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SPOT-WELDED JOINTS IN TITANIUM ALLOYS AND THEIR BEHAVIOR IN FATIGUE

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FOREWORD

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The research described in this report was conducted by the Metals Joining Division, the Applied Mechanics Division, and the Nonferrous Metallurgy Division of Battelle Memorial Institute. Persons who contributed to the planning and conduct of the investigation are listed below.

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ABSTRACT

A study of the spot welding of titanium and titanium alloys was made to determine the behavior of six-spot weldments under fatigue loading and to compare the fatigue behavior of similar weldments in titanium, aluminum, and stainless steel. Commercially pure titanium sheet, commercial titanium - 7 per cent manganese alloy sheet, experimental unalloyed titanium sheet, and Type 321 stainless steel sheet, all of 0.040-inch thickness, were used. Static tension-shear and cross-tension tests were made on single-spot welds in the materials and the tension-to-shear ratios were calculated. For equal gages and spot spacing, six-spot joints in the stainless steel sheet were slightly better in fatigue than similar joints in the titanium materials under similar loading conditions. The joints in the titanium materials were significantly better than similar joints in clad 24S-T and 75S-T aluminum alloys. (The data on the aluminum alloys were developed in previous work.) Under static tension-shear loading, the joints in the titanium materials were stronger than similar joints in the stainless steel and the aluminum alloys.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

M. R. Whitmore
Technical Director
Materials Laboratory
Directorate of Research

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SPOT-WELDED JOINTS IN TITANIUM ALLOYS AND THEIR BEHAVIOR IN FATIGUE

One of the many problems with which the user of titanium and titanium alloys is faced is that of making the joints which are necessary to fabricate useful structures. In the past few years, considerable attention has been given to the development of satisfactory arc-welding procedures for use with titanium. The properties of arc weldments made of titanium and titanium sheet have been studied in some detail. However, much less work has been done on spot welding. Studies of the properties of spot-welded joints in titanium have been restricted in most cases to properties under static loading. Little is known about the fatigue behavior of spot-welded joints in titanium and titanium alloys.

For the past year, Battelle Memorial Institute has been engaged in studies of the properties of spot-welded joints in titanium and titanium-alloy sheets, with particular emphasis on fatigue properties. The objective has been to study the fatigue behavior of multispot joints in titanium and titanium-alloy sheets and to compare their behavior with the behavior of similar joints in stainless steel and aluminum alloys. The static properties of various types of spot-welded joints also were studied. The results of the static tests were used in evaluating spot-welding schedules and as a base with which to compare the results of fatigue tests.

SUMMARY

Two types of 0.040-inch-thick commercial titanium sheet and one experimental titanium sheet were used in this investigation. The two commercial sheets were commercially pure titanium having an ultimate strength of 73,000 psi and a heat-treated titanium - 7 per cent manganese alloy having an ultimate strength of about 140,000 psi. The experimental sheet was unalloyed titanium that had an ultimate tensile strength of 53,000 psi. Annealed Type 321 stainless steel also was used in the experimental work.

Static tension tests were made on titanium and stainless steel single-spot specimens to aid in establishing welding conditions which would produce spot welds having diameters 4 to 5 times the thickness of the sheet, and to determine the tension-shear strength, cross-tension strength, and tension-to-shear ratio. The schedules selected for welding the test specimens were

not necessarily the optimum ones for the materials and sheet gage. The results of the static tests showed that the spot welds in the commercially pure titanium sheet had a lower tension-to-shear ratio than previous work had predicted. Considerable work was done to determine the cause of the low tension-to-shear ratio. The results of this work indicated that quench hardening caused by rapid cooling from above the alpha-beta transformation temperature was to blame. However, the evidence obtained cannot be called conclusive and other influences, such as the pickup of oxygen and nitrogen, or the effect of other impurities in the sheet materials, also may have been at work.

The static tests also showed that postweld furnace heat treatments improved the static tensile properties of spot welds in the titanium - 7 per cent manganese alloy sheet significantly. However, postwelding heat treatments made in the spot-welding machine did not improve the properties of welds in the alloy sheet.

The results of the static and fatigue tests of six-spot specimens in the titanium and stainless steel sheets are summarized in Figure 1. The information gathered in this investigation shows that while weldments in Type 321 stainless steel had the highest fatigue limits, the fatigue limits of weldments in the commercially pure titanium sheet were not much lower. For the same sheet gage and spot spacing, the study shows that spot-welded joints in Type 321 stainless steel were slightly better in fatigue than similar joints in commercially pure titanium. Figure 1 also indicates that similar spot-welded joints in the titanium - 7 per cent manganese alloy sheet had fairly good fatigue behavior. However, it is known that as-welded spot welds and their heat-affected zones in the alloy sheet are brittle. This causes some doubt as to the usefulness of spot welds in the titanium - 7 per cent manganese alloy sheet. Some ductility was obtained in spot welds and the static strength of the alloy sheet was improved by a furnace heat treatment. However, the data available at present indicate that the heat treatment did not improve fatigue behavior.

The spot diameters and welding schedules for the aluminum-alloy specimens were not available. Therefore, it was not known if the spot welds were optimum for the gage and spot spacing. For the same spot spacing and sheet gage, spot-welded joints in commercially pure titanium sheet had better fatigue behavior than similar joints in the aluminum alloys for which data were abstracted from reports of previous work.(1)*

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* Numbers refer to reference list on page 26.

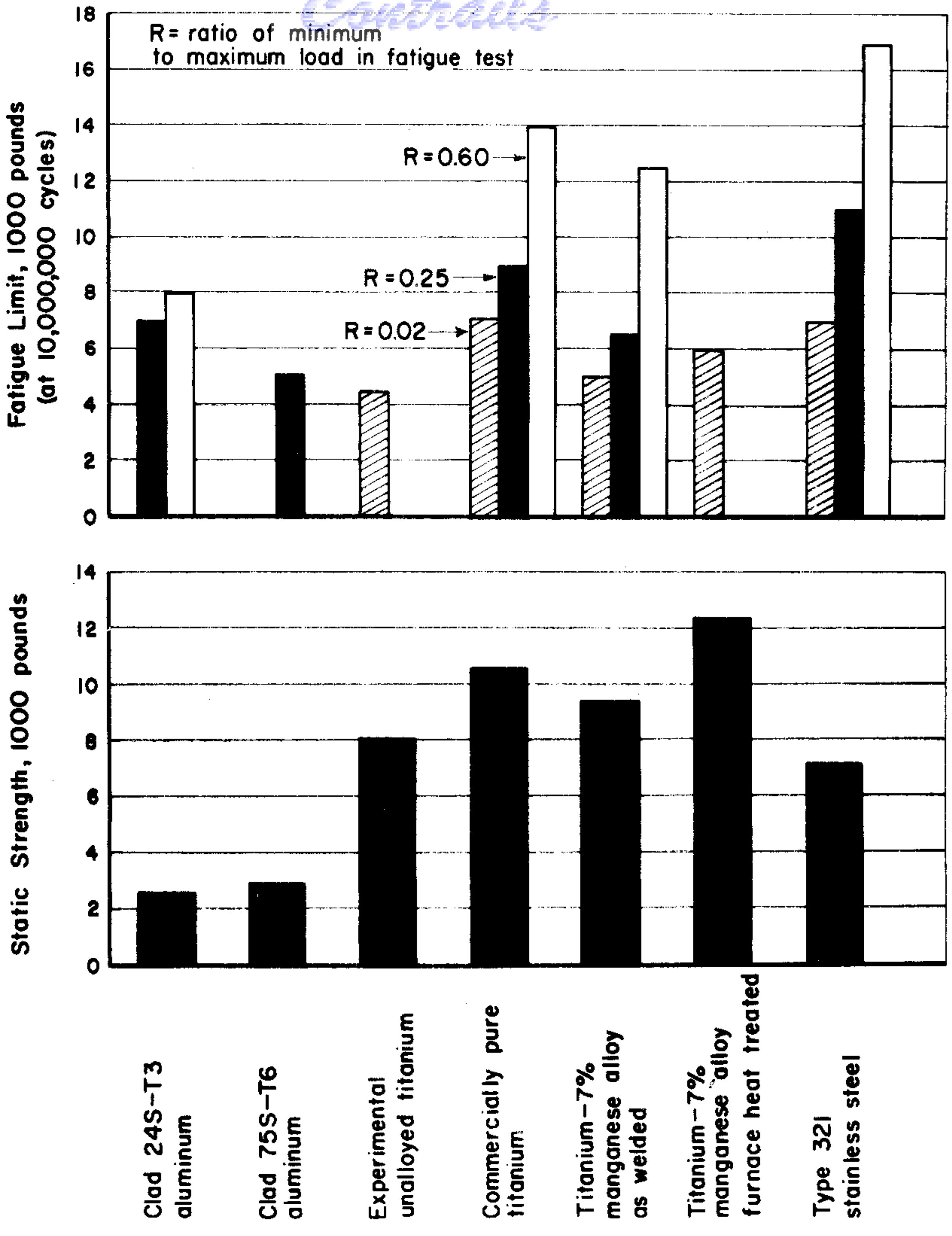


FIGURE 1. COMPARISON OF STATIC TENSION-SHEAR STRENGTHS AND FATIGUE LIMITS OF 6-SPOT LAP JOINTS IN 0.040-INCH TITANIUM, STAINLESS STEEL, AND ALUMINUM ALLOY SHEET

MATERIALS

Three types of titanium were chosen to represent the range of commercially pure titanium, an alpha-beta alloy, and an all-alpha alloy. Commercially pure titanium is a material with an ultimate tensile strength of 65,000 to 90,000 psi. It has good ductility and cannot be hardened by heat treatment. Alpha-beta titanium alloys have a wide strength range and the 7 per cent manganese alloy used in this research was considered to represent high-strength commercial alloys. The strength of the 7 per cent manganese alloy can be varied over a wide range by heat treatment. Both the commercially pure titanium and the 7 per cent manganese alloy were purchased from a commercial supplier of titanium products. The all-alpha titanium - 5 per cent aluminum - 2-1/2 per cent tin alloy was chosen to represent an intermediate-strength material. The properties of alloys of this type cannot be changed by heat treatment. At the time this alloy was needed it could not be purchased in sheet of the desired thickness. Consequently, an attempt was made to fabricate it at Battelle. Because of fabrication difficulties and lack of time, it was not possible to make sufficient static and fatigue tests on spot-welded joints in this alloy. Consequently, the results of tests that were made are omitted from this report, since they are very inconclusive.

In the course of the research work, it was found that spot welds in the commercially pure titanium sheet did not have the static strength properties that previous work had indicated they should. In particular the cross-tension strength was much lower than had been expected. Unalloyed titanium sheet was prepared at Battelle to aid in one phase of a study of the low tension-to-shear ratio. This sheet was much softer and had lower strength than the commercially pure sheet which had been purchased.

In addition to the titanium materials, annealed Type 321 stainless steel sheet was used in this work.

The mechanical properties of the various materials are given in Table 1. This table includes the properties of clad 24S-T3 and clad 75S-T6 aluminum sheet, since fatigue data for spot-welded joints in these alloys are used for comparison in later sections of this report. The compositions of the titanium materials are shown in Table 2.

TABLE 1. MECHANICAL PROPERTIES OF TITANIUM, ALUMINUM, AND STAINLESS STEEL SHEET

Sheet Material	Source	Thickness, inch	Yield Strength, psi	Tensile Strength, psi	Elongation in 2 In., per cent	Rockwell Hardness
Experimental unalloyed titanium[(a)]	Battelle	0.045	33,000	53,000	39	69 B
Commercially pure titanium	Commercial	0.040	68,500	73,000	27	99 B
Titanium - 7 per cent manganese alloy[(b)]	Commercial	0.040	133,000 to 143,000	139,000 to 154,000	15 to 20	28 C to 31 C
Type 321 stainless steel	Commercial	0.038	38,000	87,000	59	73 B
Clad 24S-T3 aluminum[(c)]	--	Under 0.063	44,000	64,000	15	72 B
Clad 75S-T6 aluminum[(c)]	--	Under 0.063	67,000	76,000	11	--

(a) Data are average for two heats of material.

(b) Material was supplied from six heats. Maximum and minimum values are shown.

(c) Typical properties.

TABLE 2. COMPOSITION OF TITANIUM SHEET MATERIALS

Sheet Material	Alloying Elements, weight per cent				
	Carbon	Oxygen	Nitrogen	Iron	Manganese
Experimental unalloyed titanium	0.01	-	0.003	0.13	-
Commercially pure titanium	0.14	0.12	0.027	0.12	-
Titanium - 7 per cent manganese alloy[(a)]	0.10 to 0.18	0.10	0.020 to 0.036	-	6.13 to 7.08

(a) Material was supplied from six heats. Maximum and minimum values of carbon, nitrogen, and manganese are shown.

SPOT WELDING

All of the spot welding during this investigation was done on a 200-kva, three-phase, low-frequency spot-welding machine. The machine has a maximum current output of 100, 000 amperes and a maximum electrode force of 10, 000 pounds. Down-slope current decay, postheat, and forging force are available.

Variations in welding time and current were investigated to find suitable spot-welding schedules for the various materials. The welding forces used were chosen from previous experience. Welding schedules finally selected were ones which produced spot welds with diameters 4 to 5 times the thickness of the sheet. They did not necessarily produce spot welds of optimum geometry for the sheet gage and material. The schedules used are given in Table 3.

TABLE 3. SPOT-WELDING SCHEDULES

Sheet Material	Welding Time, cycles(a)	Heat Control, per cent(b)	Electrode Force, pounds
Experimental unalloyed titanium	4	60	700
Commercially pure titanium	4	60	700
Titanium - 7 per cent manganese alloy	4	60	1000
Type 321 stainless steel	6	49	1000

(a) All welds made with one pulse of current.

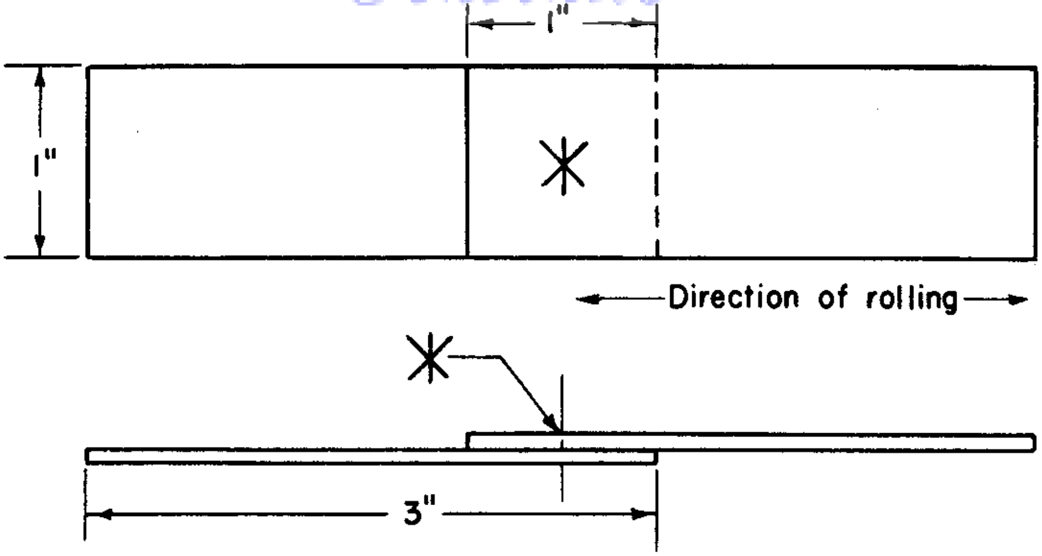
(b) Maximum current, 100, 000 amperes.

Welding electrodes used for all welds were RWMA Class 2 copper alloy with 3-inch spherical radius faces.

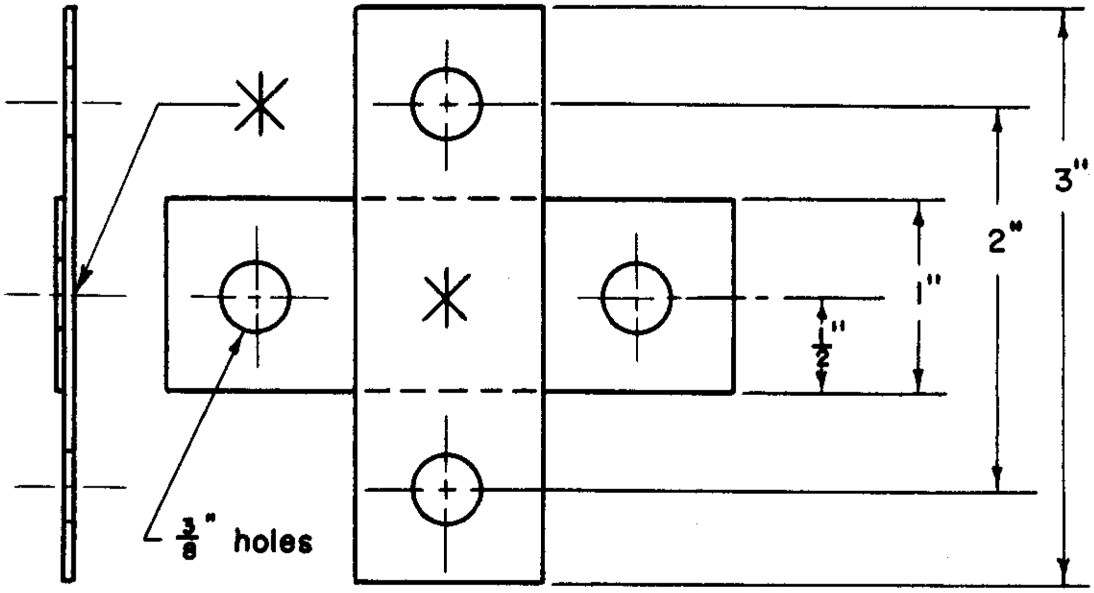
A large number of spot welds were made in the titanium - 7 per cent manganese alloy sheet. These welds were given a postwelding heat treatment in the spot-welding machine. The machine heat treatments were as varied as was possible, but none had any beneficial effect on the weld properties. Therefore, a detailed description of these welding and heat-treating schedules has been omitted from this report.

Three types of spot-welded specimens were made. Two of these were single-spot specimens. One was used for tension-shear tests and the other for cross-tension tests. Details of these specimens are shown in Figure 2. Both specimens differ in size from those recommended by the American Welding Society. This change was made to conserve titanium. Some tests were made on standard-size specimens, and it was found that the test results were not significantly different from those obtained with the reduced-size specimens.

The third type of spot-welded specimen was a six-spot weldment. The details of this specimen are shown in Figure 3. It was used for both static and fatigue tests.



Tension-Shear Test Specimen - Full scale



Cross-Tension Test Specimen - Full scale

FIGURE 2. TENSION-SHEAR AND CROSS-TENSION TEST SPECIMENS

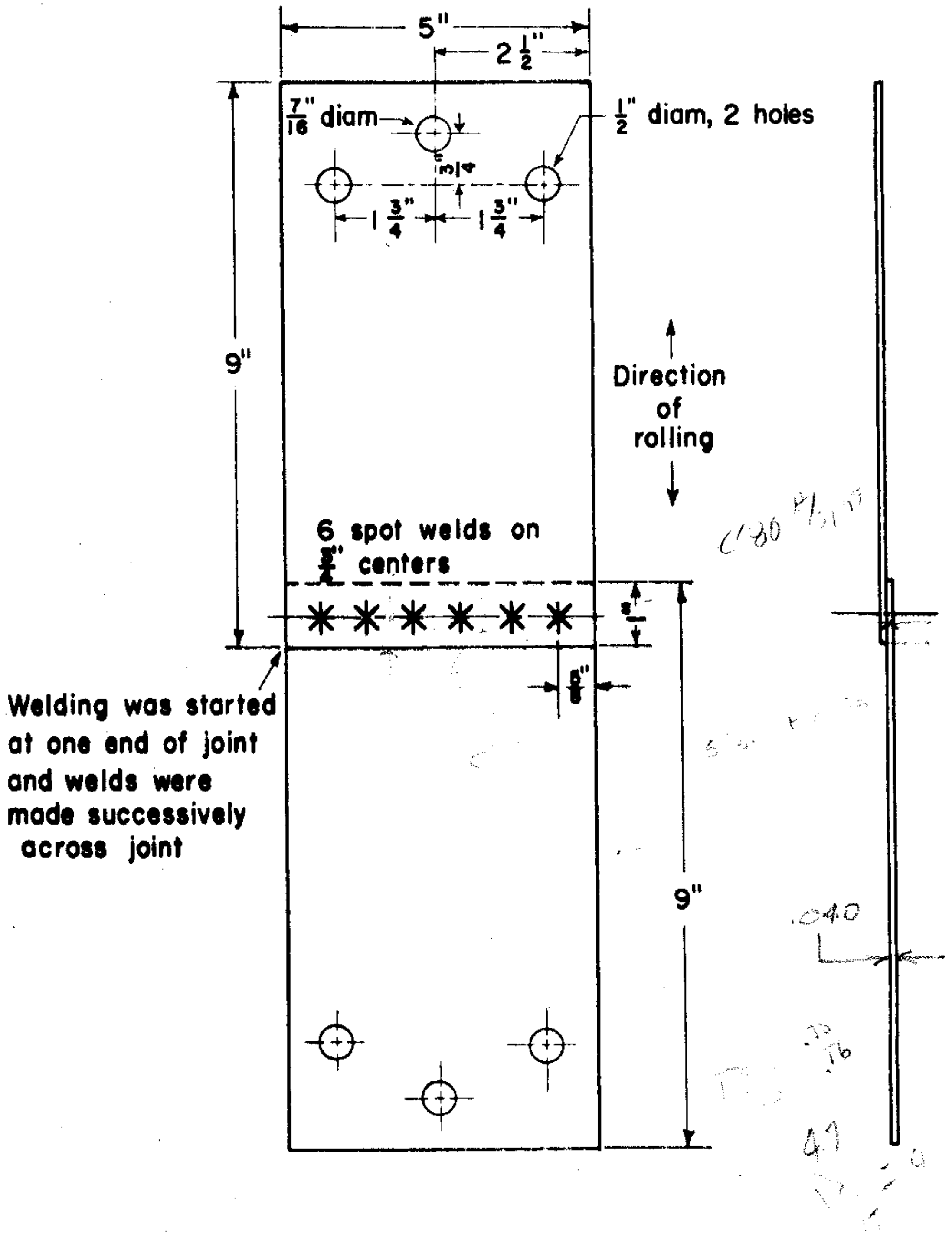


FIGURE 3. SPOT-WELDED FATIGUE-TEST SPECIMEN

STATIC TESTS

Static tests were made on both single-spot and six-spot specimens. The tests on single-spot specimens were used first to determine the proper welding schedules for each type of material. After these were determined, a series of single-spot specimens was made in each material and used to determine tension-shear and cross-tension strengths. These values were used to calculate the tension-to-shear ratios. This ratio is sometimes used as a criterion of the ductility and quality of a spot weld. Tension-to-shear ratios less than 0.25 are usually thought to indicate welds which will have poor service behavior. The results of static tests on single-spot specimens are given in Table 4.

The commercially pure titanium and titanium - 7 per cent manganese alloy specimens were tested in more than one condition. When the single spot welds in the commercially pure sheet were tested in the as-welded condition, it was found that the tension-to-shear ratio was lower than expected. Previous work had shown that for spot welds in commercially pure sheet tension-to-shear ratios of 0.35 to 0.45 should be obtained.(2)

Properties of Single Spot Welds in Commercially Pure Titanium Sheet

A study of the composition of the commercially pure sheet was carried out to determine if there was some compositional variable which might be causing the low tension-to-shear ratio. It was found that the hydrogen content of the sheet was rather high (0.019 weight per cent). Lenning, Craighead, and Jaffee have shown the deleterious effects that small amounts of hydrogen can have on the properties of titanium, particularly on notch sensitivity and ductility.(3) Since the low tension-to-shear ratio was related to the low cross-tension strength, it was thought that the high hydrogen content and a resulting increase in notch sensitivity might be to blame. Consequently, some of the sheet was vacuum annealed by heating it at 1600 F in a vacuum for 2 hours. This reduced the hydrogen content from 0.019 per cent to 0.005 per cent. However, spot welds made in the vacuum-annealed sheet did not have significantly better properties than ones made in the as-received sheet. Therefore, it appeared that it was not the presence of hydrogen that was causing the low cross-tension strength.

It was noticed that the hardness of the welds in the commercially pure sheet (both as received and vacuum annealed) was considerably higher than the hardness of the as-received sheet (281 to 283 VHN for spot welds, 220 VHN for as-received sheet). The increased hardness of the welds might be a result of contamination by oxygen and nitrogen or a quench-hardening effect caused by the presence of some beta-stabilizing alloying element. Chemical analysis showed that the only common beta-stabilizing alloy present in any significant amount was iron (0.13 per cent). It was a normal amount for this type of material. However, some spot welds were given a heat treatment which was designed to remove the effects of quench hardening. When these spot welds were tested, it was found that the cross-tension strength was significantly higher than had been obtained from as-welded specimens. Since the tension-shear strength did not change, the tension-to-shear ratio was higher (0.33 compared to 0.23). These results indicate that quench hardening was having some effect on the spot-weld properties, although it is difficult to see how the small amount of iron present could have any significant effect.

One other compositional variable might have had some effect on the cross-tension properties. This is the rather high oxygen and carbon content of the commercially pure sheet. However, hardness increases caused by these elements or by oxygen and nitrogen picked up during welding should not be affected by a postweld heat treatment. Consequently, it must be said that, at present, the reasons for the low cross-tension strength and low tension-to-shear ratio in the commercially pure sheet are not understood.

Because of the test results which were obtained on the commercially pure sheet, it was decided to obtain some unalloyed titanium sheet which had lower strength and hardness. This was done by fabricating the sheet from a titanium ingot cast at Battelle. This ingot was made from selected sponge and the sheet had a hardness of 125 VHN compared to 220 for the commercially pure sheet. As shown in Table 4, spot welds made in this sheet had significantly higher cross-tension strength but lower tension-shear strength than welds in commercially pure sheet. This made the tension-to-shear ratio for welds in the experimental sheet very high (0.60). One thing to note is that the welds in the experimental sheet also had much higher hardness (189 VHN) than the sheet. In this respect, the experimental sheet behaved the same as the commercially pure sheet.

Properties of Single Spot Welds in Titanium - 7 Per Cent Manganese Alloy Sheet

Before the spot welds in the titanium - 7 per cent manganese sheet were tested, it was realized that both the weld and the surrounding heat-affected zone would be hard and brittle. This is caused by the quench from above the alpha-beta transformation temperature which the weld and heat-affected zone undergo. The effect of the quench can be at least partially eliminated by proper postwelding heat treatment. In this work, the weldments were heated at 1400 F in argon for 2 hours, furnace cooled to 1100 F and held for 2 hours, and then air cooled. The effect of this treatment is shown by the data in Table 4. Weld hardness was reduced from 397 VHN to 294 VHN. The tension-shear strength was increased by the heat treatment, but the cross-tension strength was increased much more proportionally. This resulted in a considerably higher tension-to-shear ratio.

TABLE 4. MECHANICAL PROPERTIES OF SINGLE SPOT WELDS IN

Sheet Material		Condition of Spot Welds	Number of Tension-Shear Tests	Tension-Shear Strength, pounds		
Type	Condition			Average	Maximum	Minimum
Experimental unalloyed titanium	Annealed	As welded	10	1450	1500	1425
Commercially pure titanium	As received (annealed)	As welded	10	2090	2225	1575(a)
Commercially pure titanium	Vacuum annealed(b)	As welded	5	2100	2175	2000
Commercially pure titanium	As received (annealed)	Furnace heat treated(c)	4	2150	2225	2075
Titanium - 7 per cent manganese alloy	As received (annealed)	As welded	8	2000	2150	1750
Titanium - 7 per cent manganese alloy	As received (annealed)	Furnace heat treated(c)	9	2200	2400	2100
Type 321 stainless steel	As received (annealed)	As welded	10	1220	1275	1150
Clad 24S-T aluminum(d)	—	As welded	—	540 to 692	--	--
Clad 75S-T aluminum(d)	—	As welded	—	573 to 760	--	--

(a) This value was considerably lower than the average and the cause is unknown. The next higher value was 2050 pounds.

(b) Held in vacuum at 1600 F for 2 hours and furnace cooled in vacuum.

(c) Held at 1400 F for 2 hours in flowing argon, furnace cooled to 1100 F, held for 2 hours and air cooled.

(d) Data taken from paper by Hess, W. F., Wyant, R. A. and Winsor, F. J., "The Spot Welding of Ten Aluminum Alloys in the 0.040-Inch Gage", Welding Journal, 25 (8), 467S - 484S (1946). Values are upper and lower limits of range of values given.

0.040-INCH TITANIUM, ALUMINUM, AND STAINLESS STEEL SHEETS

Number of Cross-Tension Tests	Cross-Tension Strength, pounds			Tension-to-Shear Ratio	Maximum Weld Hardness, VHN
	Average	Maximum	Minimum		
10	875	975	800	0.60	189
10	490	575	425	0.23	283
5	515	575	500	0.25	281
4	700	750	625	0.33	247
8	280	300	200	0.14	397
10	560	625	475	0.26	294
10	940	1100	800	0.77	187
--	210 to 225	--	--	0.30 to 0.41	--
--	195 to 202	--	--	0.26 to 0.35	--

Metallographic Studies of Spot Welds

Thorough metallographic studies of spot welds in the various materials and various conditions were made. The structures of the welds, heat-affected zones, and base materials were normal for the materials and treatments used. No correlation between the results of the metallographic studies and fatigue behavior was found.

Properties of Six-Spot Joints in Titanium

The static strength properties of six-spot lap joints were determined for comparison with the results of single-spot tests and as base data for comparison with fatigue tests. The results of the tests are given in Table 5. The values for spot welds in aluminum are included for comparison.

TABLE 5. STATIC TENSION-SHEAR STRENGTH OF SIX-SPOT LAP JOINTS

Sheet Material	Weld Condition	Average Tension-Shear Strength, pounds(a)	
		Total	Per Spot
Experimental unalloyed titanium	As welded	8,100	1350
Commercially pure titanium	As welded	10,700	1780
Titanium - 7 per cent manganese	As welded	9,400	1560
Titanium - 7 per cent manganese	Furnace heat treated	12,300	2040
Type 321 stainless steel	As welded	7,100	1180
Clad 24S-T aluminum(b)	As welded	2,700	440
Clad 75S-T aluminum(b)	As welded	2,900	480

(a) Averages of three to five specimens.
(b) Data from Reference 1.

If the per-spot values are compared with the tension-shear results for single-spot specimens given in Table 4, it will be noted that the values for the six-spot specimens in titanium and stainless steel sheet were about 10 per cent lower than the values for the single-spot specimens. To make sure that this was not a result of specimen geometry, a number of six-spot specimens were made from commercially pure sheet and sheared into 3/4-inch-wide single-spot tension-shear specimens. These specimens and a number of 3/4-inch-wide single-spot specimens that were welded individually were tested at the same time. It was found that the first spot weld made in the six-spot specimens had about the same tension-shear strength as the single-spot test specimens. The remaining spot welds from the six-spot specimens had lower tension-shear strengths. It appears that shunting of a portion of the welding current through the preceding weld was responsible for the lower strength of the second and subsequent welds. No attempt was made to adjust for the effect of shunting when the fatigue specimens were welded.

FATIGUE TESTS

All fatigue tests were made on six-spot specimens. These were tested in tension-tension on Krouse direct-stress testing machines of 10,000-pound capacity. Load-sensing devices stopped the machines when the maximum test load decreased from the preset value. This occurred, for example, upon the formation of a macroscopic fatigue crack. The machines were adjusted to stop when the maximum load decreased 40 pounds.

Three load ratios were used, although fatigue tests were not made on welded joints of all types of material at all three load ratios. The load ratios were +0.02, +0.25, and +0.60.

Results of Fatigue Tests

The results of the fatigue tests on six-spot joints in commercially pure titanium sheet are shown graphically as S-log N curves in Figure 4. The points plotted in this figure show the distribution of the specimens tested (10 to 15 specimens for each S-log N curve), and the curves are typical for all of the tests made during the course of this investigation. The results of all fatigue tests are plotted as S-log N curves in Figures 5, 6, and 7. Curves for welded joints in clad 24S and clad 75S are also included in these figures(1). All of the curves are what are believed to be a good fit to the data obtained. By using these curves, an estimate of the fatigue limit at 10^7 cycles was made. The estimated fatigue limits are given in Table 6. This table also reports the fatigue limit as a precentage of the static strength of six-spot specimens.

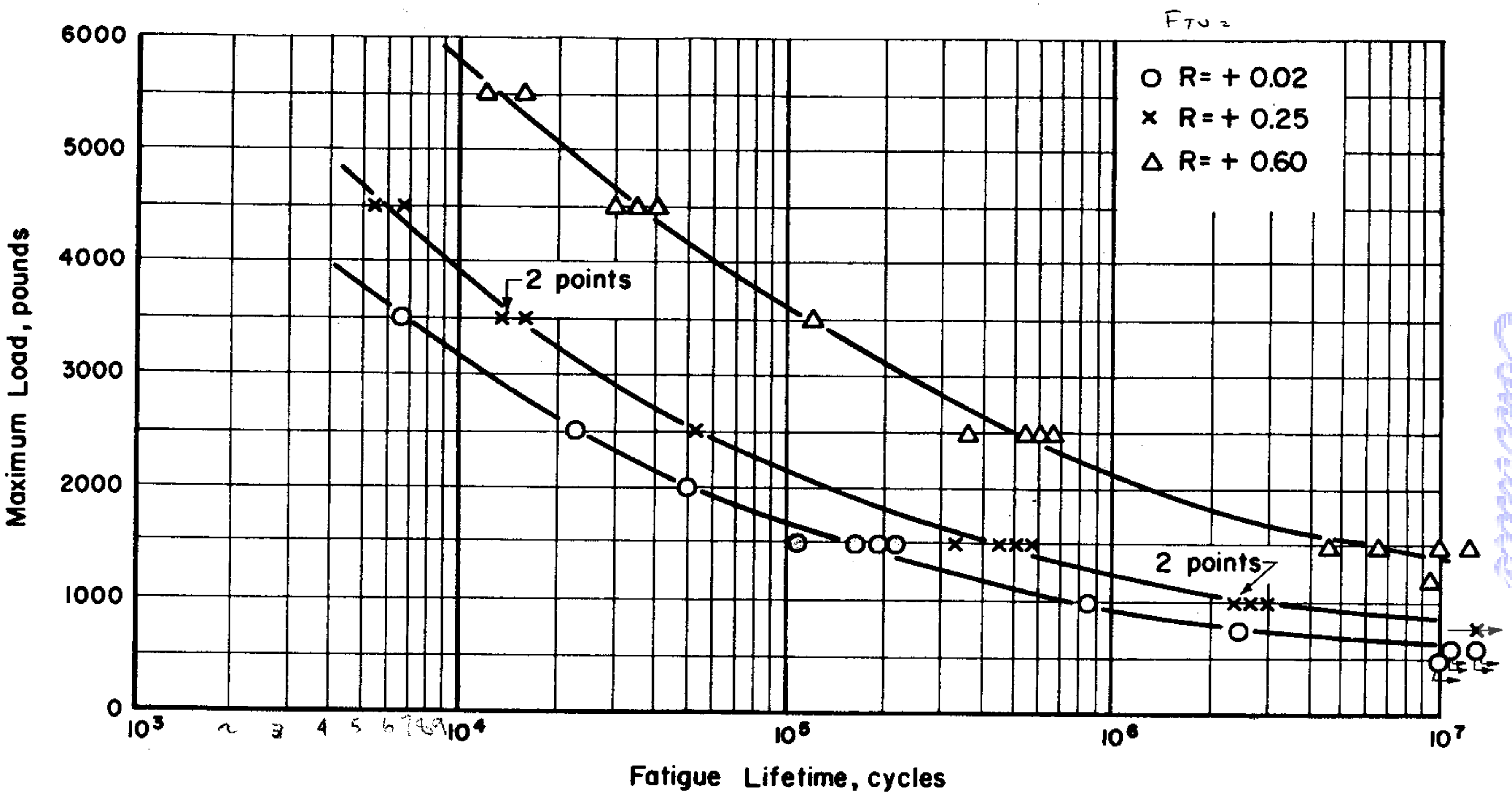


FIGURE 4. AXIAL-LOAD FATIGUE-TEST RESULTS ON 6-SPOT LAP JOINTS IN 0.040-INCH COMMERCIALLY PURE TITANIUM

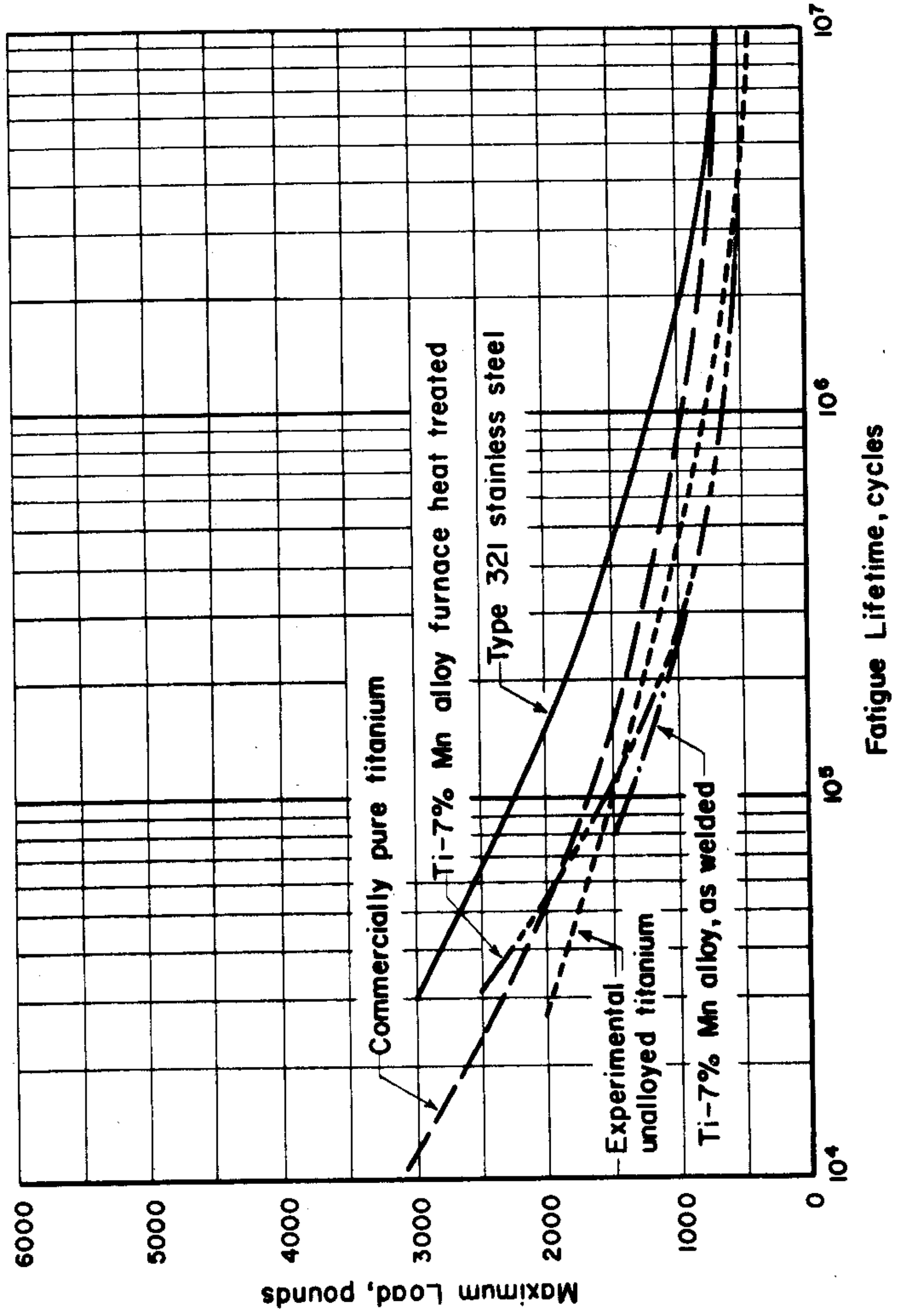


FIGURE 5. COMPARISON OF FATIGUE-TEST RESULTS OF 6-SPOT LAP JOINTS IN 0.040-INCH TITANIUM AND STAINLESS STEEL SHEET AT A LOAD RATIO OF 0.02

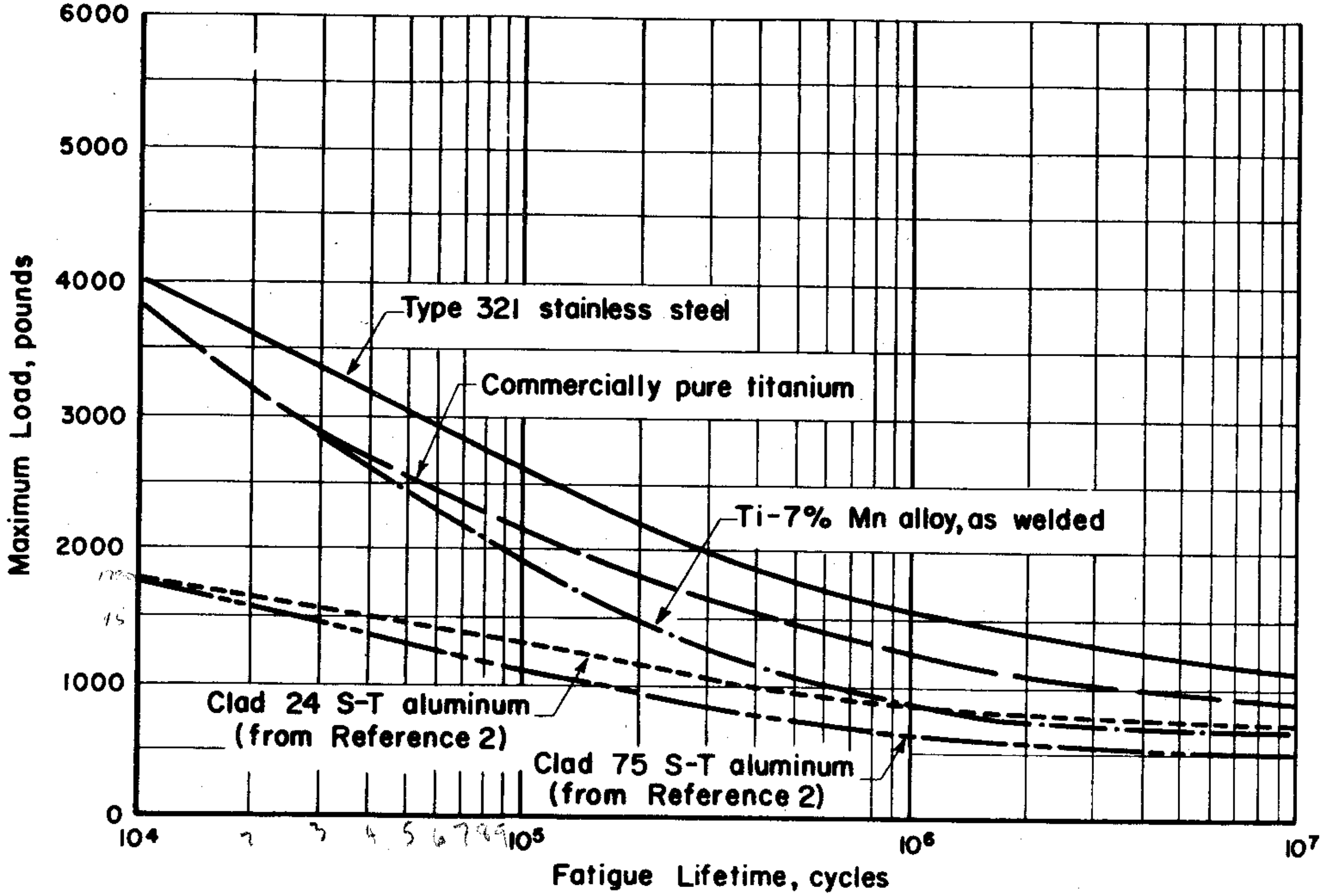


FIGURE 6. COMPARISON OF FATIGUE-TEST RESULTS OF 6-SPOT LAP JOINTS IN 0.040-INCH TITANIUM, STAINLESS STEEL, AND ALUMINUM ALLOY SHEET AT A LOAD RATIO OF 0.25

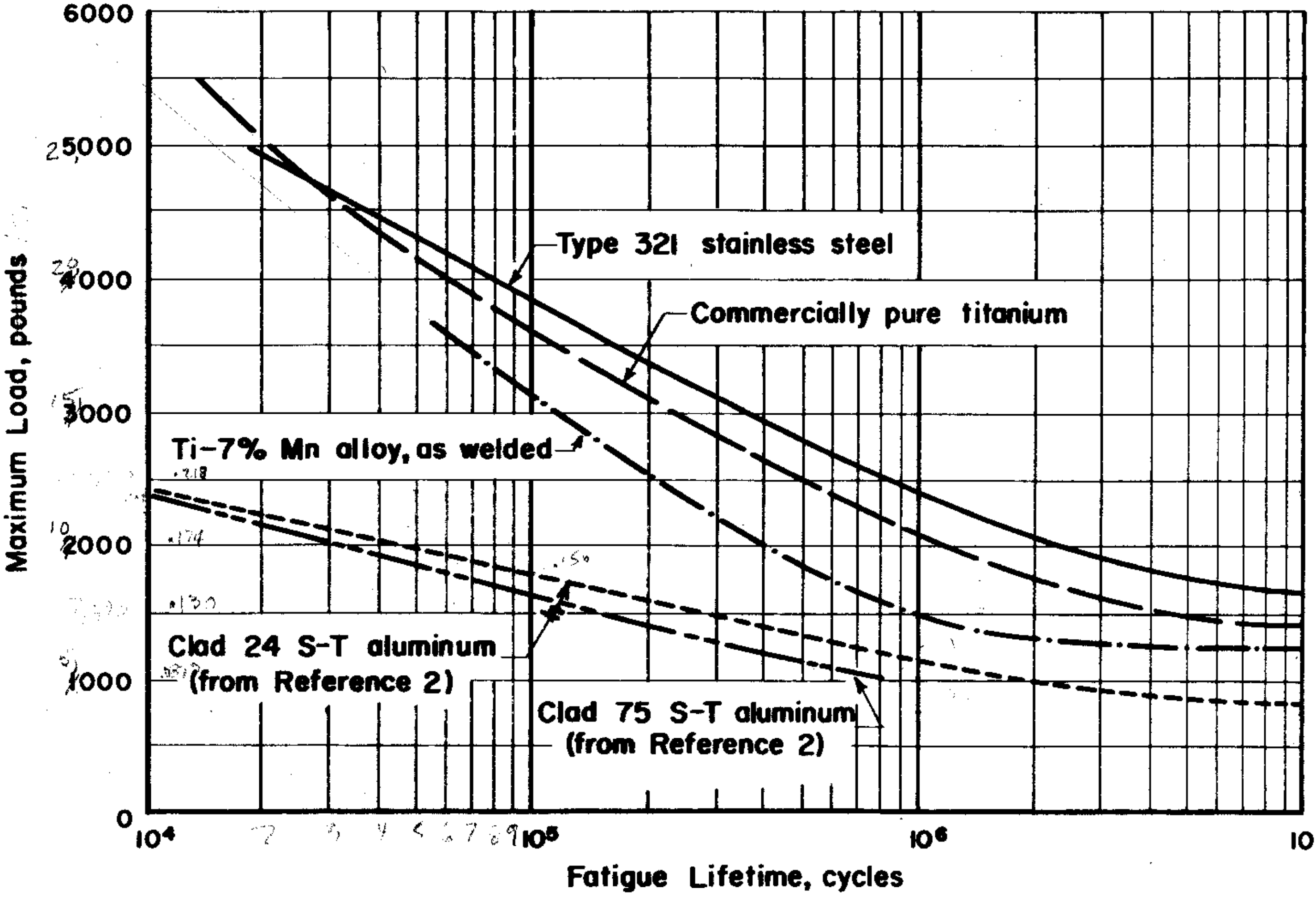


FIGURE 7. COMPARISON OF FATIGUE-TEST RESULTS OF 6-SPOT LAP JOINTS IN 0.040-INCH TITANIUM, STAINLESS STEEL, AND ALUMINUM ALLOY SHEET AT A LOAD RATIO OF 0.60

TABLE 6. ESTIMATED FATIGUE LIMITS FOR SIX-SPOT JOINTS IN TITANIUM, STAINLESS STEEL, AND ALUMINUM SHEETS

Sheet Material	Spot-Weld Condition	Estimated Fatigue Limits at 10^7 Cycles					
		R = +0.02		R = +0.25		R = +0.60	
		Total, pounds	Per Cent of Static Strength[(a)]	Total, pounds	Per Cent of Static Strength[(a)]	Total, pounds	Per Cent of Static Strength[(a)]
Experimental un-alloyed titanium	As welded	450	6	--	--	--	--
Commercially pure titanium	As welded	700	7	900	8	1400	13
Titanium - 7 per cent manganese	As welded	500	5	650	7	1250	13
Titanium - 7 per cent manganese	Furnace heat treated	500	4	--	--	--	--
Type 321 stainless steel	As welded	700	10	1100	16	1700	24
Clad 24S-T aluminum	As welded	--	--	700	25	800	30
Clad 75S-T aluminum	As welded	--	--	500	17	--	--

(a) Estimated fatigue limit in terms of per cent of static strength of six-spot specimen.

Studies of Fatigue Failures

During the investigation, a study was made of the fatigue failures in six-spot specimens of commercially-pure titanium, titanium -7 per cent manganese alloy, and Type 321 stainless steel sheet. The fatigue failures of spot welds in the aluminum alloys had been studied previously at Battelle.

Titanium

Visual examination (low-power microscope), X-ray examinations, and metallographic examinations were made on representative failed spot welds in commercially pure titanium sheet and titanium - 7 per cent manganese alloy sheet.

Typical fatigue cracks in spot welds in commercially pure titanium sheet and in titanium - 7 per cent manganese alloy sheet are shown in Figures 8 and 9, respectively.

Some similarities in the origin and growth of fatigue cracks in spot-welded joints in the two materials were observed. The origin was essentially in the notch formed by the extruded metal at the edges of the weld and the faying surface of the sheet. It is a sharp vee notch, and the region might be expected to be particularly vulnerable to fatigue failure. For either of the sheet materials, growth of the fatigue crack showed no consistent trend on the basis of lifetime. Thus, for any lifetime, the cracks might progress either in the base metal or through the heat-affected zone.

Stainless Steel

A brief study was made of the fatigue failures in the six-spot lap joints in Type 321 stainless steel sheets. Visual examination was made of all the fatigue specimens. Metallographic examination was made of representative spot welds that failed at high and low maximum loads.

It was found that the nucleii of the fatigue cracks were at the notch formed between the two sheets at the edge of the corona bond of the welds. The cracks progressed outward toward the sheet surfaces at the edge of the heat-affected zones on the tension sides of the spot welds.

Aluminum Alloys

A rather detailed study of the fatigue failures of spot welds in clad 24S-T aluminum alloy was reported by McMaster and Grover in 1947(4).

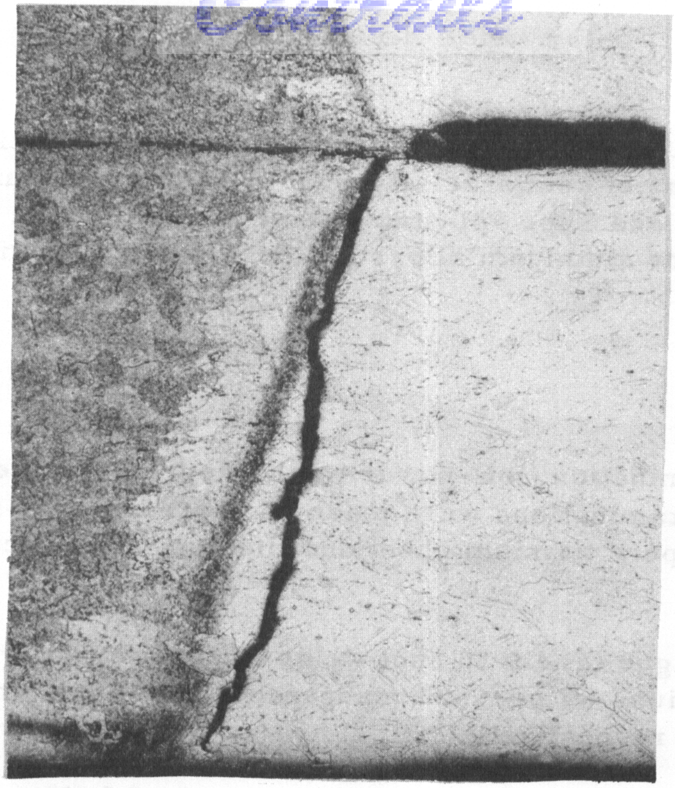


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FIGURE 8. TYPICAL FATIGUE CRACK AT A SPOT WELD IN COMMERCIALLY PURE TITANIUM SHEET

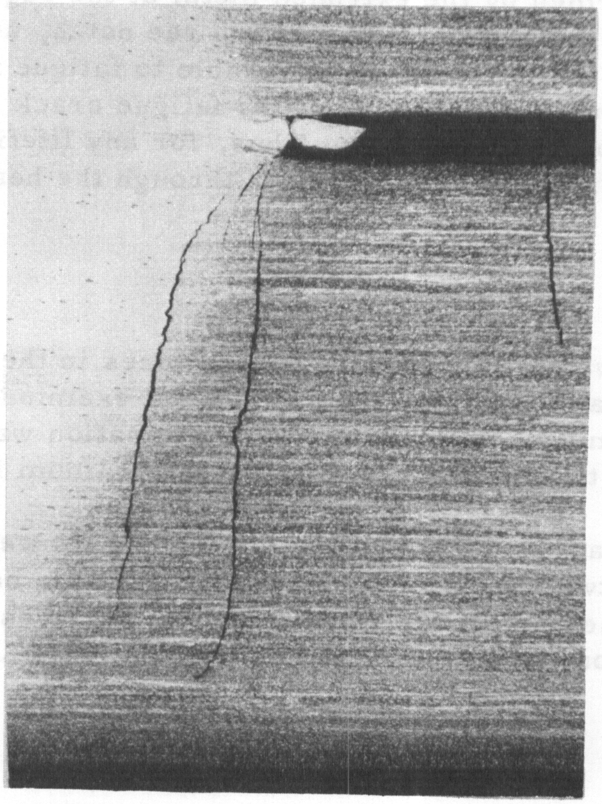

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FIGURE 9. TYPICAL FATIGUE CRACKS AT A SPOT WELD IN TITANIUM - 7 PER CENT MANGANESE ALLOY SHEET

The fatigue tests were made under the same research program described in Reference 2. Five characteristic modes of fatigue failure were observed in the aluminum spot-welded specimens. These were as follows:

(1) Shearing of the nugget at the faying plane.

(2) A crack propagating from the inner extremity of the clad inclusion through the weld nugget and parent metal to the sheet surface.

(3) A crack propagating from the nugget periphery at the interface along the boundary between the weld nugget and the parent alloy (in the heat-affected zone) and then through the parent material to the surface.

(4) A crack propagating from the interface at the nugget extrusion between the faying planes through unaffected base metal to the outer sheet surface.

(5) A crack propagating from the outer extremity of the corona bond at the interface through unaffected base metal to the outer sheet surface.

Discussion of Results of Fatigue Tests

The results of the fatigue tests of the multispot joints in the titanium materials indicate that the fatigue properties are influenced primarily by the strength and ductility of the base sheet. The properties of the weld nugget and heat-affected zone do not appear to have much influence on fatigue behavior. For example, there seems to be no relation between the tension-to-shear ratio and fatigue limit at any of the stress ratios used in the fatigue tests. Weldments of the titanium - 7 per cent manganese alloy had the same fatigue limit in both the as-welded and heat-treated conditions, while the tension-to-shear ratios in the two conditions were quite different (0.13 to 0.26). If the results of fatigue tests on weldments in the commercially pure and experimental unalloyed sheet are compared, the lack of correlation between the tension-to-shear ratio and fatigue limit are again evident. In this case, the material with the much higher tension-to-shear ratio (0.60 as compared to 0.23) had the lowest fatigue limit (450 pounds as compared to 700 pounds). If comparisons are made between fatigue limit and other properties of spot-welded joints, this same lack of correlation is evident.

The studies of the mode of failure in the fatigue tests showed that failure (in titanium and stainless steel weldments) always started in the base plate and was related to the geometry of the specimen rather than the metallurgical structure. The notch formed by the extruded metal and the faying surface of one of the sheets seemed to be the point at which the fatigue crack always started. Once started, these cracks would progress to the outer surface of the sheet without seeming to follow a preferred path. In some cases, the crack progressed through what seemed to be unaffected base metal, in other cases through a heat-affected zone. In no case did the crack enter the weld nugget. Therefore, it appears that the stress pattern imposed by the geometry in the vicinity of the spot weld and the properties of the unaffected base metal govern the fatigue limit of spot-welded joints in titanium.

The results of the fatigue tests indicate that the fatigue limit increases as the base-metal strength increases and also as the ductility increases. Thus, since the ductility of a metal usually decreases as strength increases, there should be some optimum combination of strength and ductility which produces the maximum fatigue limit. For the titanium materials used in this research, the optimum seems to be the commercially pure titanium sheet. The experimental unalloyed sheet is more ductile but has lower strength and a lower fatigue limit. The titanium - 7 per cent manganese alloy sheet is stronger but has lower ductility and a lower fatigue limit.

The sheet gage and spot spacing for the titanium materials and the stainless steel were the same as those for the aluminum alloys studied previously. Therefore it is possible to compare the three materials from the standpoint of the behavior of similar multispot joints in the same sheet gage. In fatigue, stainless steel is stronger than commercially pure titanium, titanium - 7 per cent manganese alloy, and clad aluminum alloys 24S-T and 75S-T. Furthermore, the commercially pure titanium is better than the aluminum alloys.

It must be admitted that the fatigue data for the weldments in the titanium - 7 per cent manganese alloy indicate that their fatigue behavior is not too bad when compared with similar joints in stainless steel and aluminum. However, there is some reluctance to accept this evidence at face value, since it has been shown that the spot welds in the titanium alloy are very brittle. On the other hand, spot welds in the commercially pure sheet are ductile, and the fatigue data can be used for comparison with greater confidence.

CONCLUSIONS

From the results of the static and fatigue tests on spot-welded joints in unalloyed and alloyed titanium, stainless steel, and aluminum, the following conclusions were made.

(1) Spot-welded joints in the high-strength titanium - 7 per cent manganese alloy sheet had somewhat poorer fatigue strengths than similar joints in average strength, commercially pure titanium sheet of the same gage.

(2) Furnace heat treatment did not improve the fatigue behavior of spot-welded joints in the titanium - 7 per cent manganese sheet. However, furnace heat treatment improved the static behavior of the joints significantly. Machine postweld heat treatment of spot welds in the alloy sheet did not improve their behavior in static tests. Postweld heat treatments made in the spot-welding machine probably would not improve the fatigue behavior of joints in titanium - 7 per cent manganese alloy sheet.

(3) Sheet gage and spot spacing being equal, spot-welded joints in low-strength, very ductile unalloyed titanium sheet were no better in fatigue than similar joints in commercially pure titanium sheet of higher strength.

(4) There appears to be no relation between the tension-to-shear ratios determined from tests on single-spot specimens and the fatigue behavior of spot-welded joints in various types of titanium sheet.

(5) The fatigue limits of spot-welded joints in unalloyed and alloyed titanium sheet were somewhat lower than for similar joints in stainless steel sheet of equal gage and spot spacing under the same loading conditions. Spot-welded joints in titanium sheet had higher fatigue limits than similar joints in clad 24S-T and clad 75S-T aluminum alloy sheet of the same thickness.

(6) Under static tension-shear loading, spot-welded joints in unalloyed and alloyed titanium sheet were stronger than similar joints in Type 321 stainless steel and clad 24S-T and clad 75S-T aluminum alloy sheet of equal thickness.

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