, resulting in a surface with less contact resistance. Also, the oxidation that can occur at the weld interface during the initial portion of nugget formation may also explain the differences between welds made in vacuum and welds made in air. There is also the possibility of oxide dissociation in a vacuum at high temperatures. Decreased contact resistance would explain the increased current obtained when welds were made in vacuum. This would then suggest that the heating at the weld interface might not have been as great in a vacuum as in air due to the decreased resistance at the initial interface. It is probable that the decreased strength of titanium welds in a vacuum was due to a decreased spot weld area. Thus, the use of higher welding currents could probably produce suitably high welding strengths in titanium.

Equipment Design for Use in Space

The data plotted in Figures 4 through 12 indicate the considerations to be made when designing equipment for welding in space. If the loose particles formed by expulsion do not create any problems in the applications envisioned. then a low electrode force of about 300 pounds is the maximum required.If there are limitations on the amount of power that can be delivered, it would be advantageous to provide for welding times of up to 0.85 second or more. There is no apparent need for providing downslope controls. Since, in our investigation we observed no sticking of electrodes, it would appear that standard electrode alloys could be used.

Welding currents required in a vacuum to make satisfactory spot welds are listed below:

0.032-Inch-thick 2014-T651 aluminum:	18,000 to 23,000 amperes
0.063-Inch-thick 304 stainless steel:	4,000 to 11,000 amperes
0.063-Inch-thick Ti-6Al-4V:	5,000 to 11,000 amperes.

CONCLUSIONS

(1) Spot welding is an excellent candidate process for joining 2014 aluminum, 304 stainless steel, and Ti-6Al-4V sheet in space.

(2) Low electrode forces (about 300 pounds) produce welds with tensile shear strengths comparable or better than welds made at 1500 pounds. No expulsion was formed by titanium, but the aluminum and stainless steel alloys formed expulsion more readily at low electrode forces.

(a) Wu, K. C., and Krinke, T. A., "Resistance Spot Welding of Titanium Alloy 8Al-1Mo-1V", Welding Journal Research Supplement, 44 (8), 365s-371s (August, 1965).

(3) Welding times of up to 50 cycles (0.85 second) produce higher strength welds for stainless steel and titanium than do welding times of 10 cycles. Provision for long welding times would help decrease the welding current requirements for welding in space.

(4) Prolonged exposure to vacuum prior to welding tends to reduce the total load a weld can sustain in tensile shear for both titanium and possibly aluminum. This may mean that exposure to a vacuum for periods of a few months would substantially increase the welding currents required.

RECOMMENDATIONS

Further studies should be conducted to more fully determine how weld resistance spot welding will perform in space. These studies, similar to the one reported here, should cover:

(1) Effect of exposure to vacuum on welding conditions and weld strength

(2) Selection of various surface preparation processes and evaluation of their effect on welding conditions and weld properties

(3) Effect of ambient temperatures on welding conditions and weld properties (e.g., room temperature $\pm$ 200 F).

These studies were not within the scope of the reported program and should be conducted if resistance spot welding is to be used for joining in space.

ACKNOWLEDGMENTS

The extensive amount of data developed during this program was due primarily to the rapid and efficient work of William Stefanov. Bill expedited the work at critical moments and also endured the usual endless troubles that plague an initial setup. His contribution to this program was invaluable.

Jim Furr of the Optical and Electron Microscopy Division prepared and photographed the weld sections shown.

* * *

All data and observations from this program are recorded in Battelle Laboratory Record Book Number 24959.

DLC/DGH/REM:mh/jc
February 29, 1968