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**Resistance Spot Welding
of Ti-6Al-4V Alloy**

By D. M. Jarboe

Published June 1980

Topical Report

H. B. Pressly, Project Leader

Prepared for the United States Department of Energy
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**Kansas City
Division**

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CONTENTS

Section	Page
SUMMARY.	6
DISCUSSION	7
SCOPE AND PURPOSE.	7
PRIOR WORK	7
ACTIVITY	7
<u>Weld Joint Design.</u>	7
<u>Joint Requirements</u>	7
<u>Welding Equipment.</u>	7
<u>Material and Weld Sample Configuration</u>	11
<u>Power Level and Electrode Force Evaluation</u>	12
<u>Electrode Tip Radius Evaluation.</u>	18
<u>Storage Condition Evaluation</u>	18
<u>Effect of Spot Welding on Base Metal Properties.</u>	20
ACCOMPLISHMENTS.	21
REFERENCE.	24

ILLUSTRATIONS

Figure		Page
1	Assembly to be Welded.	8
2	100-kVA Spot Welder (Polaroid)	9
3	Flow Diagram of Weld Schedule Operation. . . .	10
4	Resistance Spot Weld Lap-Shear Specimen Before and After Welding (Polaroid).	12
5	Lap Shear Samples After Shear Testing (Polaroid)	13
6	Cross Section of Spot Welds Produced With 4.0-kN Electrode Force (Polaroids)	14
7	Shear Strength Versus Weld Power, Average Data	17
8	Nugget Diameter Versus Weld Power, Average Data	18
9	Weld Penetration Versus Weld Power, Average Data	19
10	Sheet Separation Versus Weld Power, Average Data	20
11	Indentation Versus Weld Power, Average Data. .	21
12	Shear Strength Versus Storage Time	23

TABLES

Number		Page
1	MIL-W-5868 Spot Weld Requirements.	9
2	Shear Strength of Spot Weld Samples.	13
3	Results of Weld Power/Electrode Force Evaluations.	16
4	Effect of Electrode Tip Radius on Shear Strength and Nugget Diameter	22

SUMMARY

To establish guidelines for resistance spot welding of Ti-6Al-4V alloy, experiments were performed to evaluate the effects of welding power, electrode force, electrode tip radius, and storage conditions on weld quality.

The tests revealed that increases in either weld power or electrode force results in higher strength welds. This trend was observed even when weld power was high enough to weld the electrodes to the test samples.

Electrode tip radius had no effect on the resultant welds. Although the tip radius was varied from 5.1 to 20.3 cm, nugget diameter and shear strength remained the same.

Elapsed time between cleaning (pickling) and welding also had little effect on weld strength. Cleaned samples were stored before welding for up to 10 days, either sealed with a desiccant in vapor barrier bags or wrapped in tissue paper and left open. No significant shift in strength was noted for either storage method; in addition, those samples stored in bags showed little if any improvement in strength over those left open.

Overall, the Ti-6Al-4V alloy was very weldable by the resistance spot welding technique. Results of this study indicate welding of this alloy is relatively insensitive to process variations. Data obtained have been used to define a welding process for a current production part.

DISCUSSION

SCOPE AND PURPOSE

The objective of this project was to establish guidelines for resistance spot welding of Ti-6Al-4V alloy. To accomplish this objective, experiments were performed to evaluate the effects of welding power, electrode force, electrode tip radius, and storage conditions on weld quality.

Resistance spot welding is one area within a study of titanium joining, which was originally part of an endeavor on titanium fabrication.

PRIOR WORK

Resistance spot welding has been used more than any other resistance-welding process for joining titanium and its alloys.¹

ACTIVITY

Weld Joint Design

Resistance spot welding is being used to join two assemblies. The material defined for both pieces is solution annealed Ti-6Al-4V.

Twelve evenly spaced welds were to be made around the flange. These welds provide structural support to the assembly and maintain alignment during subsequent electron beam welding. The assembly and resistance spot weld joint design are shown in Figure 1.

Joint Requirements

At the beginning of this endeavor, joint requirements had not been defined. To assure the work would be valid if the spot welds were designated as critical joints, work proceeded as if the welds were to be Class A, as defined by MIL-W-5868. The basic joint requirements for this category are given in Table 1.

Welding Equipment

All welding was performed on a 100-kVA resistance spot welder (Figure 2). A microprocessor-based controller on the welder

Figure 1. Assembly to be Welded

allowed preprogramming the weld schedule parameters, such as percent power, number of firing cycles, and timing of electrode clamping and release. Once the schedule was entered, the micro-processor controlled all the weld schedule. Loading of the parts and initiation of the welding operation were manual tasks. A simplified flow diagram of a welding operation is given in Figure 3.

The actual selection of the electrode force also was a manual operation. Selection was accomplished by adjusting an air regulator supplying pressure to the ram attached to the top electrode. A load cell placed between the electrodes was used to determine actual loads. The electrodes used for this study were class 2 copper alloy, 1.58 cm in diameter. A spherical tip radius of 10.2 cm used for all weld schedule experiments.

Table 1. MIL-W-5868 Spot Weld Requirements

Parameter	Requirement
Shear Strength per Weld	5.6 kN Minimum 7.3 kN Minimum Average
Nugget Diameter	3.81 mm Minimum
Penetration	20 Percent Minimum 90 Percent Maximum
Sheet Separation	0.15 mm Maximum
Indentation	0.13 mm Maximum

Figure 2. 100-kVA Spot Welder

*1 WELD LOOP = 3 TRANSFORMER CYCLES

Figure 3. Flow Diagram of Weld Schedule Operation

Two major problems were encountered with the equipment during this study. The first was a tendency for the air pressure controlling the electrode force to drift. This drifting was controlled by determining the electrode force with a load cell after every five welds and making the necessary regulator adjustments. The second problem appeared to be day-to-day variation in actual welding power, which caused shifts in shear strength values of welds produced by identical schedules but on different days. The most likely source of this problem is variations in line power available to the welding transformers. After the problem was recognized, attempts were made to do all welding associated with one area of evaluation at one time.

Material and Weld Sample Configuration

The material used in this project was solution-annealed Ti-6Al-4V, as defined in AMS 4911C. The certified chemical composition of this alloy is 0.021 weight percent (w/o) carbon, 0.10 w/o iron, 0.014 w/o nitrogen, 6.2 w/o aluminum, 4.2 w/o vanadium, 0.015 w/o hydrogen, and 0.13 w/o oxygen; balance of the alloy is titanium. In the longitudinal direction, tensile strength is 990 MPa and yield strength is 900 MPa; in the transverse direction, strengths are 1010 MPa and 940 MPa, respectively. Elongation in both directions is 10 percent.

The single lap-shear samples used for most of the experiments consisted of two strips of Ti-6Al-4V sheet measuring 2.55 by 7.6 cm. The ends of the two pieces were overlapped 2.5 cm for welding (Figure 4).

Initially, the strips were to be cut from 1.8-mm-thick sheet and subsequently machined to a thickness of 0.9 mm at the ends to be welded. The purpose was to simulate both the material thickness in the joint area of the aft support and a machined surface texture. In the interest of reducing sample costs, however, consideration was given to using 0.9-mm-thick sheet stock and the as-rolled surface. To determine the validity of this approach, both types of samples were prepared.

The machined samples were produced with a surface roughness of 1.625 μm . All the specimens were cleaned in a three-stage process, beginning with an acetone solvent cleaning. The second step was an alkaline dip at 82 $\pm 5^\circ\text{C}$ for 4 to 5 minutes, followed by a warm water rinse for a minimum of 1 minute. In the third step, acid pickling, the samples were immersed in a 30-percent HNO_3 + 3-percent HF solution for 2 minutes, ± 5 seconds. Immersion was followed by three rinses, in tap water for a minimum of 2 minutes, then in deionized water for a minimum of 1 minute, then in either ethanol or hot deionized water, before blowing dry with clean compressed air or nitrogen.

Figure 4. Resistance Spot Weld Lap-Shear Specimen Before and After Welding

Both sets of samples were welded within 4 hours of cleaning, using 12 cycles at 42 percent power and an electrode clamping force of 3.1 kN. This weld schedule was determined by beginning with a typical stainless steel cycle and adjusting the power level until a reasonably strong weld was achieved. The samples then were pulled to failure. In each case, failure occurred by the weld nugget pulling out of the sheet material rather than failure of the nugget itself (Figure 5). Table 2 presents the maximum load recorded for each sample in both sets. A comparison of the results indicated very little difference in average strength between the two groups; statistically, the groups are almost identical. Based on these results, the decision was made to proceed with 0.9-mm-thick material with the as-rolled surface finish.

Power Level and Electrode Force Evaluation

This series of experiments was conducted to determine the effects of power level and electrode force on the resultant welds with respect to the requirements given in MIL-W-5868. After cleaning, samples were welded at various power levels using electrode forces of 2.2, 3.1, and 4.0 kN. Each weld then was radiographed to determine if any internal defects were present. None of the welds showed any signs of internal porosity or cracking.

Selected samples were metallographically examined to verify the radiographic results. Measurements were made of indentation, sheet separation, weld penetration, and nugget diameter. Figure 6

Figure 5. Lap Shear Samples After Shear Testing

Table 2. Shear Strength of Spot Weld Samples

Sample	Shear Strength (kN)	
	Machined	As-Rolled
1	8.6	7.5
2	8.2	7.8
3	7.8	9.3
4	7.3	8.5
5	8.3	7.6
6	7.5	8.5
7	8.0	8.1
8	7.8	7.6
9	8.5	
Average	8.0	8.1
Standard Deviation	0.441	0.650

25 PERCENT POWER

30 PERCENT POWER

35 PERCENT POWER

40 PERCENT POWER

1 mm

Figure 6. Cross Section of Spot Welds Produced With 4.0-kN Electrode Force

shows the metallographic cross sections for the samples welded with an electrode force of 4.0 kN. The remaining samples were shear tested at a crosshead speed of 1.3 mm/min to failure. The average results are presented in Table 3 and shown in Figures 7 through 11. The requirements of MIL-W-5868 also are indicated on the figures. Weld nugget diameters given are those determined by radiography. A comparison of diameter values determined by radiography and metallography showed no difference; therefore, radiography measurements were used, which permitted using all the specimens for strength testing.

The effects of electrode force and weld power on shear strength are evident in Figure 7. The only group of samples which did not meet the specification requirements were welded at 20 percent power and 2.2 kN electrode force. Increasing either parameter results in increased strength. All samples failed by pulling out the weld nugget from one strip. In no instance did the weld itself fail. This trend was true even in the case of a single sample welded at 50 percent power and an electrode force of 3.1 kN. Although a substantial amount of metal expulsion occurred and the electrodes welded to the sheet, shear strength was 15.6 kN and failure was by nugget pullout.

This trend also was evident in the nugget diameters (Figure 8). In fact, the basic shapes of the nugget diameter and shear strength curves are the same. This result is caused by the fact that the force to pull the nugget out of one sheet will be related to the circumference of the weld nugget. None of the groups failed the weld nugget diameter requirements of MIL-W-5868.

Weld penetration values (Figure 9) are grouped closely, particularly above 35 percent power. None of the values are near the 20 percent minimum. The 90 percent maximum limit, however, is approached at the higher weld power values. Electrode force within the range evaluated does not affect weld penetration to any great degree. Apparently, penetration is primarily a function of weld power.

The data on sheet separation (Figure 10) indicate a general increase with weld power; however, the effect of electrode force is not clear. Below 35 percent power, the groups welded with electrode forces of 2.2 and 3.1 kN show no difference. The group welded with a 4.0 kN electrode force clearly appears to give a greater separation. Above 35 percent power, the data indicate the least separation for the 3.1 kN group, followed by the 2.2 kN group and finally the 4.0 kN group. If the highly expanded scale of the y-axis in Figure 10 is considered, however, very little difference because of electrode force may exist.

Table 3. Results of Weld Power/Electrode Force Evaluations

Power Level (Percent)	Shear Strength (kN)		Nugget Diameter (mm)	Penetration (Percent)	Sheet Separation (mm)	Indentation (mm)
	Average	Minimum				
2.2 kN Electrode Force						
20	5.87	5.78	4.09	71.1	0.046	0.018
30	7.88	1.36	5.33	78.1	0.076	0.036
35	8.75	8.54	5.84	78.1	0.079	0.053
37	10.09	9.74	6.71	81.3	0.122	0.079
40	11.04	10.76	7.57	85.2	0.152	0.160
42	12.30	12.14	8.33	85.9	0.183	0.109
3.1 kN Electrode Force						
25	7.43	7.34	4.83	68.0	0.061	0.051
35	9.28	9.16	6.02	81.3	0.094	0.071
37	10.49	10.43	6.88	82.1	0.079	0.053
40	11.72	10.76	7.95	86.6	0.114	0.086
42	12.40	12.10	8.41	87.5	0.150	0.104
45	14.06	13.61	9.27	89.1	0.185	0.150
4.0 kN Electrode Force						
25	7.99	7.67	5.13	70.3	0.091	0.064
30	8.79	8.19	5.74	73.4	0.104	0.102
35	10.55	10.32	6.96	76.6	0.122	0.084
40	13.58	13.21	8.76	82.8	0.160	0.112

Figure 7. Shear Strength Versus Weld Power, Average Data

The effect of weld power and electrode force on indentation is shown in Figure 11. As in the case of sheet separation, increased weld power generally results in greater surface indentation of the sample by the electrodes. Once again, no clear trend is seen with respect to electrode force. Because the y-axis scale in Figure 11 is the same as in Figure 10, no real difference may exist, that is, electrode force has little, if any, effect on indentation.

Overall, results indicate a wide range of welding parameters can be used to produce high quality welds. While these results cannot be used to define a future weld schedule because of the day-to-day variation in power output of the welder, they can serve as a guide in selecting a weld schedule. A welding power range from 30 to 40 percent with electrode forces from 2.2 to 4.0 kN is recommended.

Figure 8. Nugget Diameter Versus Weld Power, Average Data

Electrode Tip Radius Evaluation

A series of samples was cleaned and then welded, using three different sets of electrodes with different spherical radii (5.1, 10.2, and 20.3 cm). Each sample was welded at 35 percent power (12 cycles) and an electrode force of 3.1 kN. After determining the nugget diameter by X-ray radiography, the samples were pull tested to failure. The results indicate virtually no difference in strength or nugget diameter (Table 4).

Storage Condition Evaluation

The effects of elapsed storage time between cleaning and welding and the storage environment on spot welds also were studied. Each day for 10 days, separate groups of samples were cleaned and

Figure 9. Weld Penetration Versus Weld Power, Average Data

placed in storage to provide samples with varying elapsed time between cleaning and welding. Two storage conditions were used: part of each group was sealed with a desiccant in vapor barrier bags, and the remainder were wrapped in tissues and left open to the general laboratory atmosphere. All the samples were welded in one session, using 35 percent power (12 cycles) and 3.1 kN electrode force.

Shear strength tests indicated a slightly higher strength for the samples stored in vapor barrier bags (Figure 12), but storage up to 10 days did not appear to affect weld strength. The overall variation shown in Figure 12, including both groups of samples from the 10-day period, is on the order of 5 percent.

Figure 10. Sheet Separation Versus Weld Power, Average Data

Although these data indicate Ti-6Al-4V parts could be cleaned several days in advance of welding, such a procedure is not recommended. The controlled conditions of sample storage precluded gross amounts of contamination such as could occur in an open manufacturing area. However, minor delays in welding can be tolerated without the need for recleaning.

Effect of Spot Welding on Base Metal Properties

To determine if the welding process had a detrimental effect on base metal properties, special samples were welded for tensile testing. These samples consisted of a 2.5-cm square welded in the center of a 15.2-cm-long by 2.5-cm-wide strip. The samples were welded at 35 percent power (12 cycles) and an electrode force of 3.1 kN. Tensile testing was performed at a crosshead speed of 1.27 mm/min. In each case, failure occurred well away from the weld nugget. The average tensile strength and elongation were 1015 MPa and 13.3 percent, respectively. These values compare closely with those listed in Table 1.

Figure 11. Indentation Versus Weld Power, Average Data

ACCOMPLISHMENTS

General guidelines have been established for the selection of spot welding schedules for Ti-6Al-4V. This alloy can be resistance spot welded easily and is capable of accommodating significant variations in weld power, electrode force, electrode tip radius, and elapsed cleaning-to-welding times.

Table 4. Effect of Electrode Tip Radius on Shear Strength and Nugget Diameter

Sample	5.1-cm Radius		10.2-cm Radius		20.3-cm Radius	
	Shear Strength (kN)	Nugget Diameter (mm)	Shear Strength (kN)	Nugget Diameter (mm)	Shear Strength (kN)	Nugget Diameter (mm)
1	9.3	5.6	9.8	5.8	9.6	5.7
2	9.7	5.6	9.9	6.0	9.6	5.7
3	9.7	5.6	9.8	6.0	9.9	5.8
4	9.0	5.6	10.1	5.8	9.6	5.7
5	9.6	5.6	9.9	5.8	9.7	5.7
6	9.6	5.6	9.6	6.0	9.5	5.7
7	9.5	5.6	9.9	5.9	9.7	5.7
Average	9.5	5.6	9.9	5.9	9.7	5.7
Standard Deviation	0.28	0.0	0.16	0.11	0.14	0.04

Figure 12. Shear Strength Versus Storage Time

REFERENCE

¹R. A. Wood and R. J. Favor, Titanium Alloys Handbook. Columbus, OH: Battelle Columbus Laboratory, Metals and Ceramics Information Center, MCIC-HB-02, December 1972, p 4:72-30.

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MECHANICAL: Resistance Welding

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