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AFML-TR-67-291

STRESS CORROSION SUSCEPTIBILITY OF WELDED ALUMINUM ALLOYS

R.V. TURLEY
E. DASH
C.H. AVERY

DOUGLAS AIRCRAFT COMPANY

TECHNICAL REPORT AFML-TR-67-291

AUGUST 1967

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Air Force Materials Laboratory
Research and Technology Division
Air Force Systems Command
Wright-Patterson AFB, Ohio

NOTICES

FOREWORD

This investigation of welded aluminum alloys was conducted by the Douglas Aircraft Company, Inc., Aircraft Division, Long Beach, California, under Contract No. AF33(615)-5419.

This contract was initiated under Project 7381, "Materials Applications," Task 738107, "Detection, Prevention and Control of Corrosion." The work was performed under the direction of Air Force Materials Laboratory, Research and Technology Division, Wright-Patterson Air Force Base, Ohio, with Mr. Fred Meyer as Project Engineer. The contract period was from July, 1966, to August, 1967. The manuscript was released by the authors in August, 1967, for publication as a technical report.

This materials program was conducted by Metallics Section personnel within the Douglas Materials Research and Process Engineering Group.

Mr. R. V. Turley was principal investigator under the direction of Mr. C. H. Avery and Mr. W. G. Christensen. Mr. Avery acted as principal investigator from July through December, 1966, while Mr. Turley was completing an overlapping AF investigation. Welding and mechanical property analyses were performed by Mr. E. Dash.

Special acknowledgment is extended to Mr. E. Hayman, Mr. R. Walkington and Mr. G. Moenning for their excellent assistance in conducting this program.

This technical report has been reviewed and is approved.

W. P. Conrardy

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Air Force Materials Laboratory
Research and Technology Division
Air Force Systems Command
Wright-Patterson AFB, Ohio

ABSTRACT

Adequate knowledge of the stress corrosion thresholds of welded aluminum alloys is required by designers to utilize mechanical properties fully. This program determined threshold stress levels for 2014-T6, X2021-T8E31, 2024-T81, 2219-T87, X7002-T6, 7039-T64, and 7106-T6. Variables were sheet and plate, long transverse grain direction, welded and post-weld heat treated, notched and unnotched. Tests were conducted using step load and constant load 500 hours alternate immersion in synthetic sea water at sustained stress levels up to 75-percent yield strength. All basic, unwelded alloys, sheet and plate, had thresholds above 75-percent yield strength. Thresholds for unnotched sheet alloys were below 75-percent yield strength for 2014-T6, as welded (W), weld + age (A) and weld + solution heat treat + age (S), X2021-T8E31 (W), 2024-T81 (W), 2219-T87 (S), 7039-T64 (S) and 7106-T6 (A) (S). The most susceptible to stress corrosion cracking was X2021-T8E31 (W). A fatigue crack at the edge of the weld bead caused increased susceptibility to stress corrosion for several of the sheet alloy-weld-tempers. For unnotched plate product, stress corrosion cracking was incurred for only 2014-T6 (S) and 7039-T64 (S) below 75-percent yield strength; this was at higher stress levels than the (W) and (A) tempers tested. A fatigue crack at the edge of the weld bead caused severe susceptibility to stress corrosion cracking for plate alloys, X2021-T8E31 (S), 7039-T64 (S) and 2014-T6 (S). An Engineering Data Materials Matrix is presented. Stress corrosion cracking typically initiated at the edge of the weld bead and progressed along the fusion line, branching into the weld bead and heat affected zone. Progression was characterized by a series of jumps exhibiting both corrosion and stress corrosion stages. Additional work is recommended in spectrum loading and natural environment stress corrosion testing, electron beam welding and basic studies of microstructural effects.

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DOUGLAS AIRCRAFT DIVISION

3855 Lakewood Boulevard Long Beach, California 90801 (213) 421-2711

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Subject: Contract AF33(615)-5419
Summary Technical Report
AFML-TR-67-291

To: Air Force Materials Laboratory
Attn: MAAS, F. Meyer
Contract AF33(615)-5419
Wright-Patterson Air Force Base, Ohio 45433

Reference: a. AFML Letter MAAS (F. Meyer) dated 14 November 1967

1. In fulfillment of the total requirements of the subject contract schedule, Item III A.(2) and Exhibit "B" Item I.C., the Contractor has published and distributed the Summary Technical Report as directed by Reference a.

2. Your copies of the Summary Technical Report are forwarded herewith as Enclosure a.

McDonnell Douglas Corporation

J. M. Palmer, Jr.

J. M. Palmer, Jr.
Assistant Research Director
Contract Research and Development

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ILLUSTRATIONS

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TABLES (Continued)

SECTION I

INTRODUCTION

This program was conducted to evaluate the stress corrosion cracking susceptibility of welded high-strength aluminum alloys in sheet and plate form.

An adequate knowledge of the stress corrosion characteristics of aluminum alloys is required by designers to utilize fully the optimum mechanical properties of welded high-strength aluminum alloys.

The results of this program provide engineering type data on threshold levels of stress for 500-hour exposure of seven welded aluminum alloys. This study includes the variables of sheet and plate thickness, post-weld heat treatment, and precracked versus smooth specimens. Of the seven alloys under consideration, four are from the "2XXX" series aluminum alloys; 2014, 2021, 2024, and 2219, and three are from the "7XXX" series; 7002, 7039, and 7106.

Each alloy was received in, or heat treated to, the artificially aged condition prior to welding. Each alloy was investigated in: (1) the basic, unwelded condition, (2) the as-welded condition, (3) the post-weld artificially aged condition, and (4) the post-weld solution heat treated, artificially aged condition. All welded specimens were tested non-destructively using techniques in accordance with the best accepted commercial practice. The weld beads were left intact, as representative of service conditions. The environment used for all stress corrosion testing was synthetic sea water solution in an alternate immersion dunker. Alternate immersion consists of 10 minutes in the solution and 50 minutes drying time in ambient air.

The first specimen of each test condition (basic and welded) was step loaded beginning with 20 percent of the yield of the corresponding tensile specimen, and in increasing steps until failure or 75 percent of yield strength. This step-loading technique was used to determine approximate threshold stress. Once failure was reached additional specimens were run in the vicinity of the stress which caused failure to establish the 500-hour threshold level.

SECTION II

CONCLUSIONS

STRESS CORROSION THRESHOLDS

1. Using 75 percent and 35 percent of the measured yield strength as the minimum satisfactory level of stress corrosion resistance (threshold) for the unnotched and notched conditions, respectively, and under the conditions of testing in this program, the following conclusions appear warranted:

   a. In the basic unwelded, long transverse grain direction, (both sheet and plate), all seven alloys are satisfactory in the unnotched condition.

   b. In the as-welded temper (W) all alloys tested (both sheet and plate) are satisfactory in the unnotched or notched condition <u>except</u> 2014-T6 sheet, 2021-T8E31 sheet and 2024-T81 sheet which should be avoided.

   c. In the post-weld artificially aged temper (A), all alloys tested (both sheet and plate) are satisfactory unnotched or notched <u>except</u> 2014-T6 sheet and 7106-T6 sheet which should be avoided.

   d. In the post-weld solution heat treated and artifically aged condition (S), all alloys tested (both sheet and plate) are satisfactory unnotched or notched <u>except</u> 2014-T6 sheet and plate, 2021-T8E31 plate, 2219-T87 sheet, 7039-T64 sheet and plate and 7106-T6 sheet which should be avoided.

2. Alloy 2021-T8E31 sheet, as-welded, had the lowest stress corrosion threshold of all the alloy-weld-tempers evaluated in the program (10.6 ksi unnotched). However, post-weld age or post-weld solution heat treat + age restored high resistance (>37.7 ksi for (A) condition and >49.8 ksi for (S) condition).

3. Post-weld age or solution heat treat + age did not improve the stress corrosion resistance of as-welded 2014-T6 sheet. The presence of a fatigue crack at the edge of the weld bead lowered the stress corrosion threshold of all three weld tempers. Stress corrosion resistance of 2014-T6 was lowest in the post-weld solution heat treat + age condition (25.9 ksi unnotched and 15.9 ksi notched).

4. Alloy 7039-T64 sheet had high resistance to stress corrosion in the presence of a fatigue crack at the edge of the weld bead in all three weld tempers; (>41.0 ksi (W), 37.0 ksi (A), 39.1 ksi (S)).

5. A fatigue crack at the edge of the weld bead lowered the stress corrosion threshold of 7106-T6 welded sheet by 50 percent when post-weld aged or post-weld solution heat treated + age.

6. The stress corrosion threshold was significantly lowered in the presence of a fatigue crack at the edge of the weld bead of post-weld solution heat treated and aged X2021-T8E31 plate, 7039-T64 plate, and 2014-T6 plate.

MECHANICAL PROPERTIES

1. Mechanical properties of all alloys in the as-welded condition were lower than the basic unwelded temper. Post-weld artificial age improved ultimate and yield strength and decreased elongation, except for 7039-T64 and 7106-T6 sheet where elongation was improved. Post-weld solution heat treat and age further improved all mechanical properties including elongation.

2. Alloy 2024-T81, generally considered unweldable, was welded satisfactorily without cracking. However, elongation was less than 1.4 percent in 2 inches in all three weld tempers of both sheet and plate. Condition (A) in sheet form had lowest elongation, 0.4 percent and also low NTS, 25.5 ksi, compared to 42.3 ksi in (W) condition and 51.7 ksi in (S) condition.

3. Alloy 2014-T6 (W) plate had lowest notch strength (16.7 ksi) of all of the plate alloy-weld-tempers evaluated in this program.

MATERIALS MATRIX

1. Stress corrosion threshold and mechanical property data developed in this program are formulated into an Engineering Data Materials Matrix on page 5 of this report to assist in a direct comparison of alloys and tempers according to design engineering requirements. Alloy-weld-tempers that exhibit low stress corrosion thresholds and should be avoided as previously discussed are shaded in the matrix.

NATURE OF STRESS CORROSION CRACKING

1. All stress corrosion cracks initiated at the edge of the weld bead except for X2021-T8E31 sheet, as-welded temper, which initiated at and failed through the cold side of the heat-affected zone.

2. Stress corrosion crack propagation occurred as an intergranular, multidirectional crack front centering along the fusion line but branching into the weld bead and the heat-affected zone and parent metal as short transverse grain direction cracks. Initial stress corrosion cracking from an existing fatigue crack often occurred as a short transverse grain direction crack in a plane at and perpendicular to the fatigue crack tip.

3. Progression of the environmental crack (notched plate) was observed as a series of jumps exhibiting both corrosion and stress corrosion cracking stages. From discrete measurements, corrosion occurred at an average rate of penetration of 0.12×10^{-3} inch/hour and stress corrosion cracking at rates up to 3.30×10^{-3} inch/hour. Continuous measurements could reveal higher stress corrosion cracking rates.

ENGINEERING DATA MATERIALS MATRIX FOR WELDED ALUMINUM ALLOYS

Alloy		BASIC UNWELDED		AS WELDED		POST WELD ARTIFICIAL AGE		POST WELD SOLN HT AND ARTIFICIAL AGE	
2014-T6	Sheet	63.2 8.7 >47.4	NE	43.8 1.1 30.7	45.9 19.4	53.5 0.7 29.4	54.0 20.7	57.5 4.9 25.9	57.9 15.9
	Plate	>49.1 8.7 65.1	NE	>21.4 1.7 28.5	>11.1 16.7	>24.2 1.1 32.3	>16.8 24.8	44.2 1.3 63.2	18.3 27.8
2021-T8E31	Sheet	66.2 8.1 >49.7	NE	33.5 2.0 10.6	37.7 11.8	50.3 0.7 >37.7	39.2 >29.3	66.4 5.9 >49.8	50.1 >39.1
	Plate	>48.2 3.7 63.8	NE	>17.5 2.8 23.3	>20.8 27.4	>27.0 2.4 36.9	>17.4 20.1	>46.8 1.8 62.4	13.7 31.1
2024-T81	Sheet	62.8 7.0 >47.1	NE	53.6 0.9 34.8	42.3 23.6	61.0 0.4 >45.8	26.5 >19.3	55.5 1.4 >41.6	51.7 >37.5
	Plate	>50.4 6.5 66.9	NE	>28.7 0.8 38.2	>19.1 25.0	>33.1 0.6 44.2	>15.7 28.3	>42.1 0.9 56.1	>21.2 28.3
2219-T87	Sheet	54.1 9.5 >40.6	NE	33.1 2.6 >24.9	43.5 >29.6	43.5 1.7 >32.6	46.3 >33.9	52.7 12.2 28.0	58.9 30.0
	Plate	>42.7 12.5 56.7	NE	>15.5 9.2 20.6	>23.5 30.3	>23.9 1.2 31.9	>28.2 38.7	>32.1 9.5 42.8	>35.3 49.6
X7002-T6	Sheet	57.5 11.6 >43.1	NE	38.7 2.5 >29.1	49.6 >38.2	49.4 1.2 >37.0	52.1 30.6	52.3 10.5 >39.3	55.9 40.5
	Plate	>41.5 13.2 55.2	NE	NE	NE	NE	NE	NE	NE
7039-T64	Sheet	51.3 10.0 >38.5	NE	33.2 4.4 >24.9	54.0 >41.0	44.6 4.9 >33.4	51.8 37.0	52.9 11.6 37.0	64.2 39.1
	Plate	>40.6 13.5 54.0	NE	>23.9 10.4 31.9	>35.1 44.1	>26.3 7.3 35.0	>33.5 40.1	31.3 9.0 52.2	17.9 50.3
7106-T6	Sheet	56.3 11.1 >42.2	NE	42.3 3.8 >31.7	57.0 29.8	53.4 5.4 25.4	54.1 12.0	60.4 8.5 37.8	66.9 13.4
	Plate	>40.6 14.4 53.9	NE	NE	NE	NE	NE	NE	NE

	UNNOTCHED	NOTCHED
SHEET	YIELD, KSI ELONG, % SCC THRESHOLD, KSI	NTS, KSI SCC THRESHOLD, KSI
PLATE	SCC THRESHOLD, KSI ELONG, % YIELD, KSI	SCC THRESHOLD, KSI NTS, KSI

NE = NOT EVALUATED
> = GREATER THAN
< = LESS THAN

UNNOTCHED SCC THRESHOLD < 75% YIELD

NOTCHED SCC THRESHOLD < 35% YIELD

COMBINATION OF ABOVE

CORROSION

1. The 7XXX series aluminum alloys incurred severe corrosion at the edge of the weld bead (top of the weld pass), with or without post-weld heat treat. This corrosion was associated with a microstructural phase formed during welding.

2. Severe corrosion occurred in the heat-affected zones of 7002-T6, 7039-T64, and 7106-T6 sheet as-welded tempers. Post-weld aging improved resistance and post-weld solution heat treat and aging restored resistance to corrosion to that of the parent metal.

GENERAL

1. Step-load alternate immersion tests approximated the constant load threshold stress for stress corrosion cracking. Step-load thresholds did vary both above and below constant load thresholds with greatest divergence observed when step-load threshold was below constant load threshold. Additional air exposure, surface film rupture upon increasing step load and mechanical working or damage of crack tips during handling are possible accelerating effects operative during step loading, and may account for lower stress corrosion cracking thresholds.

2. The use of X-ray to determine crack initiation and growth was unsatisfactory for surface crack specimens because of varying tightness of crack, feathering out of crack tips and non-planar stress corrosion cracking propagation resulting in lack of contrasting density. X-ray was satisfactory for through-the-thickness cracks with flat tips and sufficient yawning of the crack under load to give contrasting density.

3. The two-pass, square-butt, double-welded joint of 1-inch-thick sections, using TIG welding and DCSP, were satisfactory techniques for the aluminum alloys on this program. Overlap of the two passes should be maintained between 1/8 inch and 1/4 inch to ensure complete penetration.

SECTION III

RECOMMENDATIONS

1. Stress corrosion thresholds were determined in this program using relatively few specimens. Additional stress corrosion testing should be performed to establish reliability sufficient for engineering design.

2. Additional stress corrosion cracking and corrosion tests should be performed in the natural environments that the welded aluminum alloys will encounter during fabrication and service. Correlation should then be made with accelerated laboratory tests. Although alternate immersion is a widely used test for aluminum alloys, disagreement between alternate immersion stress corrosion cracking threshold and that experienced in service has been noted for alloy 7079-T6 (Reference 1).

3. Increasing loads by steps is indicated to lower stress corrosion cracking thresholds which may account for certain service failures. Realistic spectrum loading should be incorporated into stress corrosion testing programs, similar to that often performed in determining fatigue worthiness of aircraft and missile structures.

4. Welding techniques, such as electron beam welding, should be investigated as a means of improving ductility and notch toughness of the weld zone of alloy 2024, which otherwise showed high strength and stress corrosion cracking resistance.

5. Stress corrosion cracks initiated at the edge of the weld bead but propagated both into the weld bead and heat-affected zone. Additional tests should be performed with notches located in these two zones, with and without weld bead reinforcement.

6. Electron microscopy, microprobe and electro-potential studies should be conducted on alloy X2021-T8E31 sheet as-welded and post-weld heat treated to determine causes of both high susceptibility (as-welded) and high resistance (post-weld heat treated) to stress corrosion cracking. Similar studies are also warranted on X2021-T8E31 and 7039-T64 plate and 7106-T6 sheet which showed increased susceptibility to stress corrosion when post-weld heat treated.

SECTION IV

MATERIALS

SHEET AND PLATE

The high-strength weldable aluminum alloys evaluated for increased susceptibility to stress corrosion cracking in the weld area are shown in Table I. Both sheet and plate products were tested. Original plans were to test plate and sheet approximately 1-inch and 0.080-inch-thick, respectively. Because of availability limitations, sheet sizes ranged from 0.064 inch to 0.125 inch and plate varied from 3/4 inch to 1.00 inch. All products were non-clad.

These materials were received in their fully heat treated condition designated as "the basic temper condition" for this program. The exception was 2024 alloy, received as T3 sheet and T351 plate, and aged at 375° ±5° for 12 hours to give the T81 and T851 "basic tempers," respectively.

ALLOY SUBSTITUTION

Limited testing was performed on alloys 7002-T6 and 7106-T6 in plate form. During the second quarter of this program, it was found that production of alloys 7002 and 7106 was being discontinued and the alloys had been removed from the Aluminum Association's list of alloys. Subsequently, the contractor investigated more promising alloys for substitution and, on 13 October 1966, verbally recommended to the Air Force Materials Laboratory the substitution of alloy 2021 sheet and plate for 7002 and 7106 plate. Specimen fabrication was near completion on 7002 and 7106 sheet so it was recommended that these be retained in the program. Approval of these recommendations was assured by the USAF Contracting Officer and the program proceeded accordingly.

WELDING WIRE

Filler welding wire was selected either according to manufacturer's recommendations or, when such recommendations were lacking, according to best commercial practice. The particular wires used for each alloy welded in the program are listed in Table I. The following comments, tabulated for each alloy, describe the reasons for the selection of each filler wire:

Alloy 2014

Filler wires 4043, 4145, 2014, and 2319 have been used in industry to weld this alloy (References 2, 3, 4, and 5), but it appeared that 4043 filler represented the widest usage. Filler wire 2319 was regarded as a close second choice. Although 2319 as a filler for 2014 is used by many fabricators and exhibits higher strength joints than 4043, the latter was preferred as being less sensitive to cracking (Reference 4) and more representative in industrial usage.

TABLE I

Test Materials

Sheet and Plate					Weld Wire		
Alloy	Product	Basic Temper	Nominal Size (inch)	Supplier	Alloy	Size Diameter (Inches)	Supplier
2014	Sheet Plate	T6	0.080 x 48 x 144 1.00 x 48 x 48	U.S. Steel Supply	4043	1/16	Arcos
X2021	Sheet Plate	T8E31	0.064 x 36 x 96 1.00 x 36 x 96	Alcoa	2319	1/16	Arcos
2024	Sheet Plate	T81 [1] T851 [1]	0.080 x 48 x 144 1.00 x 36 x 36	U.S. Steel Supply	4145	1/16	Arcos
2219	Sheet Plate	T87	0.125 x 48 x 56 0.750 x 36 x 36	Southwest Research Institute	2319	1/16	Arcos
X7002	Sheet Plate [2]	T6	0.125 x 36 x 96 0.750 x 36 x 36	Reynolds	X5180	1/16	Alcoa
7039	Sheet Plate	T64	0.125 x 30 x 48 1.00 x 30 x 48	Kaiser	5039	1/16	Kaiser
7106	Sheet Plate [2]	T6	0.090 x 36 x 96 1.00 x 36 x 44	Southwest Research Institute	X5180	1/16	Alcoa

[1] Received as T3 and T351 and aged to T81 and T851.
[2] Stress corrosion tested in basic temper condition only.

Alloy 2024

This alloy is regarded as having limited weldability (Reference 2), the welds being characterized usually by low ductility. For this reason, fusion weldments of this alloy have rarely been used commercially. Because of the extremely high crack sensitivity of this alloy to fusion welding, it was decided that filler wire 4145 should be used. This filler had exhibited the best crack-free characteristics on a similar material (alloy 2014 in Reference 4) and had been used on 2024 alloy with apparent freedom from cracking (Reference 6). It was selected over 4043 filler because higher silicon content of the 4145 filler should yield greater amounts of Al-Si and Al-Si-Cu eutectic liquids, which would tend to heal incipient cracks during solidification of the weld metal (Reference 4).

Alloy 2219

This alloy is generally welded with 2319 filler wire. For example, the welding handbook (Table 69.36 of Reference 2) shows only 2319 filler for this alloy.

Alloy 2021

The manufacturer of this alloy recommended filler 2319.

Alloy 7002

The manufacturer of this alloy recommended either 5356 or X5180 filler wire. After using 5356 filler and encountering cracking difficulties, X5180 was finally used (see section under Welding Procedure for further details).

Alloy 7039

The manufacturer of this alloy recommended 5039 filler.

Alloy 7106

The manufacturer of this alloy recommended X5180 filler.

All welding wires used were 1/16-inch diameter on 12-inch diameter spools, and where applicable, were ordered to specification MIL-E-16053K. A special packaging requirement directed the vendor to supply packaging such that each wire spool was heat-sealed in an air-evacuated, argon-filled polyester or polyethylene bag.

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SECTION V

PROCEDURES, EQUIPMENT AND FACILITIES

TEST SPECIMENS

Configurations

The specimen configurations used in this investigation for tension and stress corrosion testing, notched and unnotched are shown in Figures 1 through 6.

Manufacturing Sequence

Beginning with each alloy in the fully heat treated basic temper condition, plate and sheet form, the sequence of operations followed in preparation of test specimens was as follows:

1. Saw weld panels and control specimen blanks.
2. Mill weld panel edges (plate only) and machine control specimens complete.
3. Test (control specimens only).
4. Weld panels.
5. Saw specimen blanks from weld panels.
6. Machine specimens complete (except notches).
7. Post-weld heat treat as required.
8. Test (unnotched specimens only).
9. Machine (plate) and elox (sheet) notches.
10. Fatigue precrack.
11. Test.

Identification

Each specimen was coded as it was sawed from the weld panel (weld specimens) or basic product (unwelded control specimens) to identify it fully in regards to alloy, temper, and test as shown in Figure 7.

Cleaning

Prior to welding, all panels were cleaned per Douglas Process Standard 9.14 (Preparation of Aluminum Alloys for Welding) which consisted of: (1) vapor degrease, (2) alkaline clean, (3) de-oxidize in chromic-sulfuric-hydroflouric acid, and (4) fix in fixant and chromic acid. Following cleaning, all panels were wrapped in neutral Kraft paper. Unwelded basic control

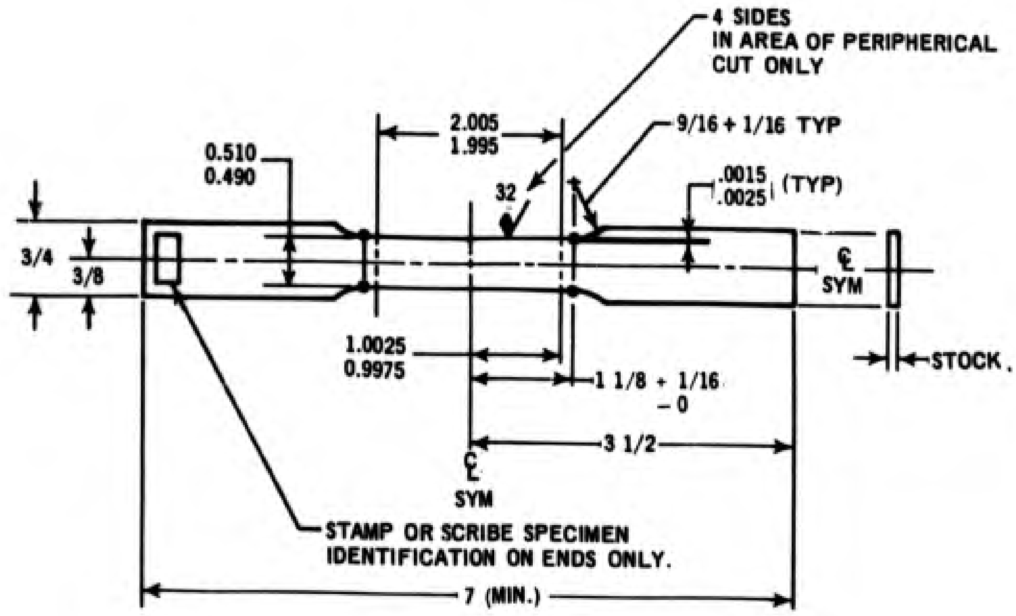


FIGURE 1. TENSILE SPECIMEN FOR BASIC TEMPER SHEET

specimens were also cleaned in this manner and lightly brushed with a stainless steel brush to correspond with the welded specimens (the weld bead area being brushed after welding).

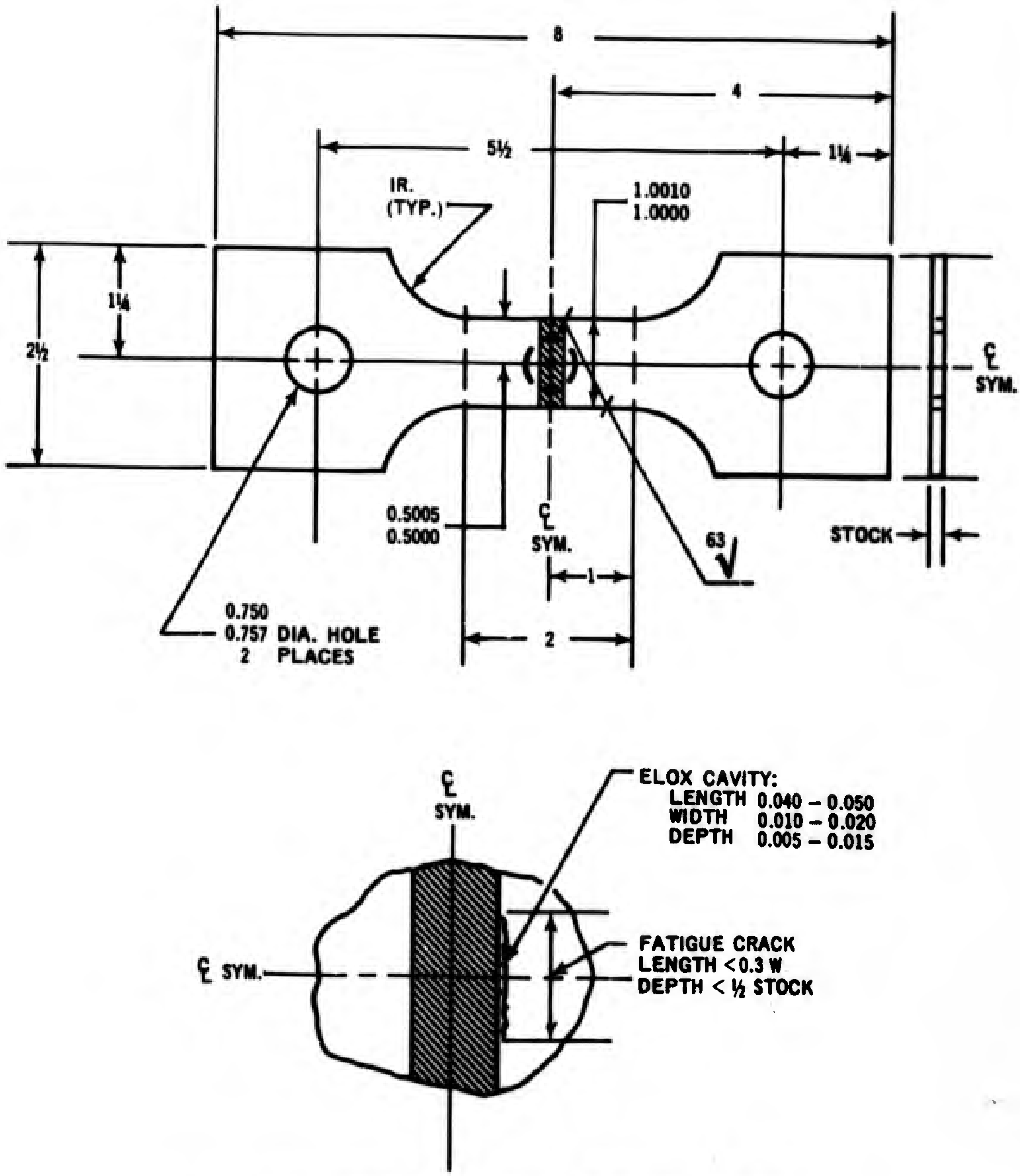
Specimens were recleaned by vapor degrease prior to heat treatment where post-weld heat treatment was required.

Immediately prior to stress corrosion testing all specimens were recleaned in an alkaline solution.

Specimens were stored individually before and after testing in sealed plastic bags.

Post-Weld Heat Treatment

Post-weld heat treatments were performed according to Douglas Processing Standards 7.00-1, MIL-H-6088D, and suppliers' recommendations to give optimum combination of stress corrosion resistance and strength, not necessarily maximum strength, and are reported in Table II. Specimens were solution heat treated in neutral salt and artificially aged in air furnaces. Solution heat treat times were somewhat longer than the minimums required. All solution heat treated specimens were given a 4-day natural age prior to artificial age. Specimens given post-weld age treatment only were aged also according to Table II.



NOTES: STRESS CORROSION SPECIMEN FOR BASIC TEMPER SHEET IS THE SAME WITHOUT WELD BEAD AND CRACK.

STRESS CORROSION AND TENSILE SPECIMEN FOR WELDED UNNOTCHED SHEET IS THE SAME WITHOUT THE CRACK.

FIGURE 2. STRESS CORROSION AND TENSILE SPECIMEN FOR WELDED AND CRACKED SHEET

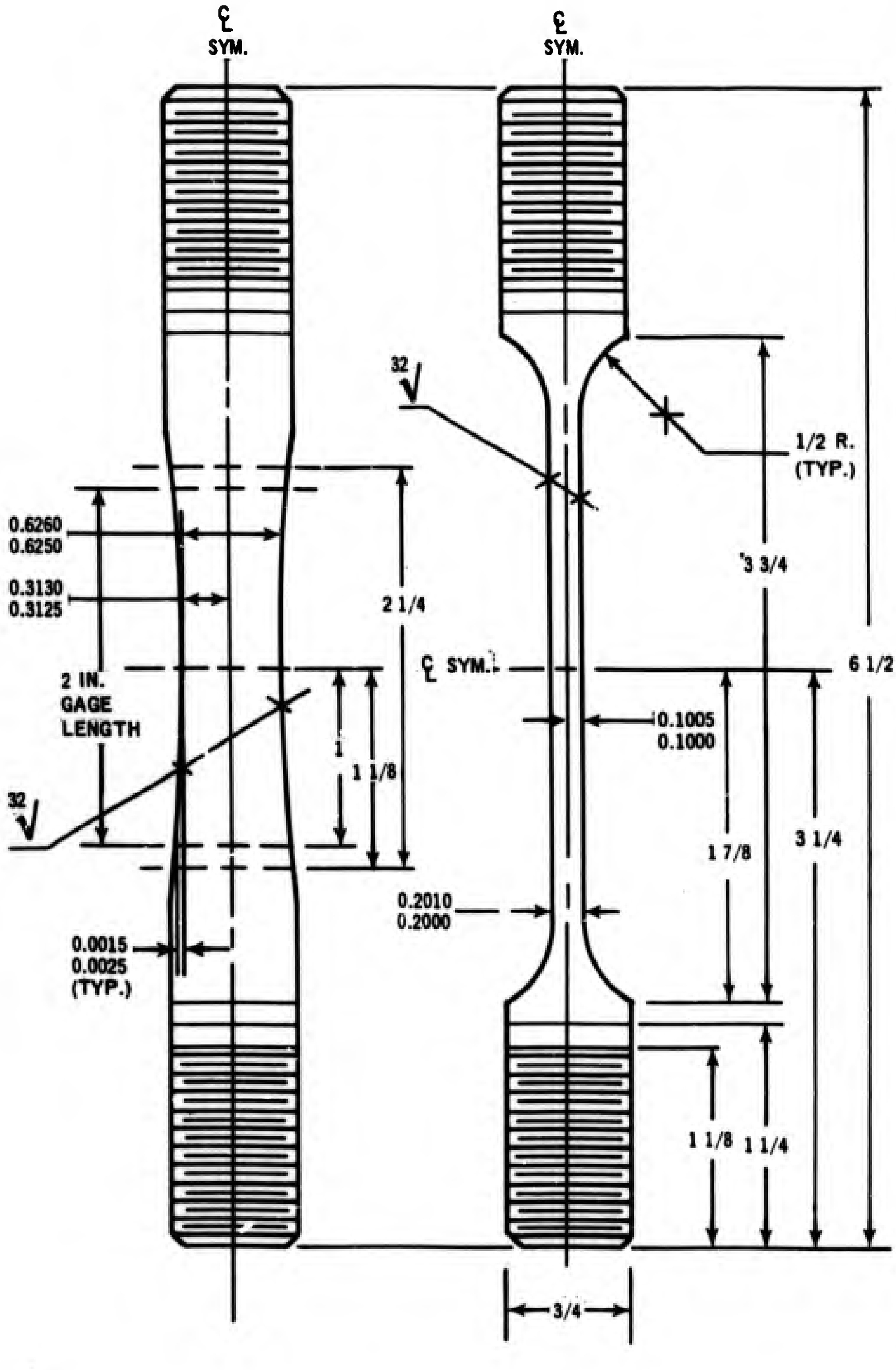


FIGURE 3. TENSILE SPECIMEN FOR BASIC 3/4" PLATE

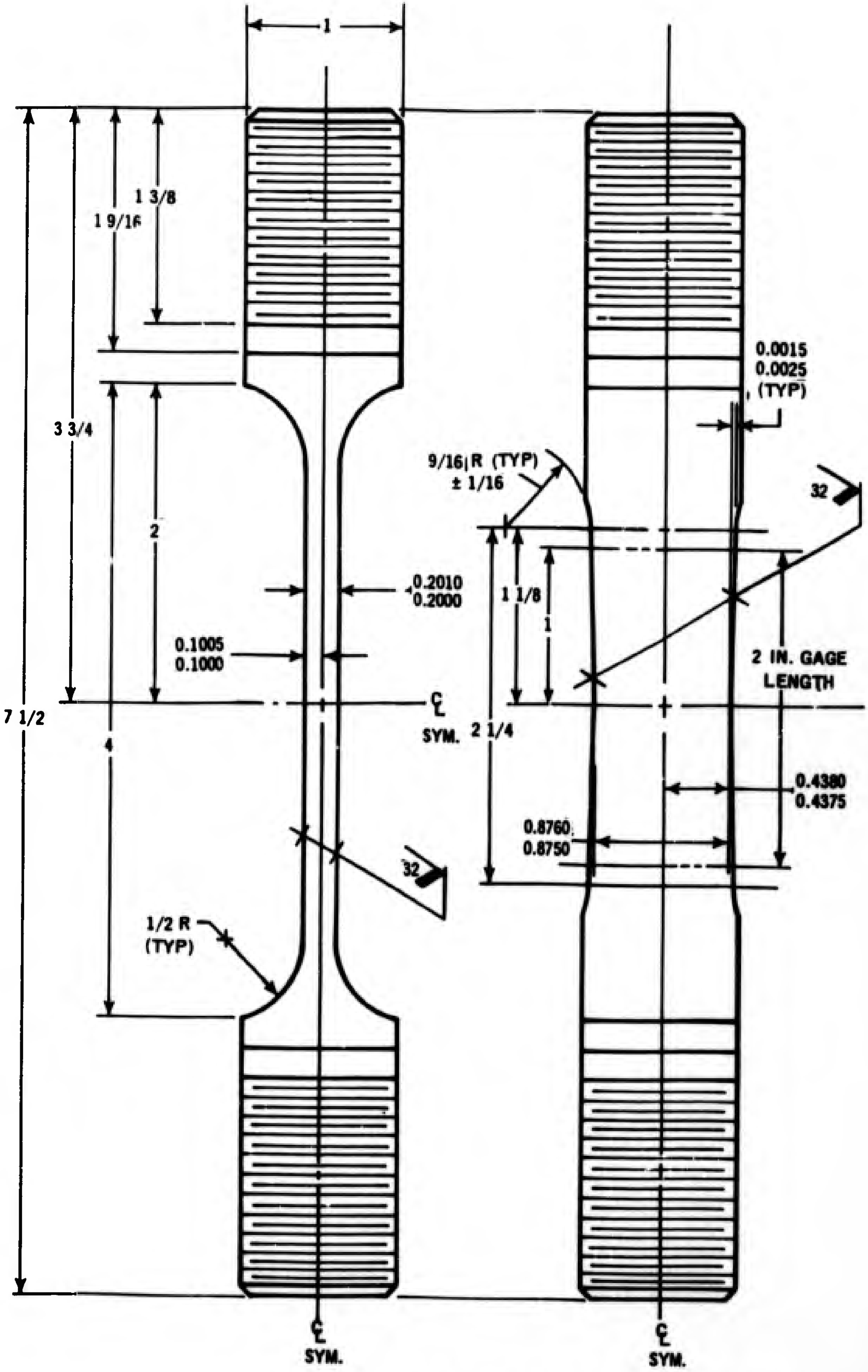
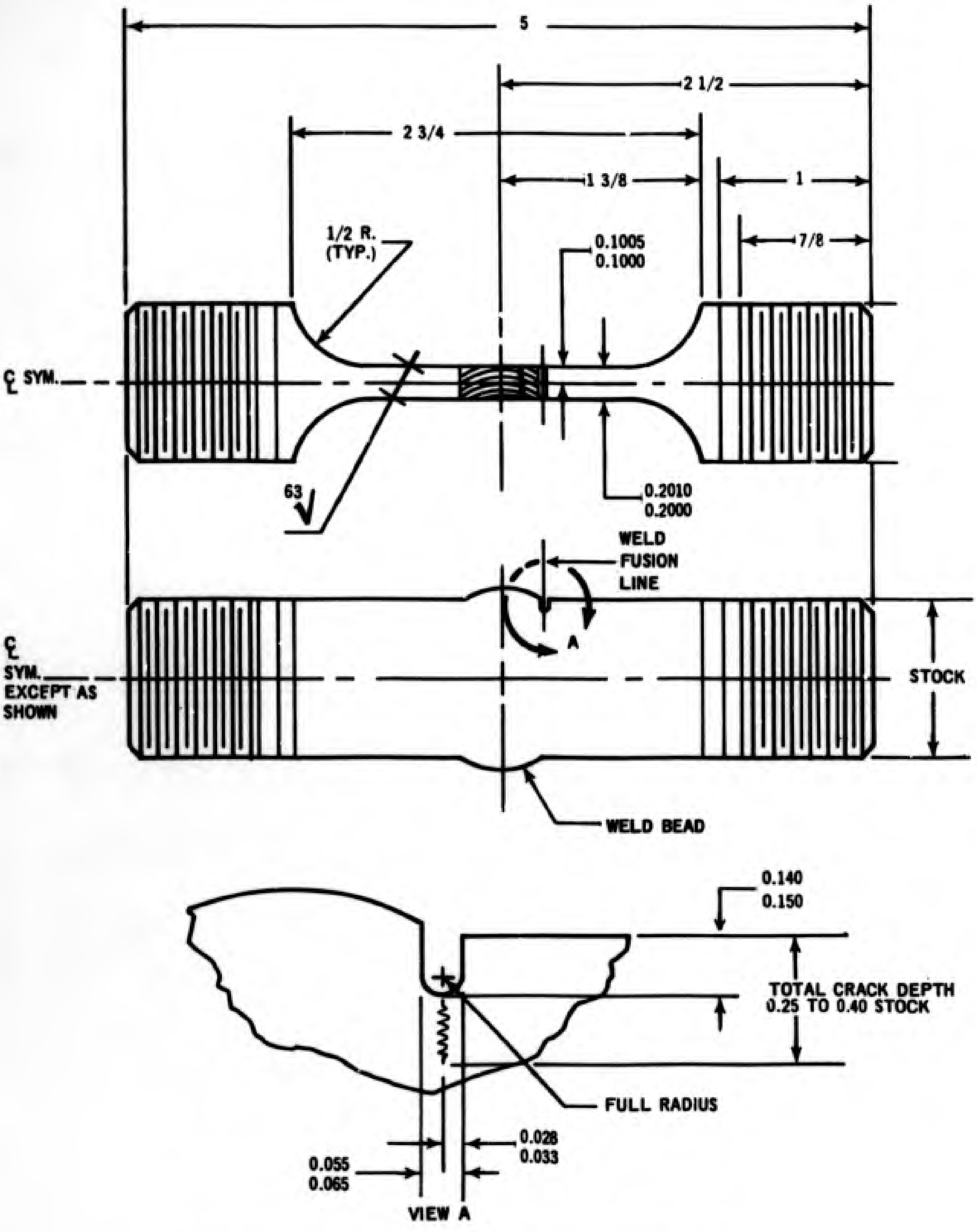
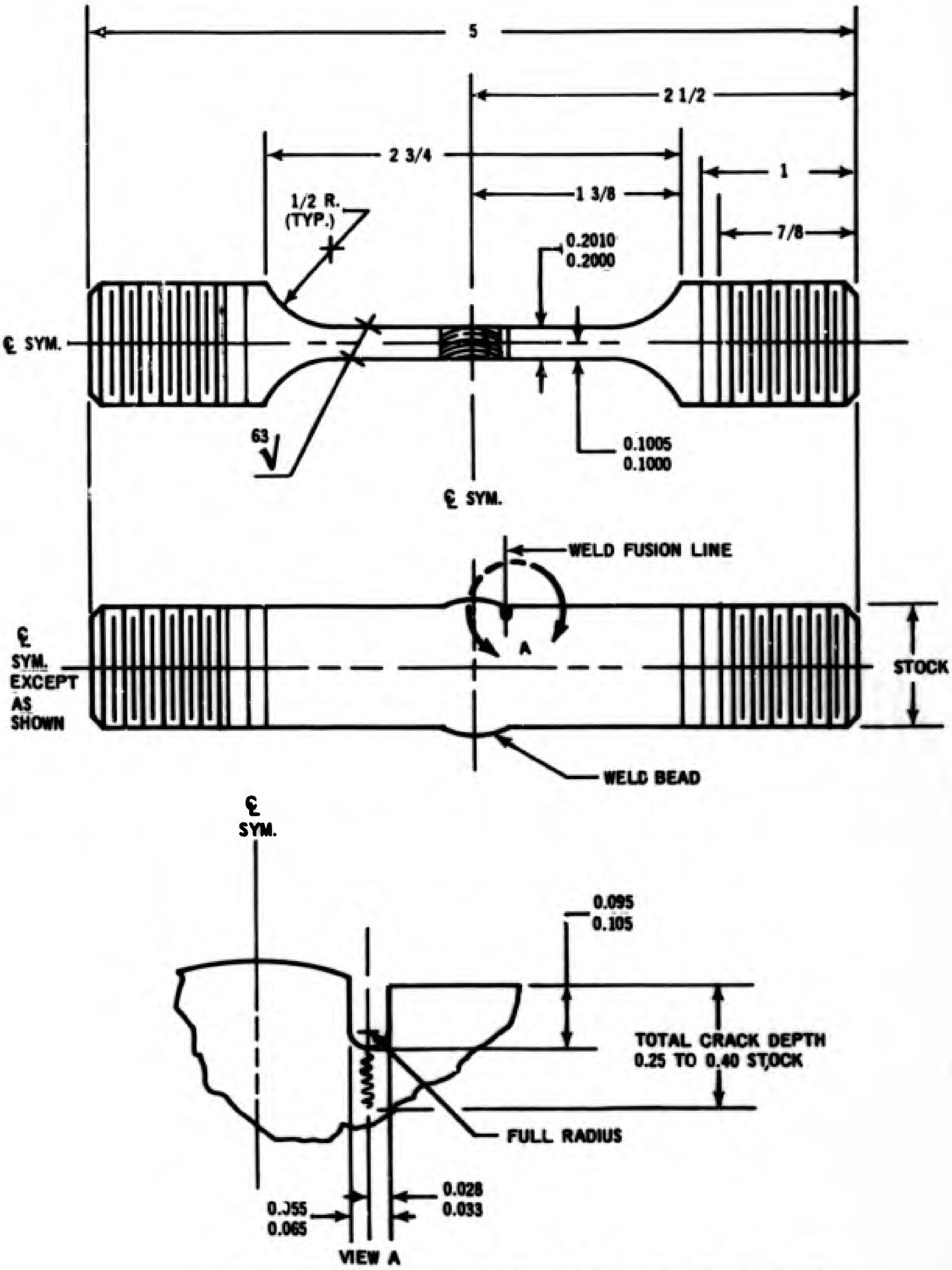


FIGURE 4. TENSILE SPECIMEN FOR BASIC 1" PLATE



NOTE: STRESS CORROSION SPECIMEN FOR BASIC TEMPER 1" PLATE IS THE SAME WITHOUT WELD BEAD AND CRACK.
STRESS CORROSION AND TENSILE SPECIMEN FOR WELDED UNNOTCHED 1" PLATE IS THE SAME WITHOUT CRACK AND TENSILE SPECIMEN HAS 2" GAGE LENGTH.

FIGURE 5. STRESS CORROSION AND TENSILE SPECIMEN FOR WELDED AND CRACKED 1" PLATE



NOTE: STRESS CORROSION SPECIMEN FOR BASIC TEMPER 3/4" PLATE IS THE SAME WITHOUT WELD BEAD AND CRACK.
STRESS CORROSION AND TENSILE SPECIMEN FOR WELDED UNNOTCHED 3/4" PLATE IS THE SAME WITHOUT CRACK, AND TENSILE SPECIMEN HAS 2" GAGE LENGTH

FIGURE 6. STRESS CORROSION AND TENSILE SPECIMEN FOR WELDED AND CRACKED 3/4" PLATE

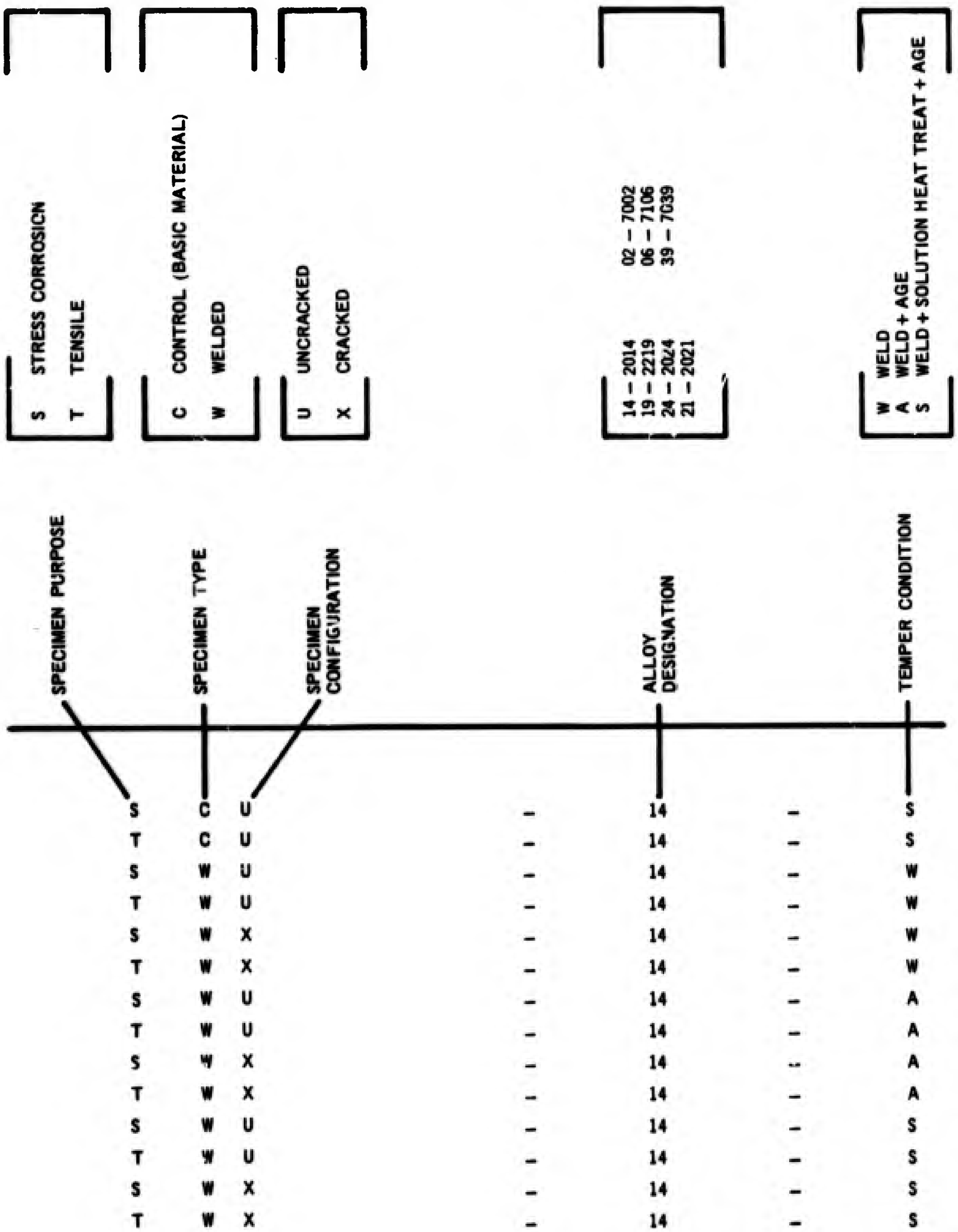


FIGURE 7. TYPICAL SPECIMEN IDENTIFICATION CODE

TABLE II Post-Weld Heat Treatment

Base Alloy	Product	Solution Heat Treat[1] Temperature (°F)	Solution Heat Treat[1] Time	Solution Heat Treat[1] Quench	Artificial Age[2] Temperature (°F)	Artificial Age[2] Time	Source
2014-T6	0.080" sheet	935 ± 10	40 min	Rt water	320 ± 10	18 hr	DPS 7.00-1 & MIL-H-6088D
	1.00 " plate		2 hr 10 min				
2024-T81 / 2024-T851	0.080" sheet	922 ± 7	40 min	Rt water	375 ± 5	12 hr	DPS 7.00-1 & MIL-H-6088D
	1.00 " plate		2 hr 10 min				
2219-T87	0.125" sheet	995 ± 10	55 min	Rt water	325 ± 10	24 hr	MIL-H-6088D
	0.750" plate		1 hr 10 min		375 ± 10[3]	36 hr	
X7002-T6	0.125" sheet	875 ± 10	55 min	Rt water	250 ± 10	48 hr	Reynolds
7106-T6	0.125" sheet	750 ± 10	55 min	160/180 F water	Heat 35 10°F/hr to 165/180°F, hold 16 hr. Continue heating 35 ± 10°F/hr to 300 ± 5°F, hold 12 hr.		Kaiser[4]
	1.00 " plate		1 hr 30 min				
7106-T6	0.090" sheet	895 ± 10	55 min	Rt water	225 ± 10 + 300 ± 10	8 hr 16 hr	Alcoa
X2021-T8E31	0.064" sheet	990 ± 5	25 min	Rt water	324 ± 10	24 hr	Alcoa
	1.00 " plate		1 hr 30 min				

1. Solution heat treated in neutral salt.
2. Artificially aged in air. All specimens naturally aged 4 days prior to artificial age.
3. Weld + age specimens were aged at 325 ± 10°F, 24 hrs.
4. Proprietary heat treatment of Kaiser Aluminum.

WELDING

Equipment

The welding equipment used in this program is shown in Figures 8 and 9 and is drawn schematically in Figure 10. Basic components of the equipment are described briefly as follows:

Power Source

Welding energy was supplied by a Miller "Gold Star" Model 330 A/BP welding machine rated at 300 amperes with a built-in high-frequency unit and receptacles for remote current and contactor control. A second similar machine was connected in parallel, as shown in Figure 10, in order to obtain sufficient energy to weld 3/4-inch and 1-inch-thick plate material.

Welding Torch

A 500-ampere water-cooled welding torch was used, which was incorporated into an Airco "Heliweld Automatic Unit" consisting of:

a. A welding machine head which was raised and lowered automatically to conform to a preset arc voltage.

b. A control box which controlled the operation of the welding machine head.

c. A filler wire feeder unit with respect to the movement of the head.

Work Positioner

The work positioner used was an Airline longitudinal positioner with a bed 8 feet long. Copper hold-down fingers provided on the positioner were used to support the sheet material over a grooved steel backup bar inserted in the backup mandrel of the positioner, as sketched in Figure 11. Also included is a Linde side beam carriage (Model OM-48) carrying a Linde Type C electronic governor, a remote control pushbutton station, the welding machine head and wire feeder units (described above), and the wire spool holder which were all mounted on the side beam track of the welding positioner.

The latter side beam track, extending 4 feet beyond the positioner bed, provided means for welding the plate on auxiliary fixturing. The latter fixturing and its cross section is sketched in Figure 11.

Weld Panels

The sheet and plate material was received in widths and lengths as noted in the Materials Section. Each sheet and plate was first sawed to obtain the necessary number of basic material "control" specimens. The remainder of the material was then sawed into panels about 4 to 5 inches in width by the remaining length of the material, as shown in Figures 12 and 13. All sheet panels were sawed with square cuts. Alloy X7002 was later sawed at an angle so that the single vee included angle was 50° when two panels were butted up prior to welding.

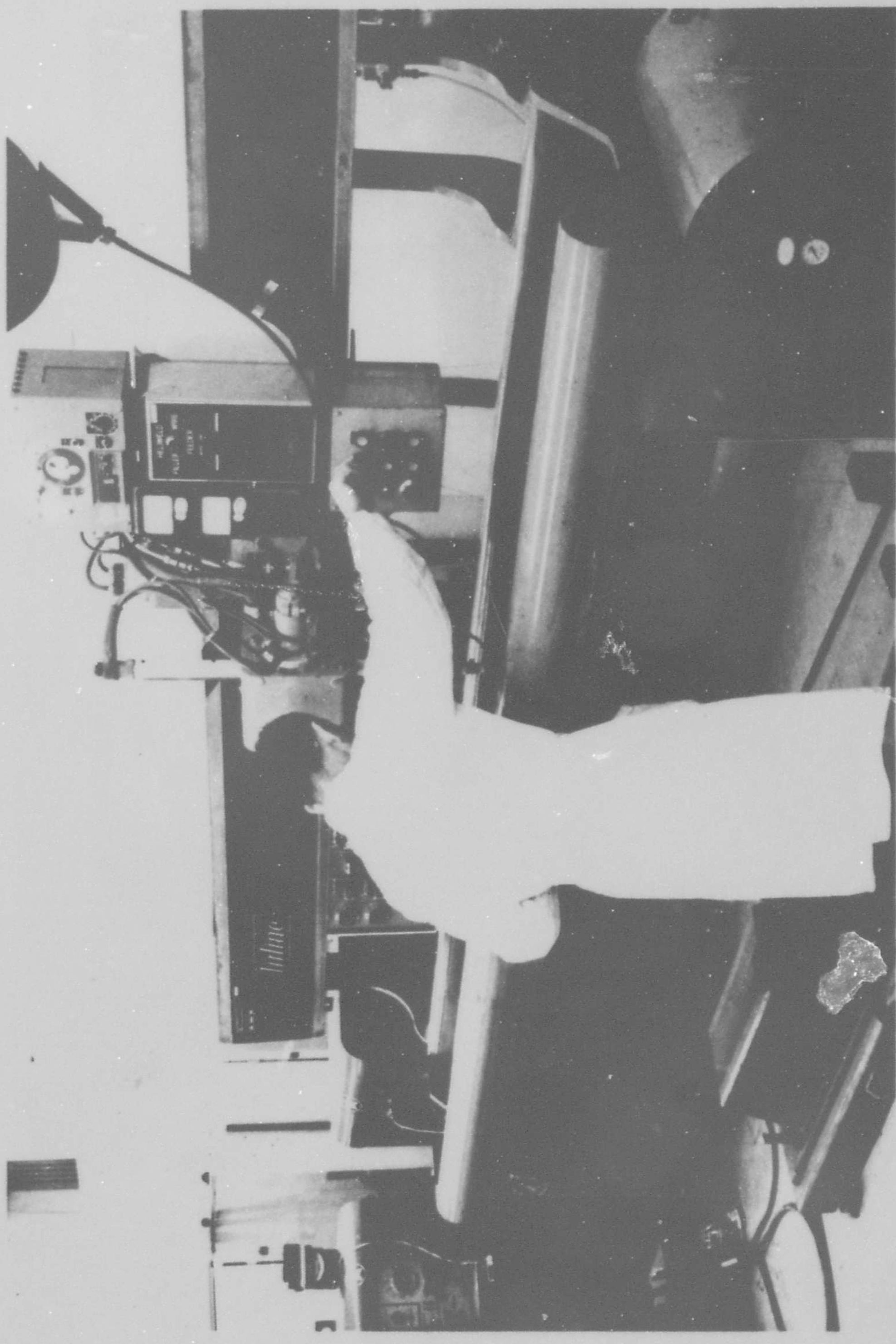


FIGURE 8. VIEW OF THE WELDING EQUIPMENT USED TO WELD SHEET PRODUCT

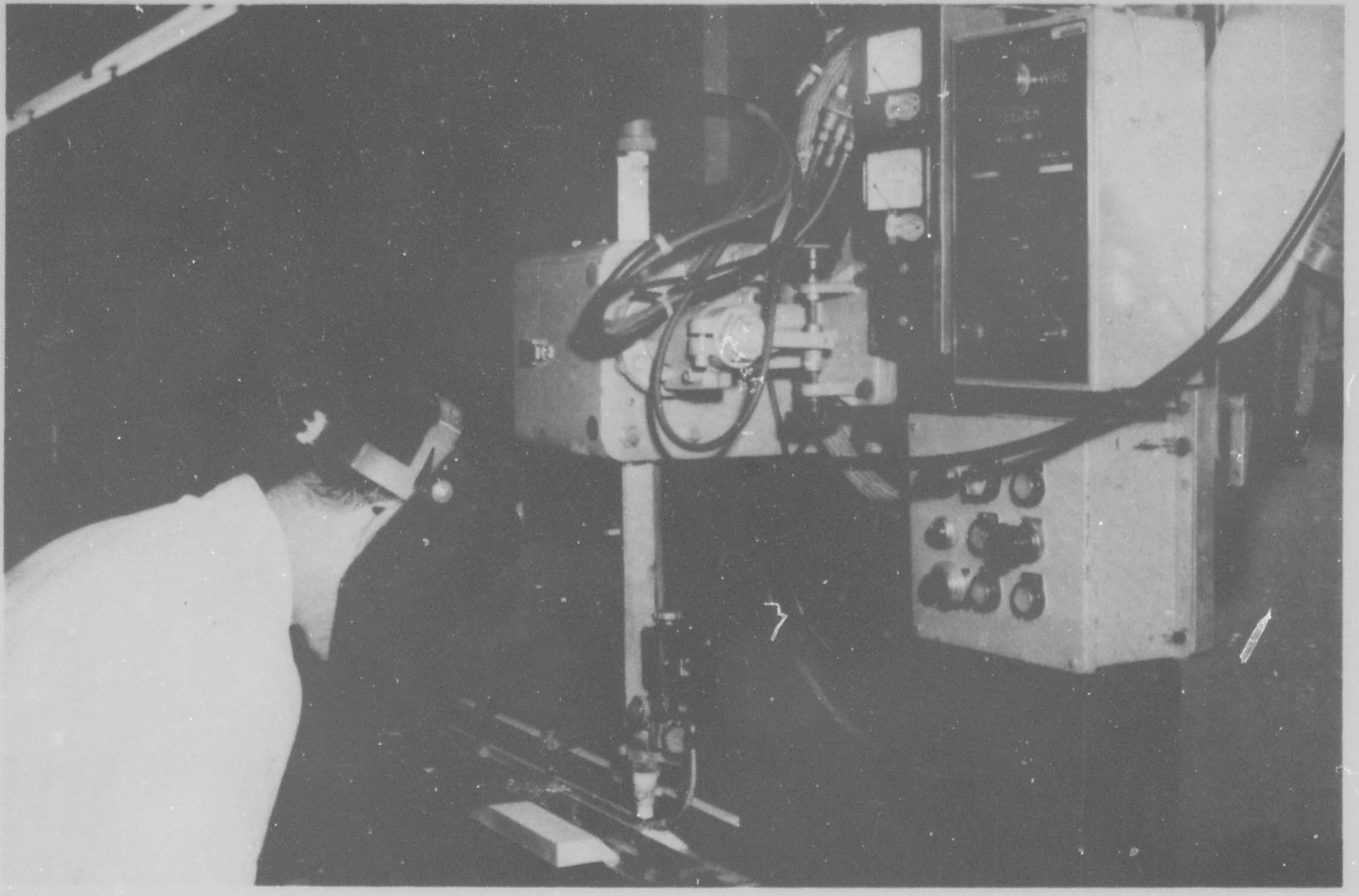


FIGURE 9. VIEW OF SET UP USED TO WELD PLATE PRODUCT

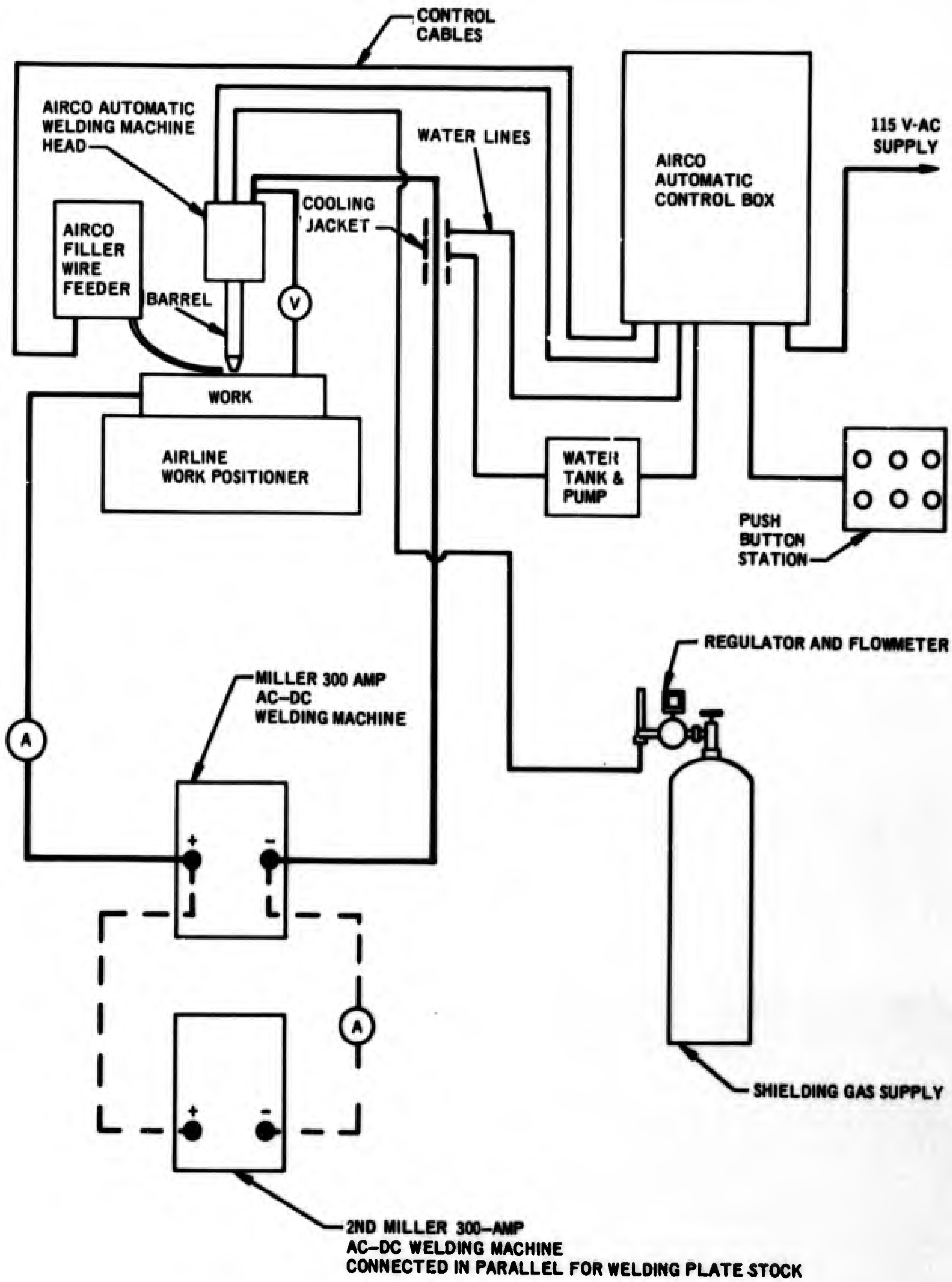
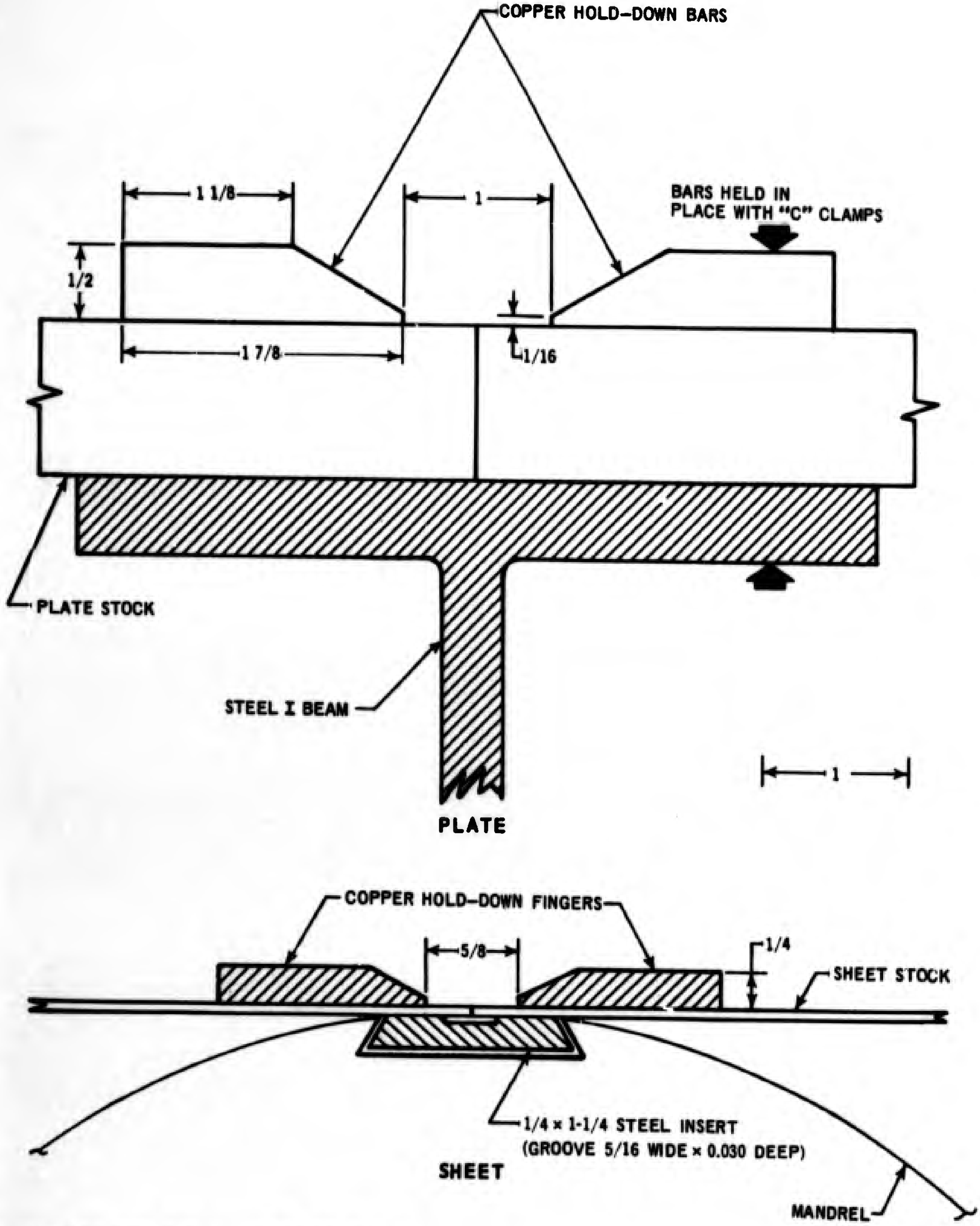


FIGURE 10. SCHEMATIC DRAWING OF WELDING EQUIPMENT SET-UP



HOLD DOWN PRESSURE FOR ALL SHEET WELDS = 68 psi

FIGURE 11. WELDING FIXTURES

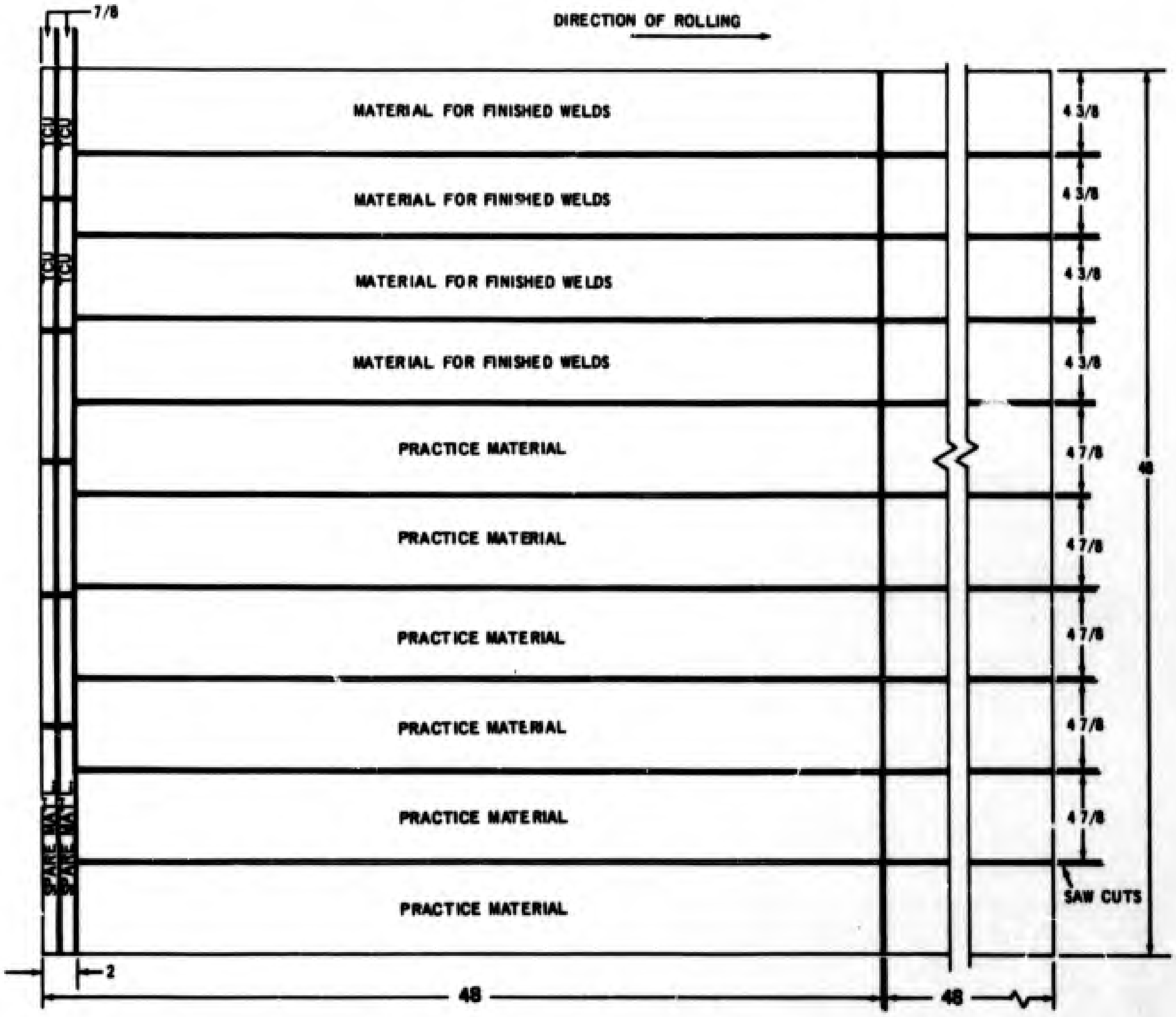


FIGURE 12. TYPICAL SECTIONING DIAGRAM FOR SHEET

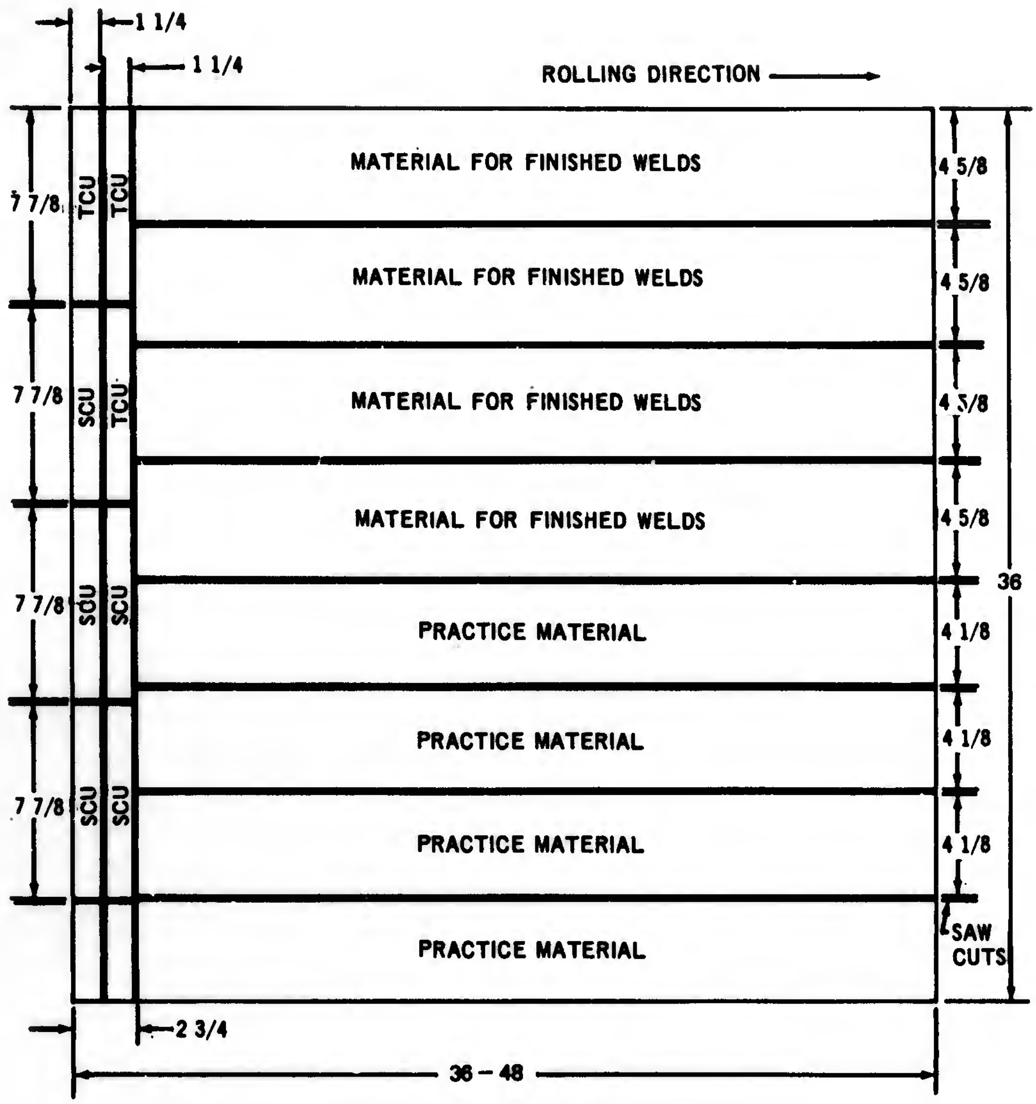


FIGURE 13. TYPICAL SECTIONING DIAGRAM FOR PLATE MATERIAL.

All plate panels were also sawed but, unlike the sheet panels which were left in the as-sawed condition, the plate panels were finish-machined to 90° square edges. All panels were made with longitudinal cuts, parallel to the direction of rolling. Within 48 hours prior to welding, all panels were chemically cleaned, as previously discussed.

Immediately prior to welding, all panels were mechanically scraped adjacent to the abutting edge for a width of about 1/4 inch, and then filed on the abutting edge with a vixen file. Operators handled the panels with clean white gloves and exercised care to prevent them from becoming contaminated with dirt, oil, etc.

Welding Techniques and Schedules

All welding was accomplished using the gas tungsten-arc process with straight polarity-direct current (TIG-DCSP), and using helium as the shielding gas. All sheet metal welds were made in one pass, while plate welds were made in two passes, one on each side.

This technique and the parameters for automatic welding of alloy 2219 are shown in Reference 7, and in Table 69.21 of Reference 2. Reference 8 also describes this technique of double-butt welding on thick 5083 aluminum alloy.

Where possible, authoritative sources such as the Welding Handbook, Reference 2, and manufacturer's welding parameters (such as References 9 and 10) were used in welding a particular alloy. Where these were unavailable, or where only limited information was available as to commercial practice, parameters were used such as to produce high-speed welds using a minimum heat input, with narrow beads and deep penetration. Parameters used in the program for all weldings are shown in Table III.

In order to minimize porosity, moisture determinations were obtained of the helium emitted from the nozzle with an Alnor "Dew Pointer" and refinements of the gas system were made so as to obtain a dew point of -45°F or colder at the torch nozzle. Periodic checks were made throughout the welding to ensure that this standard was maintained.

Sheet Welding

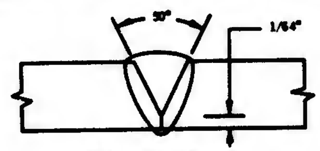
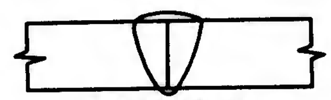
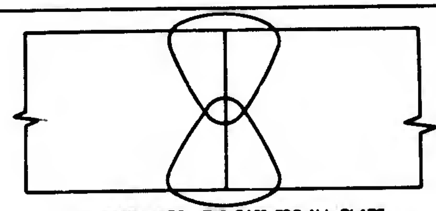
A typical procedure for a given sheet alloy and thickness is to: (1) weld short lengths on practice material, (2) visually examine the bead surface and cross sections for macro defects such as cracks, undercutting, surface holes, or poor appearance, and (3) following visually satisfactory welds on practice material, make complete butt welds, joining two panels for candidate specimen assemblies.

Each specimen assembly was X-rayed and only those were accepted which met the requirements of Class III welds of Reference 11. If a small area of a weld did not meet this standard, this section was appropriately marked on the weld panel and not used for test specimens.

Throughout all sheet metal welding, only X7002 presented difficulties. First, filler wire 5356 was attempted on this alloy with a square butt using similar parameters of current, arc voltage, travel speed, and wire feed that were

TABLE III

TIG-DCSP Parameters for Welding Aluminum Alloy Sheet and Plate

Base Metal		Filler Wire			Tungsten Electrode			Weld Travel	Arc		Shielding Gas		
Alloy	Nominal Thick (Inches)	Alloy	Dia. (In.)	Speed (In./Min.)	Type	Dia. (In.)	TIP	In./Min.	(Amps)	(Volts)	Type	C. F. H.	Joint Design and Pass Sequence
2014 T6	0.080	4043	1/16	65	2% TH	1/8	1/16"	43	125	13	He	75	 SINGLE VEE-ONE PASS FOR X7002-T6 SHEET
X2021 T8E31	0.064	2319	1/16	36	2% TH	1/8	90° Point	43	90	14	He	100	
2024 T81	0.080	4145	1/16	66	2% TH	1/8	90° Point	44	125	13	He	40	
2219 T87	0.125	2319	1/16	81	2% TH	1/8	1/16"	43	210	12.5	He	50	
X7002 T6	0.125	X5180	1/16	75	2% TH	1/8	90° Point	17	140	13	He	40	 SQUARE BUTT-ONE PASS FOR 2014, 2021, 2024, 2219, 7039 & 7106 SHEET
7039 T6	0.125	5039	1/16	22	2% TH	1/8	90° Point	12	165	10	He	125	
7106 T6	0.090	X5180	1/16	66	2% TH	1/8	90° Point	42	150	11	He	40	
2014 T6	1	4043	1/16	15	2% TH	3/16	3/32	4	590	12	He	100	 SQUARE BUTT - TWO PASS FOR ALL PLATE NOTE: 1. PARAMETERS ARE THE SAME FOR EACH PASS. 2. SECOND PASS MADE AFTER PLATE COOLED TO ROOM TEMPERATURE (70°F)
X2021 T8E31	1	2319	1/16	11	2% TH	3/16	3/32	7	590	12	He	100	
2024 T851	1	4145	1/16	11	2% TH	3/16	3/32	6	590	12	He	100	
2219 T87	3/4	2319	1/16	10	2% TH	5/32	5/64	6	385	12	He	125	
7039 T64	1	5039	1/16	10	2% TH	3/16	5/64	4	590	11	He	100	

used successfully on the same thickness of 2219. It was found that only a few amperes above a critical current setting caused unsatisfactory surface appearance of the weld bead. Below this critical setting, insufficient penetration was obtained accompanied by longitudinal cracking. The unsatisfactory appearance, referred to above, consisted of a continuous striated pattern having transverse crevices a few thousandths of an inch deep, spaced about 1/64 inch apart. Subsequently, the manufacturer recommended a change from 5356 to X5180 filler wire for welding X7002. Using this filler, and various settings with a square butt, both with zero and 0.035-inch root openings, satisfactory welds could not be obtained. Various combinations of weld settings could not consistently eliminate the presence of both longitudinal and transverse cracking, particularly at the beginning of the weld. Finally, use of a single vee joint design and a comparatively slow weld travel speed of 17 inches per minute yielded satisfactory welds.

The only other sheet metal welding accomplished at a comparatively slow weld travel speed was on 1/8-inch-thick alloy 7039, which was welded at 12 inches per minute in accordance with the alloy manufacturer's recommendations.

Plate Welding

Generally, welding of the 3/4- and 1-inch-thick plates did not present major difficulties. The typical procedure used comprised the following steps: (1) weld the two passes on a practice panel; (2) make macro sections near the beginning and at the end of the weld; (3) adjust the parameters to yield penetration of 1/8-inch minimum overlap of the two passes and also to give satisfactory weld surface appearance, and (4) weld additional plates using the established parameters. Before machining the test specimens, the latter plates were checked for sufficient overlap of the two passes, as described above, and X-rayed to ensure absence of defects such as cracks and excessive porosity. In every case, welding of the second pass was done only after the plate had cooled to approximately room temperature.

The technique for plate welding outlined above was satisfactory except for the welding of some of the 7039 alloy plate. For some undetermined reason a variation occurred in heat input between the start and finish of the weld such that at several areas along the welded joint of this alloy there was no overlap of the two passes. This lack of penetration varied as much as 1/8 inch between the passes. The fact that such an unpenetrated or unfused portion of the butt joint between the two passes cannot be detected by ordinary nondestructive methods, as pointed out by References 7, 12, and 13, was confirmed during the activities of this program. Those test specimens of alloy 7039 which did not show a distinct overlap of the passes upon macro etching cross sections were discarded.

Radiographic Equipment and Schedules

All X-rays of sheet and plate stock were made with a Sperry SPX-160E-8C machine with a beryllium window 0.092-inch thick, and with a 1.5 mm focal spot size. Depending upon the thickness, the following schedule was used: 50 to 100 kilovolts, 10 to 20 milliampere-minutes, at a source-to-film distance of 24 inches. Gevaert D-4 film was used with a developing time of 6 minutes at 70°F.

FATIGUE PRECRACKING

Fatigue cracking was accomplished in flexure fatigue on a Krause fatigue machine with 5000-pound capacity. Sheet specimens were precracked at 1000 CPM. The machine was modified with a variable speed drive during the program enabling speeds from 80 to 1800 CPM for precracking the plate specimens. Load was applied by bending the specimen over a steel toe placed immediately below the notch. The toe was surfaced with fiber board to protect the bottom edge of the aluminum specimen from indentation and fretting during cracking. Crack initiation and propagation was observed at about 20X with a macroscope using a Strobe light during running and constant light with the specimen stopped for final crack length (sheet) or depth (plate) measurement.

Selection of location for the fatigue crack was based on the most SCC-susceptible zone as determined during unnotched specimen stress-corrosion tests. The edge of the weld bead was found most susceptible to SCC during initial SCC tests of both sheet and plate so the fatigue cracks were placed accordingly.

Fatigue cracking of sheet specimens incurred considerable difficulty in (1) controlling and predicting fatigue crack length and depth, (2) preventing secondary cracks from forming in line with the main crack along the edge of the weld bead, and (3) distinguishing the fatigue crack as if initiated and propagated.

The difficulties were attributed, in general, to weld reinforcement which resisted bending of the specimen over the toe and prevented concentration of the stress at a single point on specimen centerline. Varying degree of weld reinforcement from alloy to alloy and specimen to specimen contributed to the problem. The edge of the weld bead also served as a line of stress concentration and macroscopic observations during fatigue cracking revealed irregularities in the fusion line and surface microporosity were fatigue crack origins as well as the elox notch, thus resulting in multiple cracks in line with the main fatigue crack or a line origin rather than a point origin.

Shallow depth of fatigue crack was found with several initial sheet alloy-weld tempers, not extending beyond the depth of the elox notch, and a few specimens were subsequently precracked without the elox notch. The tendency for multiple cracks increased, however, so use of the elox was continued.

Distinguishing the fatigue crack during cracking was difficult because of the heterogeneous surface texture at the edge of the weld bead.

The final technique used to minimize the above cracking problems with the sheet alloys, but not entirely successful, was to fine hand-sand the edge of the weld bead in the area to be fatigue cracked to remove macroscopic irregularities and give a smooth surface for viewing the crack.

Sheet specimens exhibiting multiple, long ($>0.5x$ width) or deep ($>0.5x$ thickness) cracks were not used for stress-corrosion tests when this could be determined during fatigue cracking and additional specimens were fabricated. However, because of viewing difficulties and inconsistent a/2C ratios, several specimens were found with these deviations after test as shown in the tables of data. The majority of surface crack lengths were held to <0.3x width per ASTM recommendations (Reference 14).

The sequence of precracking specimens consisted of first precracking tension test specimens from the weld-temper set and tension testing to determine residual strengths and actual precrack length and depth (sheet) and depth (plate). Fatigue cracks were developed near the maximum size recommended by ASTM to promote net section residual strengths < 0.8 x yield strength. Following cracking of tension specimens the remaining specimens of the test set were fatigue cracked accordingly. This approach was satisfactory with the edge notch plate specimens which exhibited a relatively flat crack tip (see fracture surfaces in Section VIII). The fatigue cracks for sheet specimens, however, were inconsistent and considerable variation resulted in crack lengths and depths (see fracture surfaces in Section VII). The heterogeneous nature of the fusion line was also considered a contributor to inconsistencies.

Precracking loads were set and monitored as deflection at specimen end and bending stresses were calculated from conventional beam formula. Sheet specimens were precracked with stresses from 0.50 to 0.65 yield strength except for 2219-T87 and X7002-T6 series and as-welded temper of X2021-T8E31, 2014-T6 and 7106-T6 which were precracked at stresses near the yield strength to develop crack length within a reasonable length of time (50,000 to 100,000 cycles). Calculated stresses at the base of the notch of plate specimens were also at yield stress levels.

TESTING

Mechanical Properties

Tension tests were conducted on appropriate specimens to: (1) qualify the materials; (2) determine sustained load levels for SCC tests; and (3) determine residual strength and elongation after SCC testing. All tension tests were conducted at room temperature using a loading rate of 95 KSI/minute. Gage lengths for the various specimens were as indicated on the specimen drawings. Sheet specimens were pin loaded for tension testing. Plate specimens were loaded with threaded fittings held by spherical seats. All yield strengths were calculated using 0.2-percent offset.

Universal testing machines used for tension testing were a 60,000-pound Baldwin, hydraulic, and a 30,000-pound Riehle, screw. Extensometers were Class B2, per ASTM E83-64T.

Sustained Loading SCC Specimens

Sustained loading of plate specimens for environmental exposure was accomplished in three- and six-spring constant-load aluminum stress corrosion jigs capable of applying loads up to 6000 and 12,000 pounds, respectively (Figure 14). Sustained loading of sheet specimens was accomplished in two- and four-spring steel jigs capable of applying loads up to 4000 and 8000 pounds, respectively (Figure 15). Calibration testing using electrical strain-gaged load cells in place of specimens indicated accuracy of applied

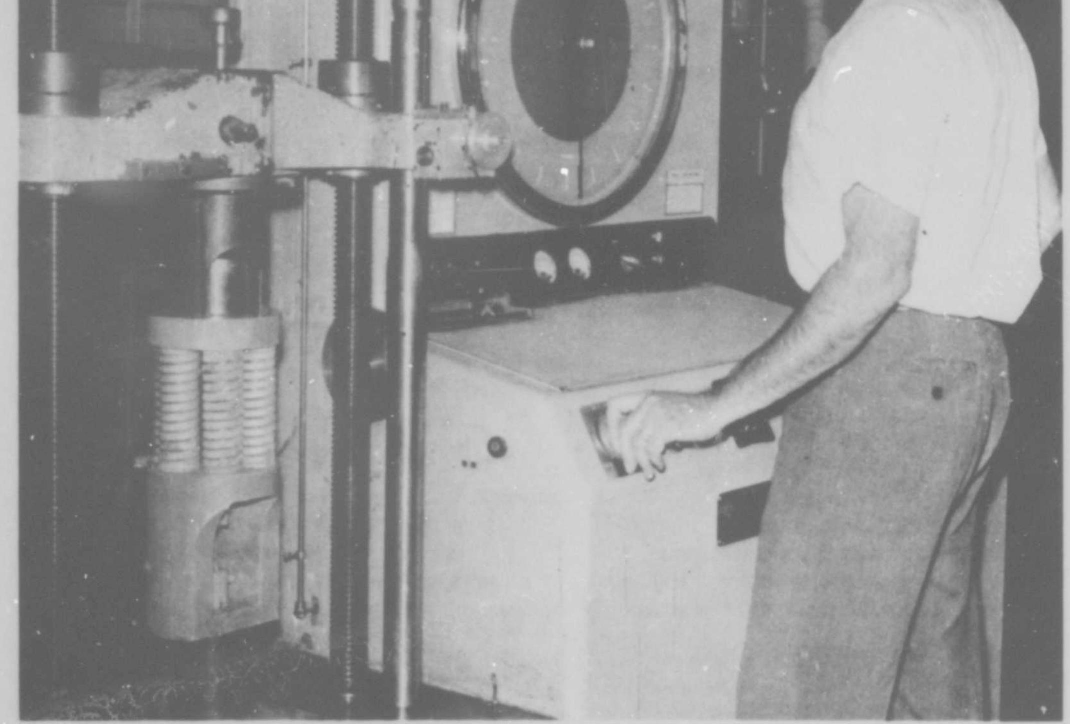


FIGURE 14. VIEW OF RIEHLE TEST MACHINE LOADING A SIX SPRING STRESS CORROSION JIG.

loads to be within 2 percent for the aluminum jigs and within 3 percent for the steel jigs.

For the threaded plate specimens, the spring load was transmitted through lubricated spherical seats at both specimen attach ends of the jigs to minimize bending. Sheet specimens were pin loaded.

After sustained loading specimens, each jig was coated with a warm dip polyethylene wax (Finch Paint Co. Coating CA-79) to prevent any galvanic action between specimen and jig--the specimen being protected during dipping. The machined edges of the SCC specimens were then coated with chem mill maskant (Organoceram 1-2020) so that only the mill surface was exposed to the alternate immersion environment.

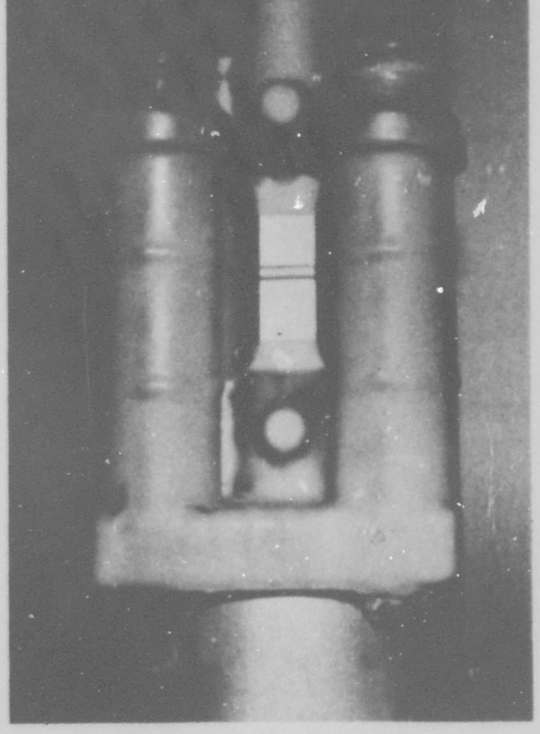


FIGURE 15. TYPICAL FOUR-SPRING LOADING JIG FOR STRESS CORROSION TESTING

Alternate Immersion

Alternate immersion testing was performed in the "dunker" which consists of a bottom chamber for the storage of the fluid (synthetic sea water), a pump, and an upper test chamber. During test, the fluid is pumped into the upper chamber until an overflow pipe is reached which allows excess fluid to drain back into the lower storage chamber. Pumping is continued to immerse the gage length of the test specimen for 10 minutes. During this 10-minute immersion cycle, a second pump is also activated and the fluid filtered to minimize contamination. At the completion of the 10-minute immersion cycle, the pumps shut off and the fluid in the upper chamber drains through a restricted flow port in the bottom of the upper chamber back into the lower storage chamber. The specimens are then exposed to air for 50 minutes, after which the cycle repeats. This cycle continues for the duration of the 500-hour test by means of an automatic timer. Air temperature was 75, ±20°F and fluid temperature was controlled at 80° ±5°F. Humidity within the room varied from 40 to 50 percent. The fluid in the tank was substitute ocean water (without heavy metals) per ASTM No. D1141-52 and the pH was controlled between 7.8 to 8.2. Specific gravity and pH were checked once a week but very few adjustments were required.

Stress-corrosion jigs were hung vertically in the upper chamber from insulated cross-bars to prevent galvanic action between specimens and between specimens and the tank structure.

Specimens were inspected a minimum of once, and generally twice a day, for failure.

Stress-Corrosion Testing

Stress-corrosion tests were conducted using both step-load and constant-load techniques, the step-load procedure being used to determine the approximate SCC threshold, followed by constant-load tests to establish the threshold.

In the step-load tests, the first specimen of each test set was stressed at 20 percent of the yield strength of the corresponding tensile control specimen. If failure did not occur in 2 to 4 days alternate immersion, the specimen load was increased in 5- to 10-percent increments until failure, or 75-percent yield strength was reached (approximately 500 hours exposure). Once failure was reached, three specimens were run under constant load in the vicinity of the stress which caused failure to establish the 500-hour threshold level. If no failure occurred, one specimen was run at 75 percent yield strength to confirm that the threshold was above 75 percent.

Precracked specimens were tested in a similar manner with sustained stresses being based on net section notch strength. Consideration was given to sustained loading of precracked specimens by stress intensity levels. However, the unpredictability of the fatigue crack geometry of the sheet specimens, and multi-directionality of the propagating stress corrosion crack observed with initial specimens, indicated considerable error in this approach so stress intensity values were calculated for specimens selected after conclusion of the test.

Net section stress for sheet specimens was based on gross area (specimen width times thickness) minus fatigue crack area, the crack area considered one-half the area of an ellipse equal to 0.7854 × 2c × a where 2c = length of crack, and a = depth of crack. Net section stress for plate specimens was based on gross area (specimen width times thickness) minus the rectangular plane of the notch plus precrack.

During step-load tests, specimens were manually removed from the alternate immersion tank and X-rayed to determine if cracking had initiated or propagated. The stress was then increased to the next step and the specimen returned to the tank for an additional 2 to 4 days alternate immersion. Because of the number of specimens being exposed in alternate immersion concurrently, air exposure during handling between steps averaged 7 hours. Constant-load precracked specimens were also X-rayed after 0 and 250 hours exposure to determine crack lengths.

RADIOGRAPHIC TECHNIQUES

Prior to each X-ray examination, specimen edges were masked with lead foil tape to prevent scatter radiation or burnout effect. The notched plate specimens were also masked with a lead slug in the notch.

The X-ray beam was 90° to the surface of the sheet specimen viewing the length of weld and fatigue crack. The X-ray beam for the plate specimens was 90° to the plate thickness viewing the depth of weld bead and fatigue crack.

Sheet specimen surface damage from corrosion was visible using this technique. The surface fatigue crack, however, was difficult to read accurately, was generally shorter than actual and, in some cases, shallow fatigue cracks could not be seen. The shorter X-ray crack length would be expected because of shallow depth at the fatigue crack ends. However, there was considerable spread between X-ray crack length and actual crack length which prevented correlation from this standpoint. This was attributed to varying degrees of tightness of the surface fatigue crack which minimized contrasting density between crack plane and sound metal. This was verified during step-load tests when certain cracks yawed, resulting in a gradual increase in X-ray crack length with increasing load, but remaining shorter than actual fatigue crack length and with no evidence of environmental damage noted on the fracture face when tension-tested and examined macroscopically.

Monitoring of crack growth in the sheet specimen was further limited in that environmental crack propagation did not remain in the plane of the precrack, which would have increased contrast in density but, instead, moved into the weld bead or followed the fusion line forming a curvilinear surface.

The X-ray data from sheet alloy tests were considered as evidence of environmental damage when: (1) sudden, significant increases in X-ray crack lengths were noted, (2) X-ray crack length exceeded actual fatigue crack length, and (3) environmental damage was evident on fracture surfaces after exposure.

Data from X-rays of sheet SCC specimens are included in the SCC data tables for illustration and should be considered in view of the above limitations.

The above difficulties were not experienced during inspection of the edge-notched plate specimens and initial X-ray crack depth measured corresponded to the fatigue crack depth. With the plate specimen the X-ray viewed a "through-the-thickness" crack at the edge of the specimen when underload yawned and gave measurable contrast in density on the film.

The X-ray equipment was a Machlett AEG-50-A. Focal spot size was 1.5 mm with a 1.0-mm-thick beryllium window. Kilovoltage was 40 and milliamp minutes varied from 30 to 90, depending upon material and thickness. Distance from source to film was 18 inches for plate and 24 inches for sheet. The film used was type D4-M-510-B with 6-minute developing time at 70°F. Crack lengths, designated "X-ray Crack Length," were measured on X-ray film using a comparator with 0.005 inch the smallest division.

MICROSCOPY

Fracture surfaces were examined visually and with a Bausch and Lomb stereozoom microscope at 10 to 45X after testing to determine characteristics of corrosion, stress corrosion, and mechanical failure relative to fracture surface texture and weld zone. Specimen surfaces were examined for degree and location of corrosion attack. Fatigue crack lengths and depths were also measured after test for correlation with prediction from surface measurement and X-ray measurements and recalculation of sustained stress as required.

Final corrosion and stress-corrosion crack lengths and depths were measured when they could be accurately presented as such. However, many specimens exhibited steps, angles, curvilinear surfaces, several planes and vague terminations in the crack extension area, and could not be realistically measured as discussed in the text for the various alloys.

Subsequent to fracture examination, representative specimens were selected and sectioned for metallographic study of the various fracture zones and origins of failure as characterized by cracking (intergranular or transgranular), corrosion (intergranular or pitting), microstructure (weld bead, fusion line, heat-affected zone, parent metal), and direction of damage progression.

Emphasis was placed on determination of mode of failure of environmental test specimens; that is, whether corrosion or stress corrosion. Corrosion was considered the primary mode if the microstructure exhibited random intergranular attack with grains surrounded, or pitting followed by transgranular cracking. Intergranular cracks with rounded tips were also considered corrosion oriented. Sharp tip, intergranular cracks with little tendency to surround grains and with greater tendency towards linearity (generally 45° to 90° to the sustained load) were considered stress-corrosion cracks.

Narrow, sharp tip cracks in short transverse grain direction were also considered SCC because they formed in a stress field (beyond the fatigue crack tip in the case of notched specimens rather than along the fatigue crack) and, in a given area, were few in number. The converse of the above would be expected of exfoliation-type corrosion.

Microscopic studies were made with a Bausch and Lomb metallurgical bench microscope, 50 to 500X, and Balphot metallograph, 25 to 1200X.

SECTION VI

RESULTS OF MECHANICAL PROPERTY TESTS

The data from mechanical property tests are presented in Tables A-1 through A-5 in the Appendix and are summarized and discussed in this section.

Mechanical properties are graphically presented for the sheet alloy-weld-tempers in Figure 16 and for the plate alloy-weld-tempers in Figure 17. These data are further shown as "efficiencies" in Tables IV and V.

SHEET

The sheet alloys are ranked as follows, based on processing history and yield strengths, 2-inch gage length (net section notch strengths are shown in parentheses).

Basic — Unwelded

Material	Strength (ksi)
X2021-T8E31	66.2
2014-T6	63.2
2024-T81	62.8
X7002-T6	57.5
7106-T6	56.3
2219-T87	54.1
7039-T64	51.3

As-Welded (W)

Material	Strength (ksi)	
	Unnotched	Notched (net)
2024-T81	53.6	(42.3)
2014-T6	43.8	(45.9)
7106-T6	42.3	(57.0)
X7002-T6	38.7	(49.6)
X2021-T8E31	33.5	(37.7)
7039-T64	33.2	(54.0)
2219-T87	33.1	(43.5)

Weld + Age (A)

Material	Strength (ksi)	
2024-T81	61.0	(25.5)
2014-T6	53.5	(54.0)
7106-T6	53.4	(54.1)
X2021-T8E31	50.3	(39.2)
X7002-T6	49.4	(52.1)
7039-T64	44.6	(51.8)
2219-T87	43.5	(46.3)

Weld + STA (S)

Material	Strength (ksi) Unnotched	Notched (net)
X2021-T8E31	66.4	(50.1)
7106-T6	60.4	(66.9)
2014-T6	57.5	(57.9)
2024-T81	55.5	(51.7)
7039-T64	52.9	(64.2)
2219-T87	52.7	(58.9)
X7002-T6	52.3	(55.9)

For the sheet alloys welded in fabrication of components, 2024-T81, 2014-T6, and 7106-T6 have the highest strength for as-welded and weld plus age tempers and X2021-T8E31, 7106-T6, and 2014-T6 in weld plus STA temper. Alloy 2024-T81, however, has limited weldability and, in weld plus age temper, has 0.4-percent elongation and is notch sensitive.

Mechanical properties of all specimens in the as-welded condition were lower than basic unnotched temper; the maximum effect of welding being upon the ductility with "elongation efficiencies" ranging from 12.7 percent to 4.4 percent. Post-weld artificial age in all cases improved the ultimate strength efficiency by about 10 percent; improved the yield strength by about 15 percent, but, generally, decreased the already depressed value of elongation efficiency except for alloys 7039 and 7106 where elongation efficiency improved. Post-weld solution heat treat and artificial age markedly improved all properties, especially ductility. Two sets of alloy specimens exceeded the original parent metal mechanical properties, 2219 and 7039; and alloys 2021, 7002, and 7106 approximated the original parent metal properties. Alloy 2024 exhibited the lowest efficiencies of the entire group in the solution heat treated and artificially aged condition, but actual values of the ultimate and yield strengths were high.

Tension fractures of the sheet specimens were predominately in the weld zone with the exception of 2219-T87 weld plus STA, 7039-T64 weld plus STA, and 7106-T6 weld plus STA which failed through the parent metal.

Notch strengths were determined for welded sheet in the as-welded and post-weld heat treat conditions preparatory to notch specimen SCC testing. Sheet specimens were surface crack specimens with a fatigue crack at the edge of the weld bead.

Selection of location for the fatigue crack was based on the most SCC susceptible zone as determined during unnotched specimen stress corrosion tests. The edge of the weld bead was found most susceptible to SCC during initial SCC tests so the fatigue cracks were placed accordingly.

The ratio of net section notch strength to 0.2-percent offset yield strength for the sheet specimens was near to or greater than 1.00 for all alloys and tempers except for X2021-T8E31 weld plus age and weld plus solution heat treat plus age (0.75 to 0.80) and 2024-T81 as-welded (0.76 to 0.82), and weld plus age (0.40 to 0.44). Fracture surfaces beyond the fatigue

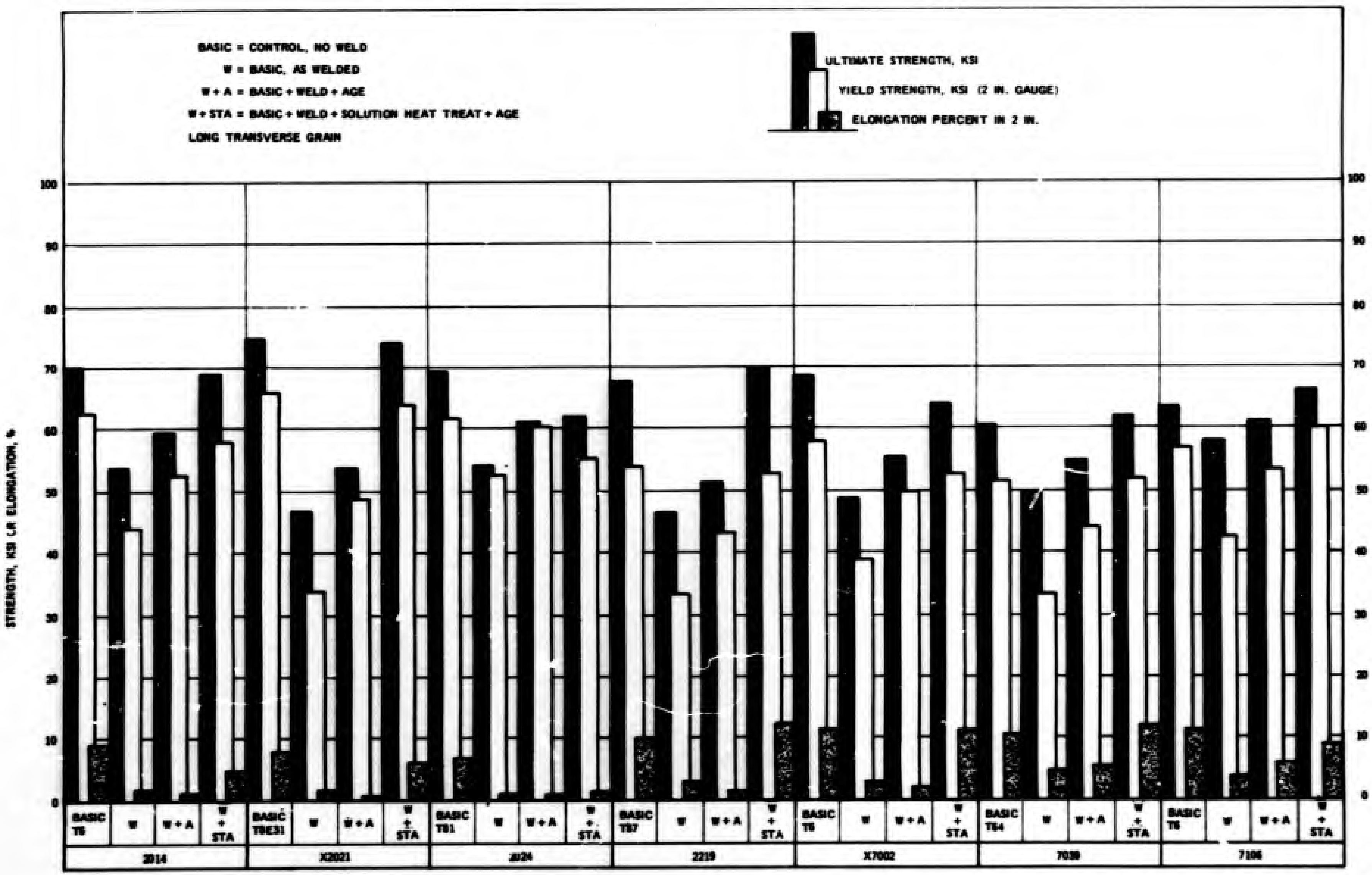


FIGURE 16. EFFECT OF WELDING AND POST WELD HEAT TREATMENT ON TENSILE PROPERTIES OF ALUMINUM SHEET ALLOYS

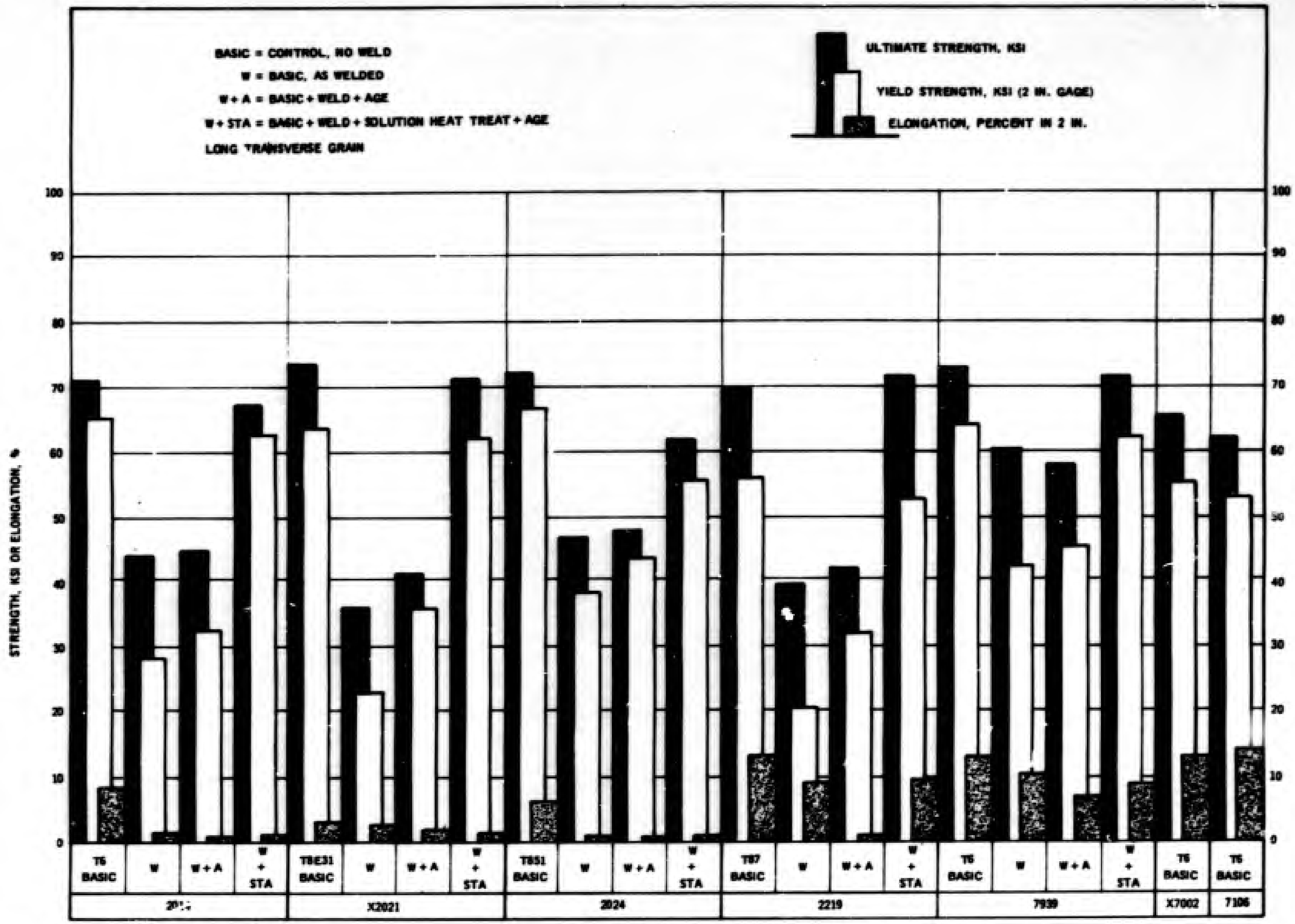


FIGURE 17. EFFECT OF WELDING AND POST WELD HEAT TREATMENT ON TENSILE PROPERTIES OF ALUMINUM PLATE ALLOYS

TABLE IV

Sheet Specimens (Unnotched)
Tension Test Data and Weld Joint Efficiencies[1]
(Average Values - Long Transverse Grain)

BASIC ALLOY	TEMPER	ULTIMATE STRENGTH		YIELD STRENGTH		ELONGATION		FRACTURE[2] ZONE
		Average Value KSI	Average Efficiency[1] %	Average Value KSI - (2 in. Gauge)	Average Efficiency[1] %	Average Value % - 2 in.	Average Efficiency[1] %	
2014	Basic Unwelded	70.32	-	63.19	-	8.7	-	
T6	As Welded	53.85	76.6	43.83	69.3	1.1	12.7	EWB
(0.080 in.)	Weld + Age	59.59	85.0	53.47	84.5	0.7	8.0	EWB
	Weld + STA	67.99	96.7	57.50	91.0	4.9	56.3	EWB
X2021	Basic Unwelded	76.14	-	66.23	-	8.1	-	
T8E31	As Welded	46.95	61.6	33.46	50.6	2.0	24.7	EWB
(0.064 in.)	Weld + Age	54.09	71.1	50.30	75.9	0.7	8.6	EWB
	Weld + STA	74.36	97.5	66.42	100.0	5.9	72.9	EWB/PM
2024	Basic Unwelded	69.74	-	62.80	-	7.0	-	
T81	As Welded	54.12	77.6	53.59	85.5	0.9	12.9	WB
(0.080 in.)	Weld + Age	61.92	88.6	61.03	97.4	0.4	5.7	WB
	Weld + STA	62.22	89.2	55.46	88.1	1.4	20.0	WB
2219	Basic Unwelded	67.66	-	54.14	-	9.5	-	
T87	As Welded	46.85	69.1	33.14	61.2	2.6	27.4	EWB
(0.125 in.)	Weld + Age	51.64	76.4	43.50	80.5	1.7	17.9	EWB
	Weld + STA	69.92	103.0	52.65	97.5	12.2	128.2	PM
X7002	Basic Unwelded	68.34	-	57.52	-	11.6	-	
T6	As Welded	48.81	71.5	38.73	67.2	2.5	21.6	EWB
(0.125 in.)	Weld + Age	54.92	80.5	49.37	85.9	1.2	10.3	EWB
	Weld + STA	64.72	94.8	52.34	91.0	10.5	90.5	EWB/PM
7039	Basic Unwelded	60.04	-	51.32	-	10.0	-	
T64	As Welded	50.45	84.0	33.20	64.7	4.4	44.0	EWB/WB
(0.125 in.)	Weld + Age	54.94	91.5	44.59	87.0	4.9	49.0	EWB/WB
	Weld + STA	62.43	103.9	52.87	103.0	11.6	116.0	PM
7106	Basic Unwelded	63.22	-	56.26	-	11.1	-	
T6	As Welded	57.82	91.5	42.25	75.1	3.8	34.2	EWB
(0.090 in.)	Weld + Age	61.41	97.0	53.39	94.9	5.4	48.6	EWB
	Weld + STA	66.38	104.8	60.44	107.1	8.5	76.6	PM

[1] Efficiency Defined as: $\frac{\text{Value of Welded Sheet}}{\text{Value of Unwelded Sheet}} \times 100$

[2] WB = Weld Bead
EWB = Edge of Weld Bead
PM = Parent Metal

TABLE V

Plate Specimens (Unnotched)
Tension Test Data and Weld Joint Efficiencies[1]
(Average Values - Long Transverse Grain)

BASIC ALLOY	TEMPER	ULTIMATE STRENGTH Average Value KSI	ULTIMATE STRENGTH Average Efficiency[1] %	YIELD STRENGTH Average Value KSI (2 in. Gauge)	YIELD STRENGTH Average Efficiency[1] %	ELONGATION Average Value % - 2 in.	ELONGATION Average Efficiency[1] %	FRACTURE[2] ZONE
2014 T6 (1 in.)	Basic Unwelded	71.28	-	65.11	-	8.7	-	
	As Welded	44.69	62.7	28.52	43.7	1.7	19.5	WB
	Weld + Age	45.09	62.4	32.31	49.6	1.1	12.7	WB
	Weld + STA	67.45	94.5	63.20	97.0	1.3	14.9	EWB
X2021 T8E31 (1 in.)	Basic Unwelded	73.27	-	63.76	-	3.7	-	
	As Welded	35.98	49.1	23.27	36.5	2.8	75.6	WB
	Weld + Age	41.35	56.4	35.93	56.4	2.4	64.9	EWB/WB
	Weld + STA	71.49	97.5	62.37	97.6	1.8	48.6	EWB
2024 T851 (1 in.)	Basic Unwelded	72.37	-	66.91	-	6.5	-	
	As Welded	47.78	66.0	38.23	57.1	0.8	12.3	EWB
	Weld + Age	48.30	66.7	44.17	66.1	0.6	9.2	EWB
	Weld + STA	62.34	86.1	56.09	84.0	0.9	13.8	EWB
2219 T87 (3/4 in.)	Basic Unwelded	70.08	-	56.68	-	12.5	-	
	As Welded	38.79	55.4	20.63	36.4	9.2	73.6	EWB/WB
	Weld + Age	42.22	60.4	31.85	56.1	1.2	9.6	EWB/WB
	Weld + STA	61.80	88.2	42.83	75.5	9.5	76.0	PM
7039 T64 (1 in.)	Basic Unwelded	63.11	-	53.95	-	13.5	-	
	As Welded	49.85	79.0	31.90	59.1	10.4	77.0	PM
	Weld + Age	47.83	75.7	35.01	65.0	7.3	54.1	PM
	Weld + STA	61.53	97.6	52.18	96.7	9.0	66.6	WB
X7002 T6 (3/4 in.)	Basic Unwelded	64.90	-	55.15	-	13.2	-	
7106 T6 (1 in.)	Basic Unwelded	62.22	-	53.94	-	14.4	-	

[1] Efficiency Defined as $\frac{\text{Value of Welded Plate}}{\text{Value of Unwelded Plate}} \times 100$

[2] WB = Weld Bead
EWB = Edge of Weld Bead
PM = Parent Metal

precrack were predominately shear lip for all specimens, indicating a plane stress condition, except for 2014-T6 as-welded (33 to 40 percent shear lip), weld plus age (25 to 30 percent), 2024-T81 as-welded (5 to 15 percent), and weld plus age (5 to 15 percent), as measured (1) from the tip of the fatigue crack to the unnotched surface, and (2) through the thickness at a point midway between fatigue crack end and specimen edge.

PLATE

Ranking of the plate-weld-temper data in a manner similar to the sheet gives:

Basic — Unwelded

Material	Strength (ksi)
2024-T851	66.9
2014-T6	65.1
X2021-T8E31	63.8
2219-T87	56.7
X7002-T6	55.2
7106-T6	53.9
7039-T64	54.0

As-Welded

Material	Strength (ksi)	
2024-T851	38.2	(25.0)
7039-T64	31.9	(44.1)
2014-T6	28.5	(16.7)
X2021-T8E31	23.3	(27.4)
2219-T87	20.6	(30.3)

Weld + Age

Material	Strength (ksi)	
2024-T851	44.2	(28.3)
X2021-T8E31	35.9	(20.1)
7039-T64	35.0	(40.1)
2014-T6	32.3	(24.8)
2219-T87	31.9	(36.7)

Weld + STA

Material	Strength (ksi)	
2014-T6	63.2	(27.8)
X2021-T8E31	62.4	(31.1)
2024-T851	56.1	(28.3)
7039-T64	52.2	(50.3)
2219-T87	42.8	(49.6)

For plate alloys welded in fabrication, 2024-T851, 7039-T64, and 2014-T6 have the highest strengths in the as-welded temper, 2024-T851, X2021-T8E31, and 7039-T64 in the weld plus age temper, and 2014-T6, X2021-T8E31 and 2024-T851 in the weld plus STA temper. Strengths increase with post-weld heat treatment. Alloy 2024-T85, however, has limited weldability and low elongation in all three weld tempers (less than 1 percent). Highest notch toughness is exhibited by 7079-T64 in all three weld tempers.

The mechanical properties of the plate specimens generally responded to welding and post-weld heat treat in a manner similar to the sheet alloys. When the as-welded plate specimens were artificially aged, there was an increase in ultimate and yield strength values over those of the as-welded specimens, but with a decrease in ductility. When the as-welded plate specimens were solution heat treated and artificially aged, there was a further increase in ultimate and yield strength, with also an increase in elongation, except for alloy 2021 which exhibited a decrease in elongation in the latter condition.

Alloys 2014, 2021, and 7039 exhibited the highest ultimate strength and yield strength joint efficiencies in the post-weld solution heat treated and artificially aged condition, approaching original parent metal values, but actual values of elongation in this condition are quite low except for alloys 2219 and 7039.

It was noted that X2021-T8E31 basic, unwelded, had the lowest percentage of elongation of the basic temper alloys (3.7 percent).

Tension fractures of the plate specimens were predominately in the weld zone. Only 2219-T87 weld plus STA and 7039-T64 as-welded, and weld plus age failed through the parent metal.

Notch strengths were determined for welded plate in the as-welded and post-weld heat treat conditions preparatory to notch specimen SCC testing. These specimens were single-edge notch-type with the fatigue crack at the edge of the weld bead, which was indicated to be the SCC-susceptible zone.

The ratio of net section notch strength to 0.2-percent offset yield strength for the plate specimens was near or greater than 1.00 for the three tempers of 7039-T64 and 2219-T87. One specimen of X2021-T8E31 weld plus solution heat treat plus age temper, had a ratio of 0.98 but the other specimen was 0.43. All other specimen ratios were near or below 0.75. Fracture surfaces at a point midway between the tip of the fatigue crack and the unnotched edge were predominately shear lip for all alloys and tempers, indicating plane stress, except for 2014-T6 as-welded and weld plus age tempers and 2024-T851 as-welded and weld plus age tempers, these being predominately flat and indicating plane strain.

SECTION VII

RESULTS OF SCC TESTS – SHEET

Stress corrosion threshold stress for each of the alloy-weld-tempers was first approximated by step-load alternate immersion test and then established using constant-load tests in the vicinity of the step-load stress causing SCC failure. A relatively small number of specimens, two to four, was used to define the SCC threshold for each alloy-weld-temper. Due to scatter of data common to SCC testing, additional testing is desirable before thresholds determined herein can be considered working stress levels. Basic test data, from which results and discussion are drawn in this section, are presented in Appendix A, Tables A-6 through A-17, and are summarized first and then discussed in this section for the sheet alloys.

SUMMARY

Comparison of Step-Load and Constant-Load Data

Comparison of step-load and constant-load threshold data revealed that step-load failure did not consistently predict constant-load threshold but did serve to limit the range of stress levels requiring constant-load testing to define the SCC threshold. Step-load failures occurred both above and below constant-load threshold. Greatest divergence of threshold data was evident when the step-load specimens failed below constant-load threshold. This much larger divergence indicates a real stress corrosion accelerating effect for some alloys when upwards-step-loaded, as compared to constant load testing. In step load testing, factors considered contributing to accelerated stress corrosion are: (1) prolonged air exposure (up to seven hours between steps) which may embrittle and/or shrink passive surface films at crack tip; (2) increased load step which may mechanically rupture surface films and expose fresh metal to corroding action; and (3) the necessary handling (and jarring) during x-ray and step-loading procedures may rupture surface films or mechanically propagate the crack. It was not within the scope of this program to investigate further, but future investigations along these lines may explain some aircraft service failures that occur below the apparent SCC threshold defined by constant-load alternate immersion tests.

Stress -Corrosion Thresholds

The SCC thresholds determined on this program for the various sheet alloy-weld-tempers, notched and unnotched, are graphically presented in Figure 18, and represent the mid-stress level between minimum stress for SCC failure and maximum stress for no SCC failure from constant-load alternate immersion testing. Step-load failure is used when below constant-load threshold and is indicated by "S."

None of the seven alloys was susceptible to SCC in their basic unwelded condition up to 75-percent yield strength.

Alloy 2014-T6 was susceptible in all three weld tempers with slight decrease in SCC threshold resulting from post-weld heat treat.

Alloy X2021-T8E31 as-welded is the most SCC-susceptible alloy-weld-temper with a threshold of 10.5 ksi, but either post-weld aging or post-weld solution heat treat plus aging will restore high resistance.

Alloy 2024-T81 was susceptible only in the as-welded condition with no SCC noted with post-weld heat treatment. Weld plus age temper exhibited highest unnotched SCC threshold comparable to basic unwelded temper but low notch strength reduces its usefulness in this temper. Post-weld solution heat treat and age gave highest combination of strength and threshold values for 2024-T81 weld tempers.

Alloy 2219-T87 was susceptible only in the weld plus STA (solution heat treat plus age) condition. Highest SCC threshold values for the weld tempers were indicated with the weld plus age temper.

Alloys 7002-T6 and 7039-T64 were susceptible to SCC only in weld plus age and weld plus STA tempers. Highest thresholds, however, were with the weld plus STA temper which had the highest tensile properties of the weld-tempers.

Alloy 7106-T6 was susceptible in all three weld tempers. Highest thresholds for notched and unnotched condition were indicated by the as-welded condition. Notching reduced the SCC threshold by more than 50 percent for weld plus age and weld plus STA tempers.

From Figure 18 the sheet alloys are ranked by unnotched SCC threshold according to processing history as follows (net section notched threshold in parentheses):

Basic — Unwelded

Material	Threshold (ksi)
X2021-T8E31	>49.7
2014-T6	>47.4
2024-T81	>47.1
X7002-T6	>43.1
7106-T6	>42.2
2219-T87	>40.6
7039-T64	>38.5

As-Welded

Material	Threshold (ksi)	
	Unnotched	Notched (net)
2024-T81	34.8	(23.6)
7106-T6	>31.7	(29.8)
2014-T6	30.7	(19.4)
X7002-T6	>29.1	(>38.2)
7039-T64	>24.9	(>41.0)
2219-T87	>24.9	(>29.6)
X2021-T8E31	10.6	(11.8)

Weld + Age

Material	Threshold (ksi)	
	Unnotched	Notched (net)
2024-T81	>45.8	(>19.3)
X2021-T8E31	>37.7	(>29.3)
X7002-T6	>37.0	(30.6)
7039-T64	>33.4	(37.0)
2219-T87	>32.6	(>33.9)
2014-T6	29.4	(20.7)
7106-T6	25.4	(12.0)

Weld + STA

Material	Threshold (ksi)	
X2021-T8E31	>49.8	(>39.1)
2024-T81	>41.6	(>37.5)
X7002-T6	>39.3	(40.5)
7106-T6	37.8	(13.4)
7039-T64	37.0	(39.1)
2219-T87	29.0	(30.0)
2014-T6	25.9	(15.9)

>= no failure at maximum test level.

Nature of SCC

All but one of the SCC failures originated at the edge of the weld bead regardless of alloy or post-weld heat treatment. The one exception was X2021-T8E31, as-welded, which displayed the origin at, and line of failure through, the cold side of the heat-affected zone. The line of SCC failure for the specimens with SCC origins at the edge of the weld bead and those with fatigue cracks moved out of a plane 90° to sustained load and, in general, followed the fusion line with branches into the weld bead and into the heat-affected zone.

Corrosion

Visual examination of alloy-weld-tempers after 500 hours of alternate immersion revealed severe preferential corrosion at the edge of the weld bead (top of weld pass) for 7002-T6, 7039-T64, and 7106-T6 regardless of post-weld heat treatment and was attributed to a eutectic-type microstructural phase formed during welding. Severe corrosion was also noted in the heat-affected zone of 7002-T6 and 7106-T6 as-welded tempers with 500 hours exposure, and with 7039-T64 as-welded after 616 hours exposure. Post-weld heat treatment restored corrosion resistance of the heat-affected zone to that of the parent metal for these three alloys.

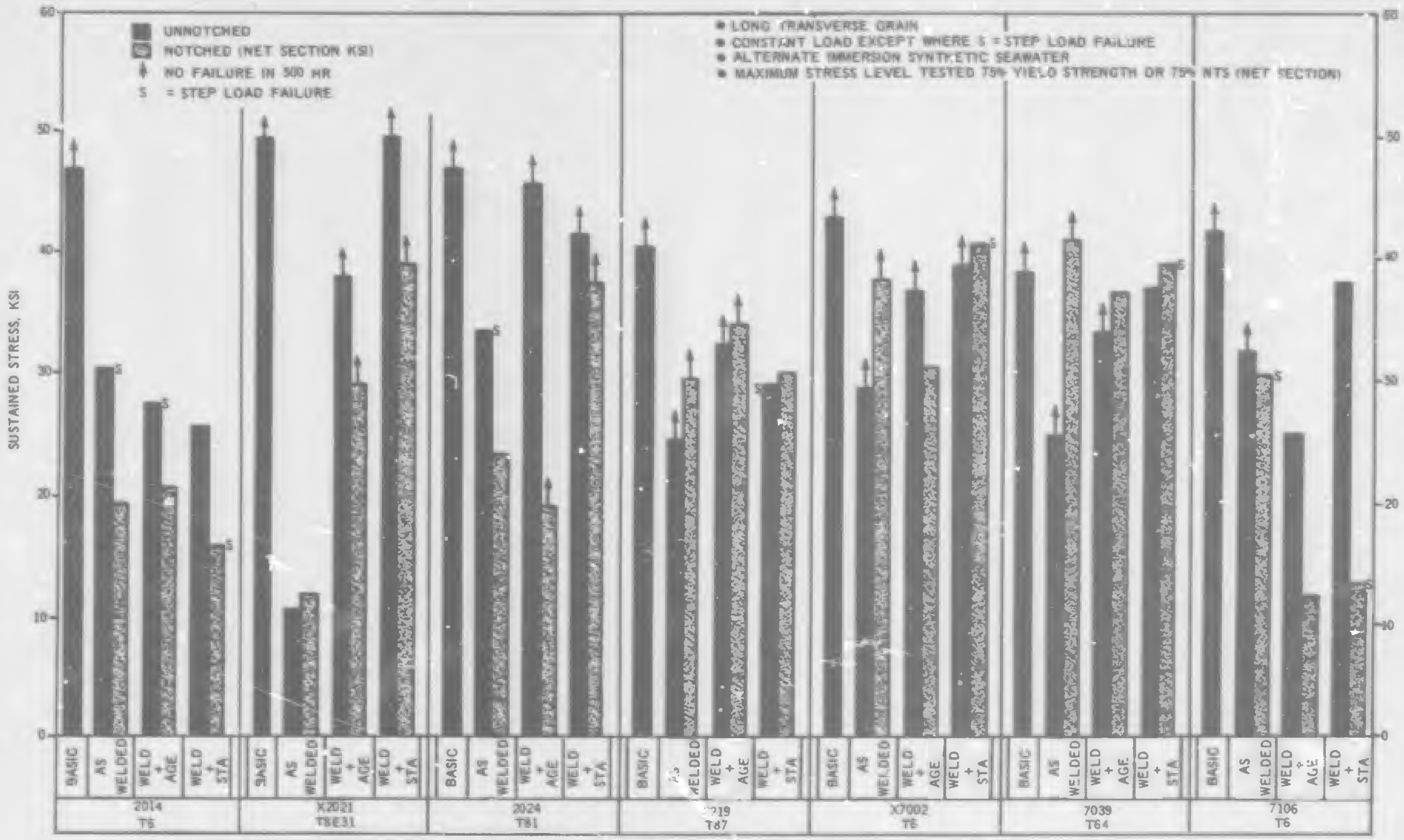


FIGURE 18. COMPARISON OF SCC THRESHOLD STRESS FOR NOTCHED AND UNNOTCHED, AS WELDED AND POST WELD HEAT TREATED ALUMINUM ALLOY SHEET.

COMPARISON OF STEP-LOAD AND CONSTANT-LOAD SCC THRESHOLDS

Stress-corrosion test data from step-load and constant-load notched and unnotched sheet are shown in Figures 19 and 20. Threshold stress levels from these data are listed in Tables VI and VII, using the SCC failure stress as threshold for the notched specimens (because crack initiation could not be clearly defined by X-ray during exposure) and the stress level midway between SCC failure and no SCC failure for the constant-load tests. The differences between step-load and constant-load threshold stress levels, where determinable, are included in the tabulations.

Four of the 7XXX sheet step-load specimen failures (as-welded temper) were attributed to corrosion and are treated as "no SCC failure" in these comparisons. The corrosion failures were associated with accumulated alternate immersion and air times in excess of 500 hours and occurred through the heat-affected zone which was corrosion prone, as discussed later. As can be seen in the tables, several step-load specimens did not fail upon completion of test, indicating SCC thresholds were above maximum test level and these results were confirmed by the constant-load tests.

Where threshold stress was below maximum test level and SCC failure occurred during exposure, relatively close agreement was found in some cases and wide disagreement in others.

In general, for unnotched specimens, step-load failure occurred either below the constant-load threshold (four cases) or not more than 4.0 ksi above the threshold (three cases). The exception was X2021-T8E31, as-welded, where the step-load specimen passed up through the apparent constant-load threshold of 10.6 ksi and finally failed at 20.1 ksi.

The step-load failure for notched specimens occurred either below the constant-load threshold or not more than 5.5 ksi above (five cases). The exception is again X2021-T8E31, as-welded, with the step-load failure 7.8 ksi above the constant-load threshold.

Two cases were not considered in quoting the five cases above and five cases below for the notched specimens. These were 7002-T6 weld plus age, and 7039-T64 weld plus age. Alloy 7002-T6 step load did not fail at 38.3 ksi but did display a SCC zone approximately the same size as the two failed constant-load specimens tested at 37.2 ksi and 42.4 ksi. The relationship of step load to constant load from other notched specimens was subsequently used to approximate a constant-load threshold. The constant-load threshold for 7039-T64 as defined by minimum failure stress plus maximum no-failure stress divided by 2, gives a threshold at 37.0 ksi which is below the step-load no-failure stress of 37.6 ksi. However, the step-load stress did not reach the minimum failure stress of the constant load test, 39.4 ksi, and thus the representation of step load >37.6 ksi and constant load 37.0 ksi is unrealistic.

The position of the constant-load threshold relative to step load, then, is inconsistent and may be either higher than or lower than step-load value. It is fitting, however, to refer to the step-load threshold as

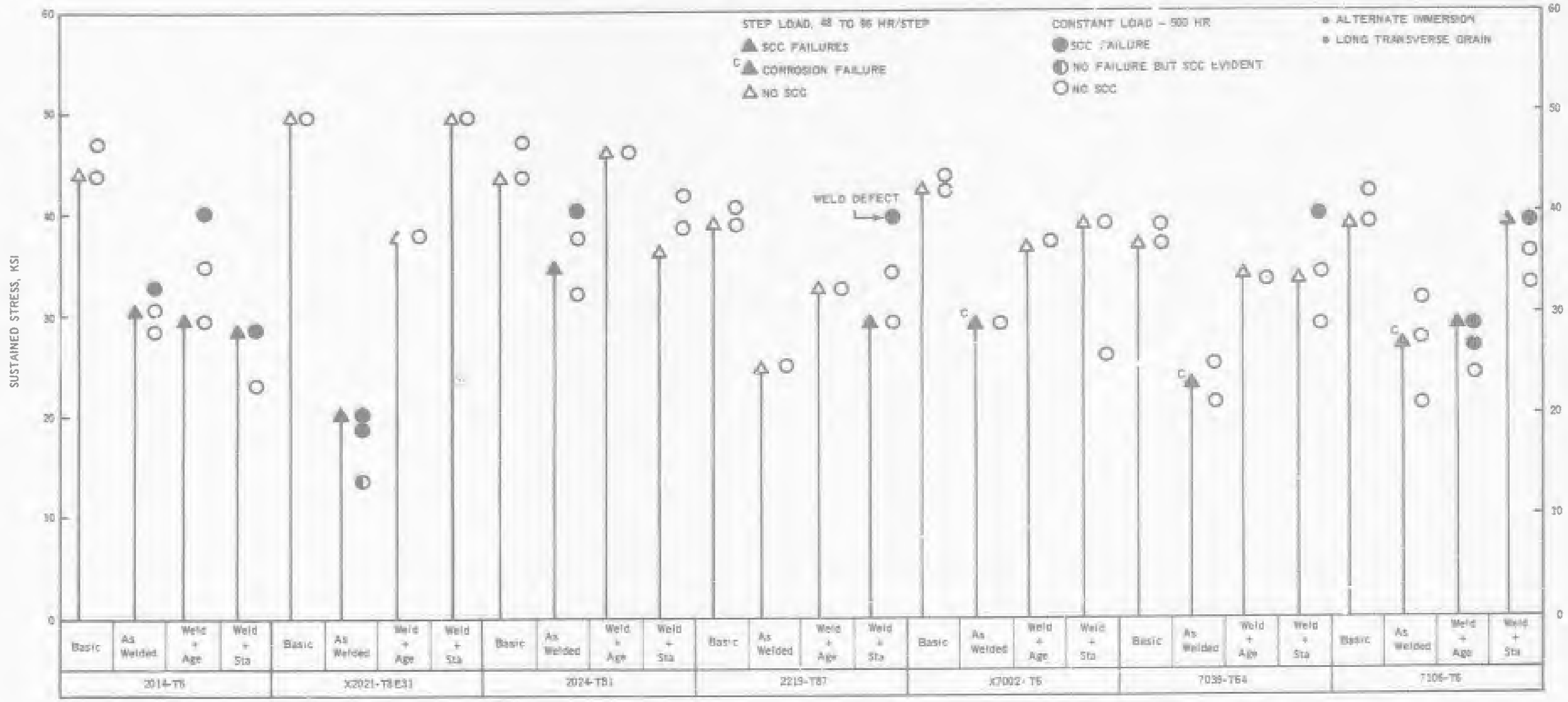


FIGURE 19. COMPARISON OF STEP LOAD AND CONSTANT LOAD SCC DATA FOR UNNOTCHED ALUMINUM ALLOY SHEET

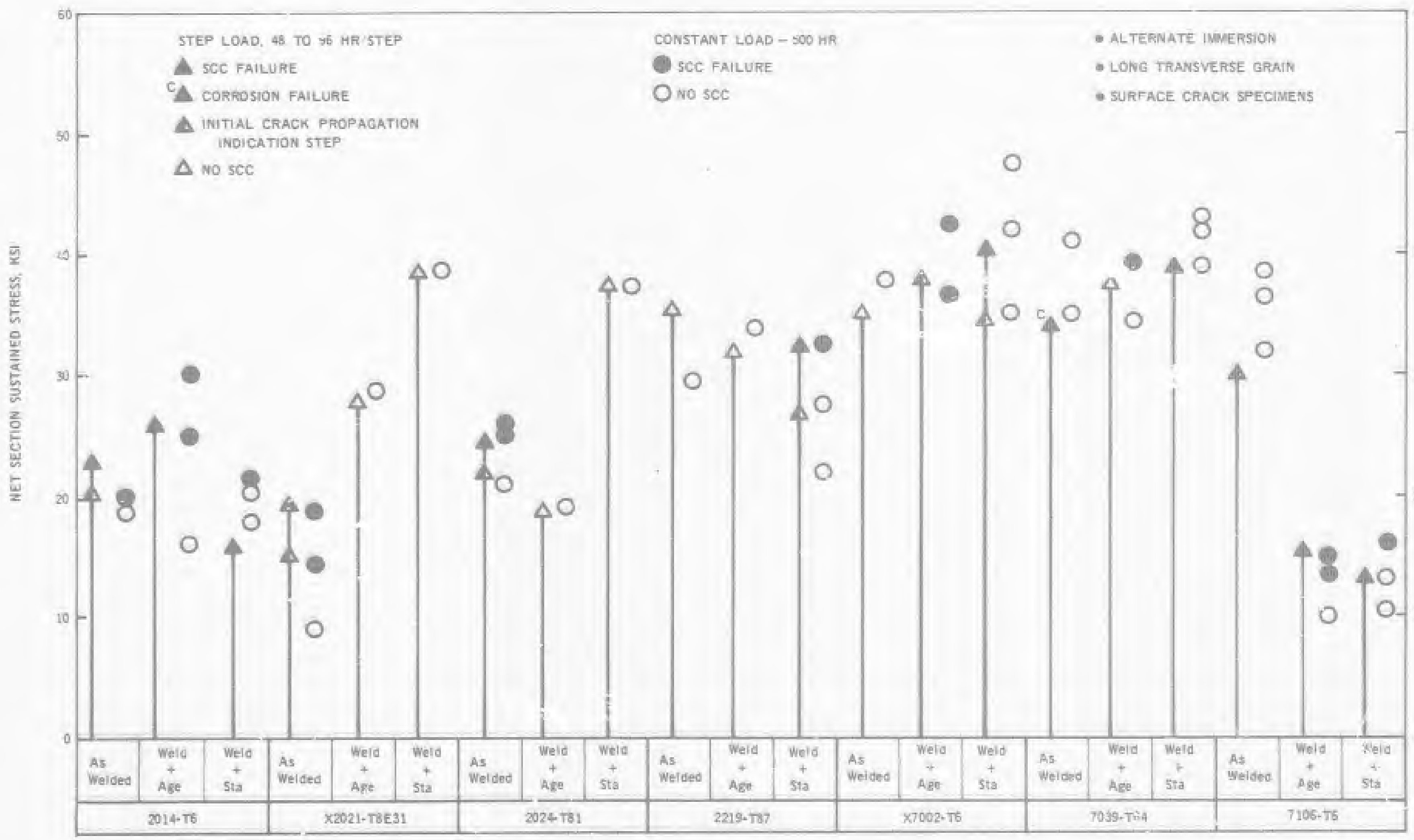


FIGURE 20. COMPARISON OF STEP LOAD AND CONSTANT LOAD SCC DATA FOR NOTCHED ALUMINUM ALLOY SHEET

TABLE VI

Comparison of Step-Load and Constant-Load SCC Thresholds for Unnotched Aluminum Sheet

		STEP LOAD FAILURE STRESS, KSI	CONSTANT LOAD THRESHOLD STRESS, KSI[1]	ΔTHRESHOLD, KSI (STEP - CONSTANT)
2014-T6	Basic	>43.9	>47.4	
	As Welded	30.7	31.8	-1.1
	Weld + Age	29.4	37.4	-7.7
	Weld + STA	28.8	25.9	+2.9
X2021-T8E31	Basic	>49.7	>49.7	
	As Welded	20.1	10.6[2]	+9.5
	Weld + Age	>37.7	>37.7	
	Weld + STA	>49.8	>49.8	
2024-T81	Basic	>43.6	>47.1	
	As Welded	34.8	38.9	-4.0
	Weld + Age	>45.8	>45.8	
	Weld + STA	>36.8	>41.6	
2219-T87	Basic	>39.0	>40.6	
	As Welded	>24.9	>24.9	
	Weld + Age	>32.6	>32.6	
	Weld + STA	29.0	>34.2	>-5.2
X7002-T6	Basic	>41.5	>43.1	
	As Welded	>29.1	>29.1	
	Weld + Age	>37.0	>37.0	
	Weld + STA	>39.3	>39.3	
7039-T64	Basic	>36.9	>38.5	
	As Welded	>23.2	>24.9	
	Weld + Age	>34.4	>33.4	
	Weld + STA	>33.4	37.0	
7106-T6	Basic	>39.1	>42.2	
	As Welded	>26.8	>31.7	
	Weld + Age	29.4	25.4	+4.0
	Weld + STA	39.3	37.8	+1.5

[1] $\text{Threshold} = \dfrac{\text{Minimum Failure Stress + Maximum No Failure Stress}}{2}$

[2] Calculated using maximum no failure, gross section stress from notched specimen tests

TABLE VII

Comparison of Step-Load and Constant-Load
SCC Thresholds for Notched Aluminum Sheet

		STEP LOAD FAILURE STRESS, KSI	CONSTANT LOAD THRESHOLD STRESS, KSI [1]	ΔTHRESHOLD KSI (STEP - CONSTANT)
2014-T6	As Welded	22.8	19.4	+3.3
	Weld + Age	26.2	20.7	+5.5
	Weld + STA	15.9	20.9	-5.0
X2021-T8E31	As Welded	19.6	11.8	+7.8
	Weld + Age	>27.6	>29.3	
	Weld + STA	>38.9	>39.1	
2024-T81	As Welded	24.5	23.6	+0.9
	Weld + Age	>19.1	>19.3	
	Weld + STA	>37.3	>37.5	
2219-T87	As Welded	>36.3	>29.6	
	Weld + Age	>32.4	>33.9	
	Weld + STA	32.7	30.0	+2.7
7002-T6	As Welded	>34.9	>38.2	
	Weld + AGE	38.3	<37.2	
	Weld + STA	40.5	>47.8	>-7.3
7039-T64	As Welded	>33.7	>41.0	
	Weld + Age	>37.6	37.0	
	Weld + STA	39.1	>43.0	>-3.9
7106-T6	As Welded	29.8	>38.7	>-8.9
	Weld + Age	15.3	12.0	+3.3
	Weld + STA	13.4	15.0	-1.6

[1] $\text{Threshold} = \dfrac{\text{Minimum Failure Stress + Maximum No Failure Stress}}{2}$

[2] Minimum Failure Stress = 39.4 KSI which step load test did not reach.

[3] Specimen did not fail but had SCC origin

being below the constant-load threshold and not more than "X" ksi above because in several cases the step-load failure was immeasurably lower than the constant-load threshold; 7002-T6 weld plus STA, notched; 7039-T64 weld plus STA notched; 7106-T6 as-welded, notched; and 2219-T87 weld plus STA, unnotched (see Tables VI and VII).

Failure of the step-load specimens at lower stress levels may indicate an accelerating effect of SCC by air exposure, or mechanical rupture of surface films during handling and step loading, exposing fresh metal to the corrodent.

The cases of step-load threshold above constant-load threshold may be attributed to inability to detect SCC initiation in the step-load test. Considering stress levels in which crack initiation was indicated prior to failure in Figure 20 reduces the Δ threshold for notched alloy-tempers; 2014-T6 as-welded, X2021-T8E31 as-welded, 2024-T81 as-welded, and 2219-T87 weld plus STA.

The step-load test was used in this program as an indicator of constant-load threshold and with the large number of specimens tested was subjected to variables of air exposure time, alternate immersion time, handling, and was limited to discrete, increasing step loads. These variables could contribute to scatter in the data. Refinements of the procedure could contribute to closer approximations of the threshold for the aluminum alloys and other alloy systems.

EFFECT OF STRESS INTENSITY ON SCC

Sheet test specimens were selected from the tables of stress corrosion test data that best fit ASTM-recommended practice (Reference 14) and K_I stress intensity values were calculated. The formula for calculating K_I from the surface crack specimen in Reference 14 is:

$$K_I^2 = \frac{1.2\pi \; P^2 a_o}{W^2 B^2} \left[\frac{1}{\phi^2 - 0.2 \left(P^2/W^2 B^2 \; \sigma_{ys}^2 \right)} \right]$$

where

P = applied load (pounds)

a_o = initial crack depth (inches)

W = specimen width (inches)

B = specimen thickness (inches)

ϕ = complete elliptical integral of the second kind

σ_{ys} = 0.2-percent offset tensile yield stress (psi)

This equation is reduced in form in Reference 15 to

$$K_I = \left[1.21\,\pi\,\sigma^2 \frac{a}{Q}\right]^{1/2}$$

where

σ = gross section applied stress (psi)

a = initial crack depth (inches)

Q = flaw shape parameter

The latter equation was used in these calculations. The equation data for step-load stress corrosion specimens are shown in Table A-16 and for constant-load stress corrosion specimens in Table A-17 in the Appendix.

Crack depth in the calculations from step-load test data is initial fatigue crack depth and gross section stress is the sustained stress causing first observed crack propagation or gross sustained stress at time of failure or gross sustained stress at last step if failure did not occur. Crack depth in the calculations from constant-load test data is also initial fatigue crack depth and stress is gross section sustained stress. Calculation of stress intensity using final stress corrosion crack shape was considered but, at time of failure the stress corrosion crack either extended through the thickness, across the specimen width, had moved out of the plane of the fatigue crack, or terminated in full shear which introduce substantial error in the formula.

Because deviations exist with the selected specimens from the standpoint of fatigue crack length or depth and high precracking stress as discussed in the Procedures Section, the K_I values calculated are considered nominal values as recommended in Reference 16.

The stress intensity data calculated from step-load and constant-load alternate immersion test data are graphically presented in Figure 21 in a manner similar to net section stress data previously presented in Figure 20, but are lacking sufficient data for defining a nominal K_{ISCC} threshold in a few alloy-weld-tempers. These data indicate a relationship of alloys, tempers, and testing similar to that previously discussed on the basis of net section stress.

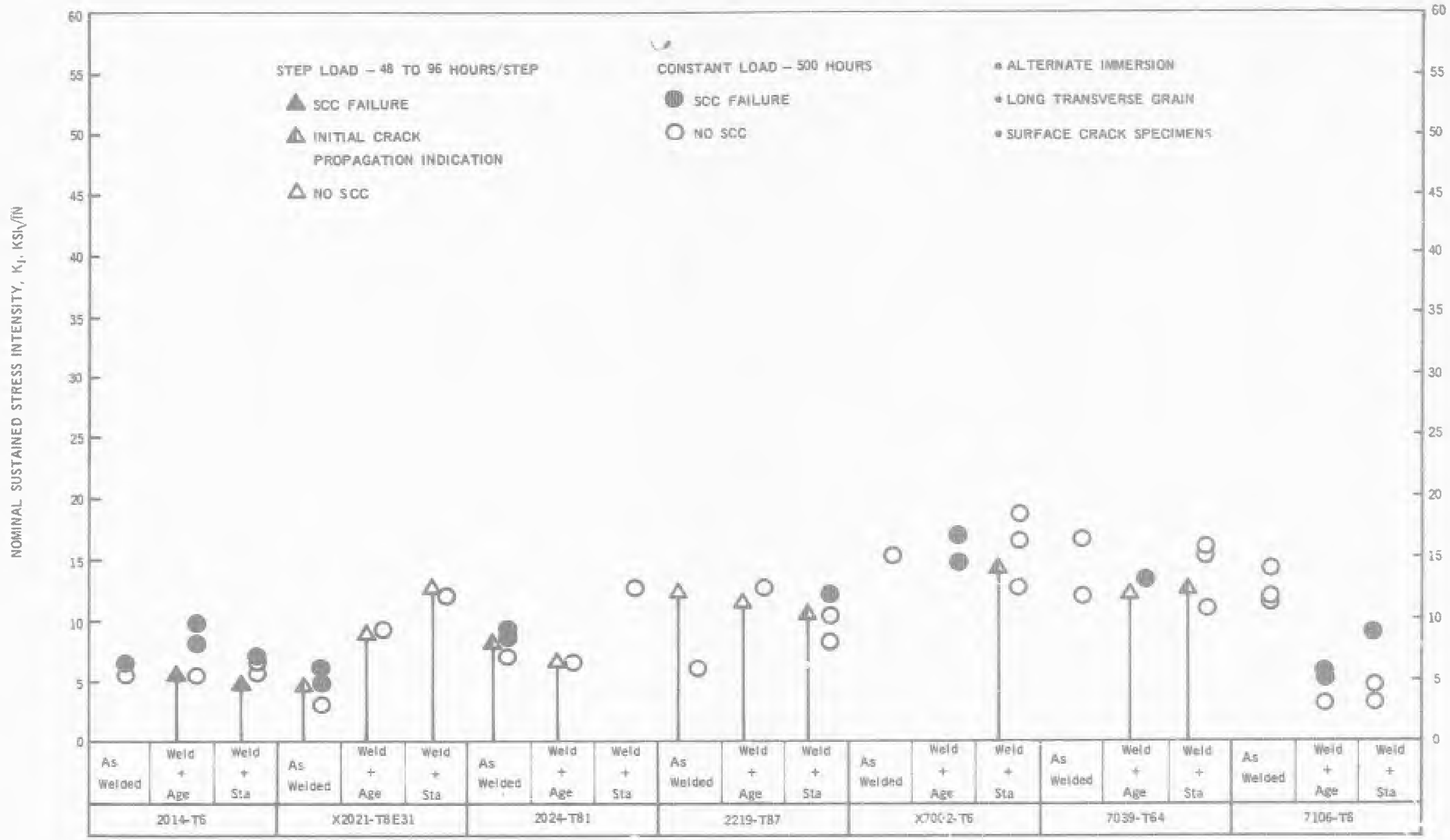


FIGURE 21. EFFECT OF STRESS INTENSITY ON STRESS CORROSION OF WELDED ALUMINUM ALLOY SHEET

EFFECT OF WELDING AND POST-WELD HEAT TREAT ON CORROSION

To determine the effect of welding and post-weld heat treatment on corrosion of the sheet alloys, representative specimens were selected from each alloy and temper and visually examined for degree of corrosion on parent metal, heat-affected zone, edge of weld metal, and weld metal. All specimens selected survived 500 hours of alternate immersion and were subsequently tension-tested to determine residual strength and elongation.

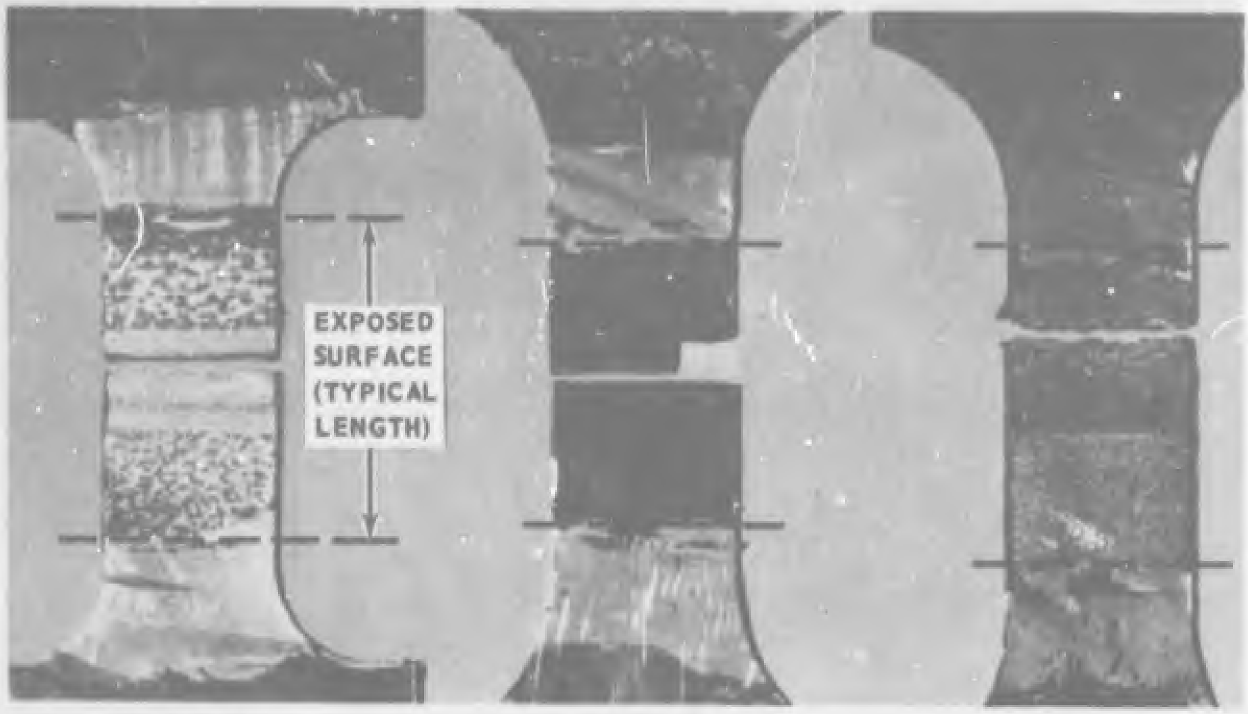
Appearance of the corroded surfaces, viewing the top side of the weld pass, are shown in Figures 22 through 28. Relative ratings of the degree of corrosion, as viewed at 10X, are presented in Table VIII.

The parent metal of 2014-T6 was more corrosion-susceptible than the weld area for as-welded and weld plus age tempers. Little difference in corrosion was noted between zones of the weld plus STA temper. Highest resistance to corrosion, considering weld zone and parent metal, was displayed by the as-welded temper and the least resistance was indicated by the weld plus age temper (see Figure 22).

The distinction between zones for 2021-T8E31 was not as evident with temper. Considering all zones, the weld plus age temper appeared most susceptible to corrosion and the weld plus STA most resistant. The as-welded temper had resistance similar to STA temper but did display preferential corrosion attack on the cold side of the heat-affected zone indicating a chemically reactive path (see Figure 23). This is significant since stress corrosion specimens that failed during test failed through this zone, although very few corrosion products were observed on these short-time exposure failures. Post-weld aging reduced and post-weld STA eliminated the selective corrosion attack. Post-weld aging and STA also eliminated stress corrosion failures.

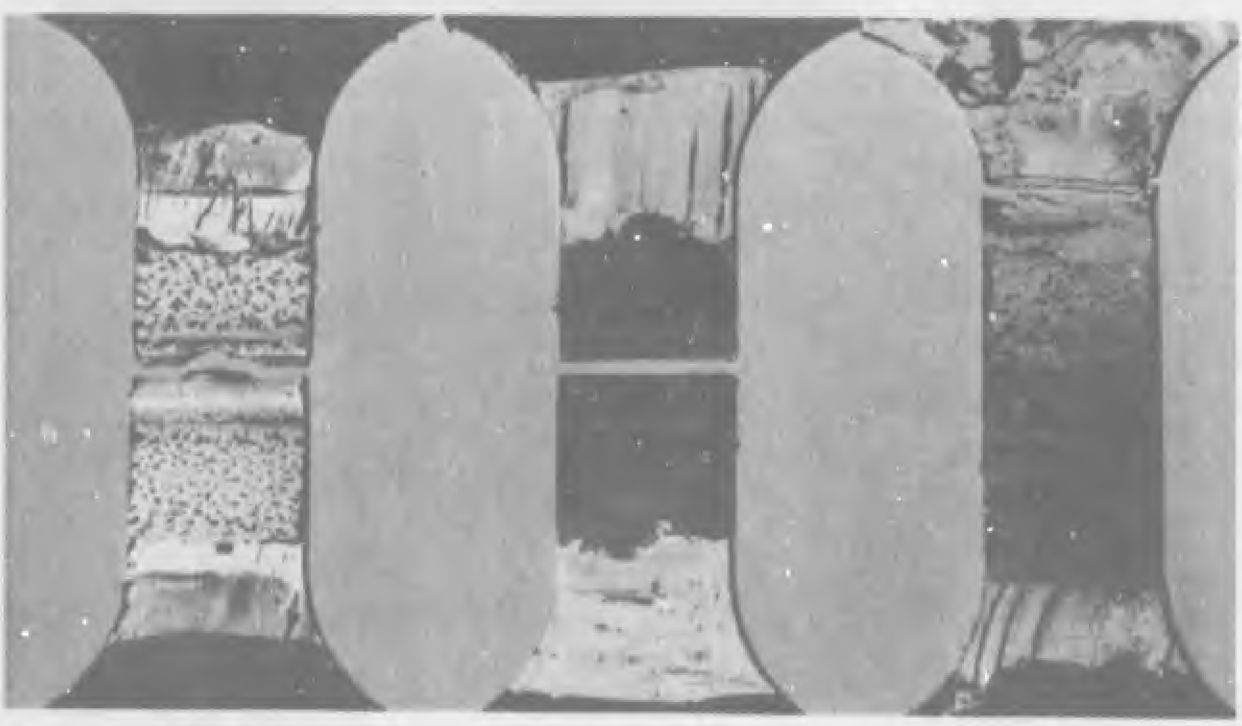
Corrosion appearance of 2024-T81 remained relatively constant for the weld zone and parent metal from temper to temper (see Figure 24).

Little distinction for 2219-T87 (see Figure 25) could be made between the weld zone and parent metal except for the as-welded temper where the parent metal appeared more susceptible to corrosion than the weld zone. Considering all zones, the weld plus STA temper was most resistant to corrosion followed by as-welded temper and weld plus age temper. Note in Figure 25 two horizontal lines of selective corrosion approximately 5/8-inch apart and parallel to the weld bead. These lines were noted on a few of the specimens, independent of alloy, and are attributable to scuffing and copper contamination from the tips of the copper hold-down bars used in welding (see Figure 11 in Procedures Section). Although stress corrosion did not occur from these markings when present, selective corrosion was observed and demonstrates that although a standard welding setup was used improvement can be made to reduce contamination and lowering of corrosion resistance. In this case stainless steel hold down bars may have been a better selection than copper bars.



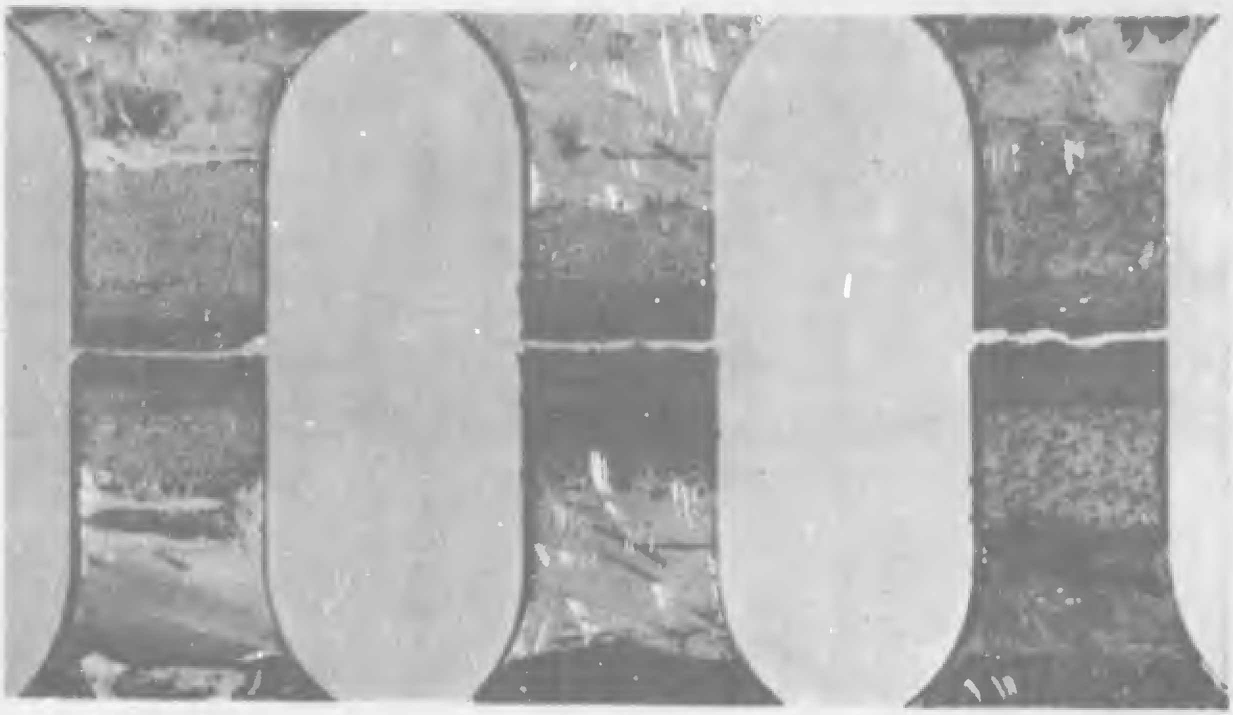
AS WELDED WELD + AGE WELD + STA

FIGURE 22. SURFACE CONDITION OF 2014-T6 WELDED SHEET AFTER 500-HOURS ALTERNATE IMMERSION. (TENSION TESTED AFTER EXPOSURE)



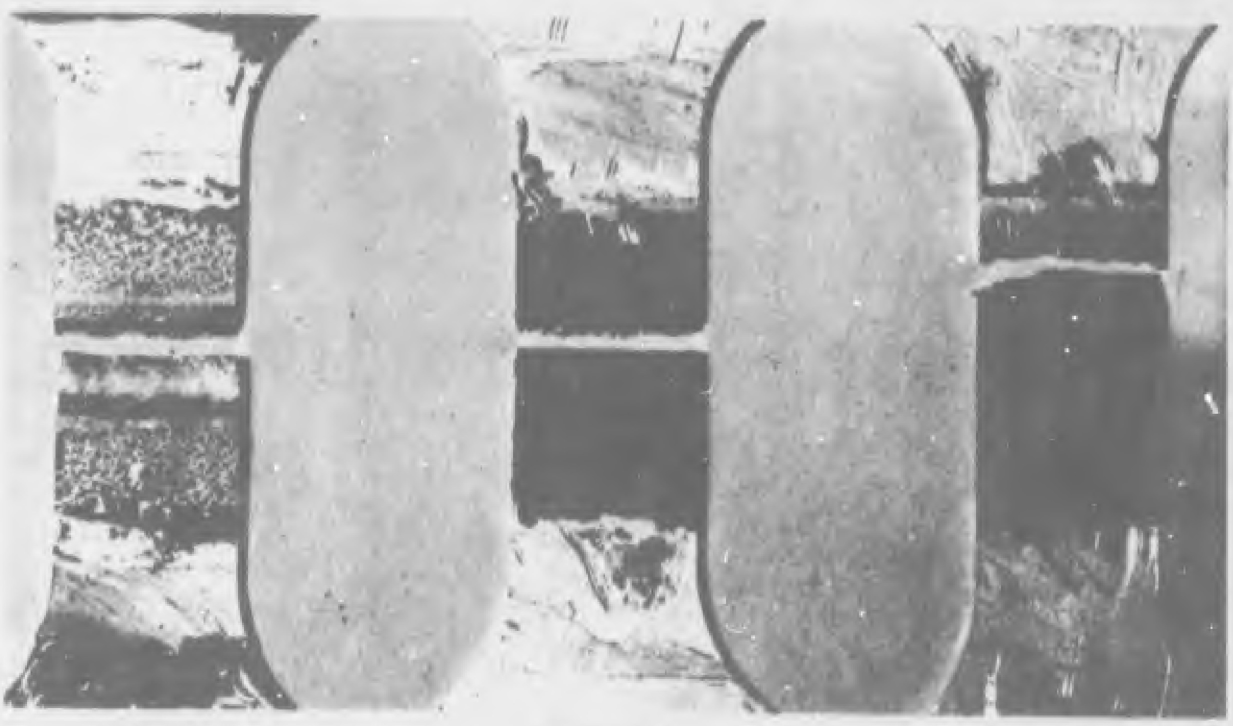
AS WELDED WELD + AGE WELD + STA

FIGURE 23. SURFACE CONDITION OF X2021-T8E31 WELDED SHEET AFTER 500-HOURS ALTERNATE IMMERSION. (TENSION TESTED AFTER EXPOSURE)



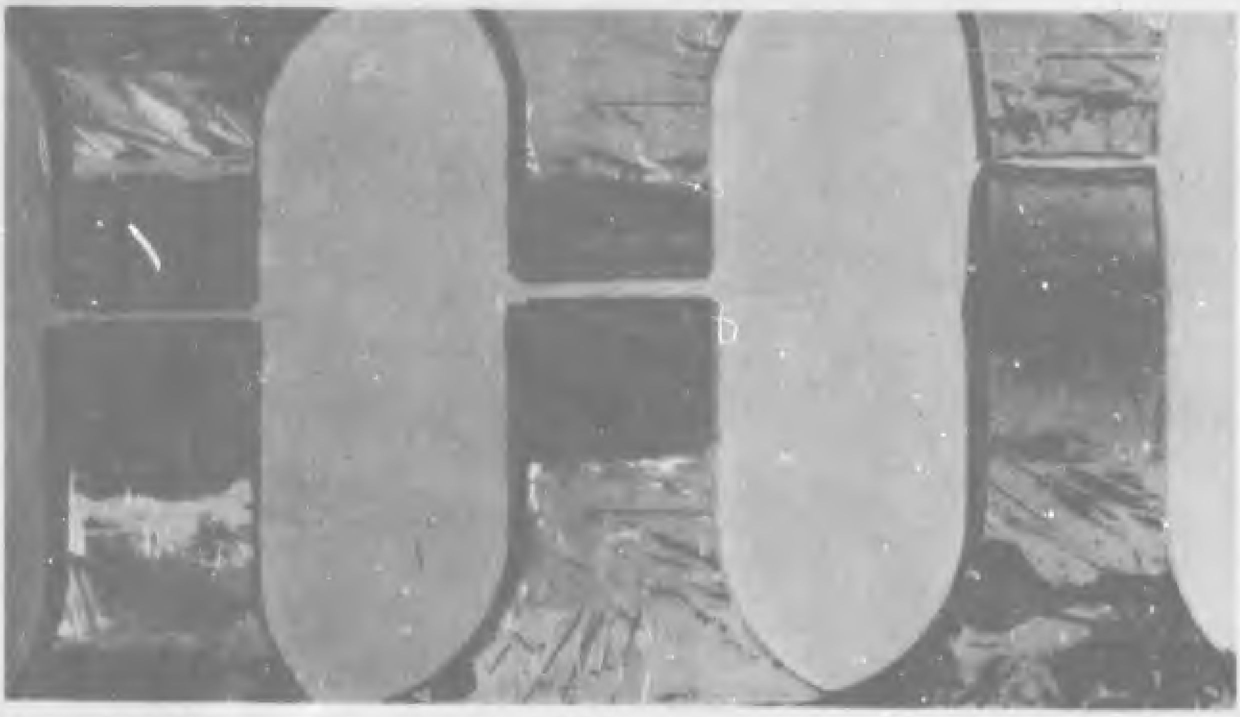
AS WELDED   WELD + AGE   WELD + STA

FIGURE 24. SURFACE CONDITION OF 2024-T81 WELDED SHEET AFTER 500-HOURS ALTERNATE IMMERSION. (TENSION TESTED AFTER EXPOSURE)



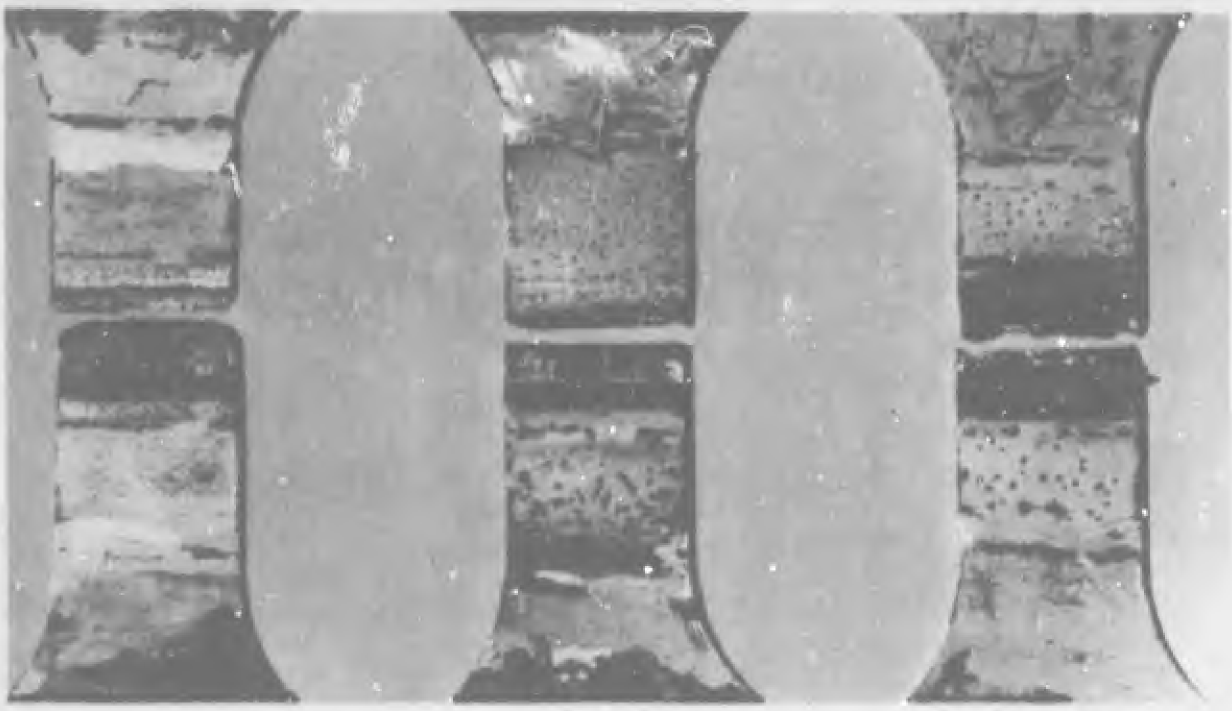
AS WELDED   WELD + AGE   WELD + STA

FIGURE 25. SURFACE CONDITION OF 2219-T87 WELDED SHEET AFTER 500-HOURS ALTERNATE IMMERSION. (TENSION TESTED AFTER EXPOSURE)



AS WELDED WELD + AGE WELD + STA

FIGURE 26. SURFACE CONDITION OF X7002-T6 WELDED SHEET AFTER 500-HOURS ALTERNATE IMMERSION. (TENSION TESTED AFTER EXPOSURE)



AS WELDED WELD + AGE WELD + STA

FIGURE 27. SURFACE CONDITION OF 7039-T64 WELDED SHEET AFTER 500-HOURS ALTERNATE IMMERSION. (TENSION TESTED AFTER EXPOSURE)

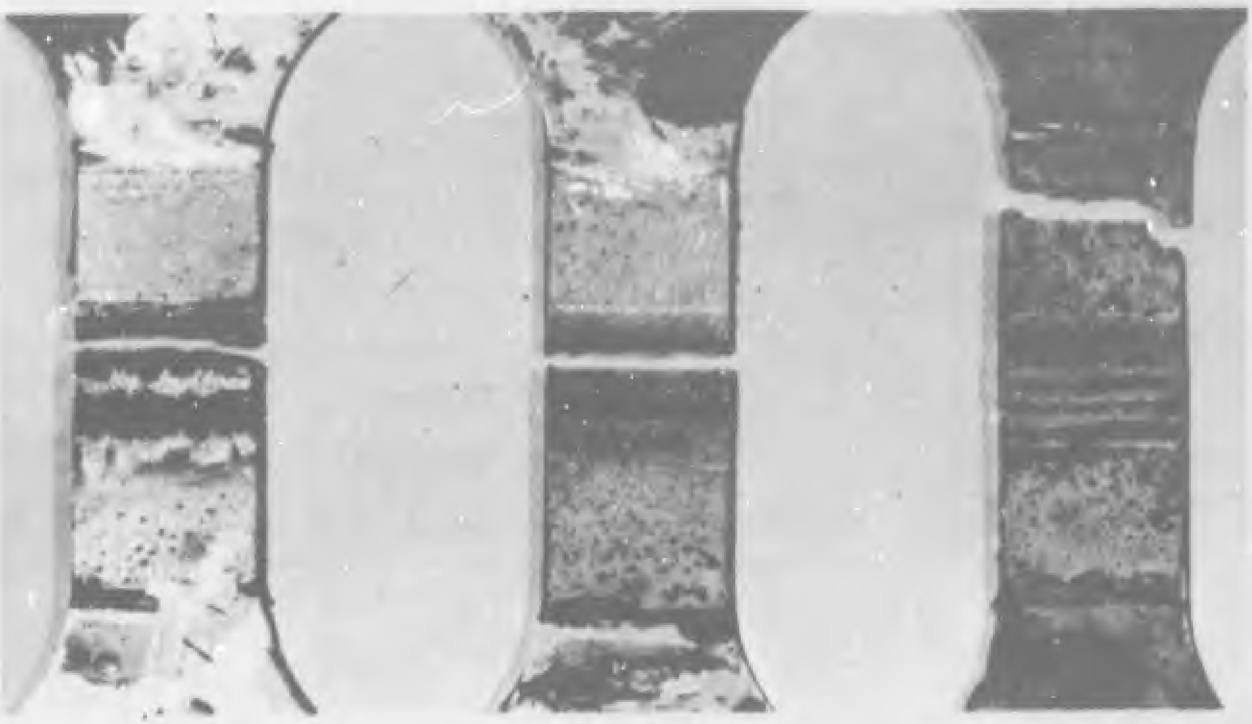


FIGURE 28. SURFACE CONDITION OF 7106-T6 WELDED SHEET AFTER 500-HOURS ALTERNATE IMMERSION. (TENSION TESTED AFTER EXPOSURE)

TABLE VIII

Corrosion Observations on Welded Aluminum Alloy Sheet SCC Specimens Exposed 500 Hours in Alternate Immersion

	TEMPER	SPECIMEN CODE	WELD BEAD	EDGE OF WELD BEAD	HEAT AFFECTED ZONE	PARENT METAL
2014 T6	As Welded	SWX-14-W-4-4	2	2	2	3-4
	Weld + Age	SWU-14-A-2	2-3	3	3	4
	Weld + STA	SWU-14-S-4	2-3	2	3	3
2021 T8E31	As Welded	SWU-21-W-4	2	3	2-5	3-4
	Weld + Age	SWX-21-A-3	3	3-4	4	4
	Weld + STA	SWU-21-S-2	2-3	3	2-3	3
2024 T81	As Welded	SWU-24-W-3	2-3	4	3	3
	Weld + Age	SWU-24-A-2	3-4	4	3-4	3-4
	Weld + STA	SWU-24-5-3	3-4	2-3	3	3
2219 T87	As Welded	SWU-19-W-2	2	2-3	2	3-4
	Weld + Age	SWU-19-A-2	4	3	3	4
	Weld + STA	SWU-19-S-2	2-3	2-3	2-3	2-3
7002 T6	As Welded	SWU-02-W-2	5	5	5	2
	Weld + Age	SWU-02-A-2	3	5T-3B	2-3	2
	Weld + STA	SWU-02-S-2	2	5T-2B	1	1
7039 T64	As Welded	SWU-39-W-2	3	5T-3B	2-3	2
	Weld + Age	SWU-39-A-5	3	5T-2B	2-3	3
	Weld + STA	SWU-39-S-4	1	5T-2B	2	3
7106 T6	As welded	SWU-06-W-4	3-4	5	5	2
	Weld + Age	SWU-06-A-3	3	4T-3B	3	3
	Weld + STA	SWU-06-S-3	2	5T-3B	2	3-4

Rating	Description
1	Very Slight Corrosion
2	Slight
3	Moderate
4	Severe
5	Very Severe

T = Top Side of Weld Pass

B = Bottom Side of Weld Pass

Corrosion appearance of 7002-T6, 7039-T64, and 7106-T6 was similar from the standpoint of severe corrosion at the edge of the weld bead on the top side of the weld pass regardless of temper (see Figures 26, 27, and 28).

This severe corrosion occurred in the area of a eutectic constituent in the microstructure formed at the edge of the weld bead during welding. Kaiser Aluminum (Reference 17) suggested that the constituent was a high-zinc eutectic not uncommon to the 7XXX series alloys and generally controlled by maintaining low heat input during welding and heat treating after welding. It was not within the scope of this program to define this phase, but it was noted principally on the top side of the weld bead pass at the edge of the weld bead, varying in degree from specimen to specimen and present on both sheet and plate specimens of the 7XXX series. The major portion of the constituent observed microscopically had the appearance of laying on the surface at the edge of the weld bead. However, in one 7106-T6 specimen it was found to penetrate along the fusion line approximately 0.012-inch deep indicating that machining the weld bead flush would not necessarily remove this corrosion problem.

Very severe corrosion was observed for the 7002-T6 alloy in both heat-affected zone and weld bead in the as-welded temper (see Figure 26). Post-weld aging improved the corrosion resistance of this area and solution heat treat plus aging fully restored corrosion resistance except for the condition at the edge of the weld bead, previously discussed. The parent metal of weld plus STA temper exhibited very little corrosion and appeared to have the highest resistance to corrosion of the alloys studied (see Figure 26).

Little difference in corrosion appearance for the 7039-T64 alloy was evident of the different zones or tempers except the weld bead of the weld plus STA temper which had very slight corrosion. The corrosion at the edge of the weld bead appeared more extensive than that of 7002-T6 and 7106-T6 alloys. Selective corrosion was also noted in the areas contacted by the copper hold-down bar, as described for 2219-T87 (see Figure 27). Longer time exposures (step-load) during SCC testing did reveal severe corrosion in the heat-affected zone of 7039-T64 as-welded.

Alloy 7106-T6 as-welded temper exhibited very severe corrosion in the heat-affected zone as did 7002-T6. Post-weld aging and post-weld solution heat treat plus aging improved corrosion resistance of the weld area but decreased resistance of the parent metal (see Figure 26).

ALLOY 2014-T6 SHEET

Stress corrosion cracking was observed for all weld tempers, notched and unnotched. Only the basic unwelded temper, unnotched, survived alternate immersion at 75-percent yield strength sustained stress for 500 hours without incurring SCC.

The as-welded temper for unnotched welded specimens exhibited highest sustained stress without failure followed by weld plus age and weld plus STA tempers. Notched thresholds were at lower values than unnotched for the three weld tempers.

Metallographic studies of the origin of failure for several specimens were conducted to determine the mode of failure. Cracks were intergranular, principally 90° to sustained load and originated at the edge of the weld bead. Typical cracks are shown in Figures 29 and 30 for unnotched as-welded temper specimen SWU-14-W-1 that failed during step-load stress corrosion testing. The crack shown in Figure 29 is a secondary crack observed at the edge of the weld bead opposite the main line of failure. The end of the crack, shown in Figure 30, is typically intergranular. The stress corrosion cracking followed the edge of the weld metal or turned into the weld bead (see Figure 31).

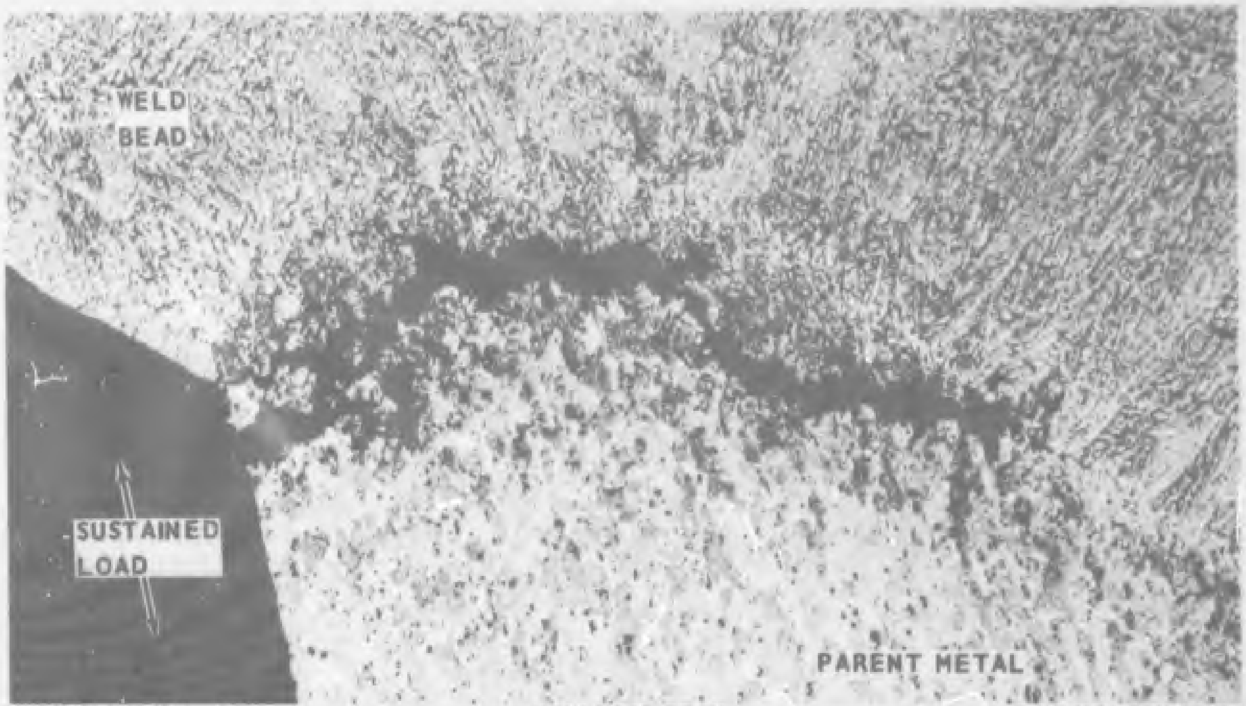
Fracture surfaces of failed specimens were examined to determine final stress corrosion crack length prior to failure. This was difficult to determine because of featureless curve linear fractures terminating in varying degrees of shear lip. Comparison with tensile specimen fracture features and correlation of intergranular cracking in the microstructure with fracture gave apparent final crack lengths. Apparent stress corrosion crack lengths are outlined on fracture surfaces of unnotched as-welded specimen SWU-14-W-1 in Figure 32. Unnotched weld plus age specimen (constant-load, F 20 hours) is shown in Figure 33. Fracture surfaces of notched specimens which failed during SCC testing are shown in Figure 34 and illustrate similarity of fracture regardless of post-weld heat treat and difficulty previously discussed in controlling fatigue crack length and depth at the edge of the weld bead. The long shallow fatigue crack is attributed to the notch effect along the edge of the weld bead and the reinforcement which prevented bending of the specimen over the foot of the cracking fixture. Although these precracked specimens did not have an elox starter notch, specimens that did showed a similar high ratio of crack length/depth and, in some cases, the crack depth did not exceed the depth of the notch.

ALLOY X2021-T8E31 SHEET

The only temper found susceptible to SCC was the as-welded temper. These tempers were highly resistant to SCC: (1) basic unwelded, (2) weld plus age, and (3) weld plus STA, the former was unnotched and the latter two notched and unnotched.

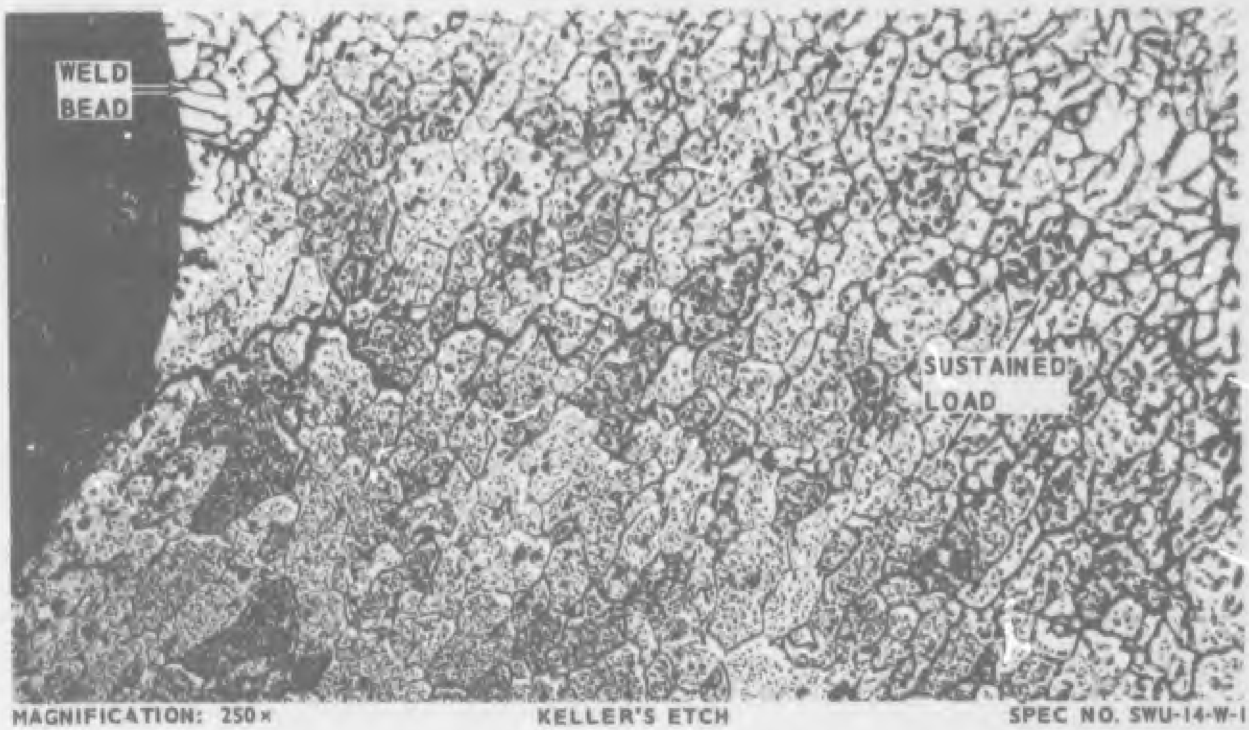
For the susceptible unnotched as-welded temper, step-load stress corrosion tests produced failures under 20.1 ksi sustained stress. Subsequent constant-load tests produced failures at 20.1 ksi in 308 hours and at 18.4 ksi in 128 hours. No failure occurred at 13.4 ksi in 500 hours and residual ultimate was 90 percent of unexposed ultimate. One crack apparently of SCC origin, 0.150-inch long × 0.040-inch deep, was observed on the fracture surface of the unfailed specimens which indicated exposure times longer than 500 hours may have caused failure.

In cases of notched as-welded specimens with a fatigue precrack at the edge of the weld bead, failure occurred during step-load testing at 19.6 ksi (net section) and was first observed at 15.7 ksi. Subsequent constant-load tests produced failures at 18.9 ksi in 80 hours, at 14.5 ksi in 34 hours, and one specimen at 9.1 ksi (7.74 ksi gross section) did not fail in 500 hours. No apparent SCC was noted on the unfailed specimen fracture surface after tension testing and residual net section strength was 95 percent of unexposed strength.



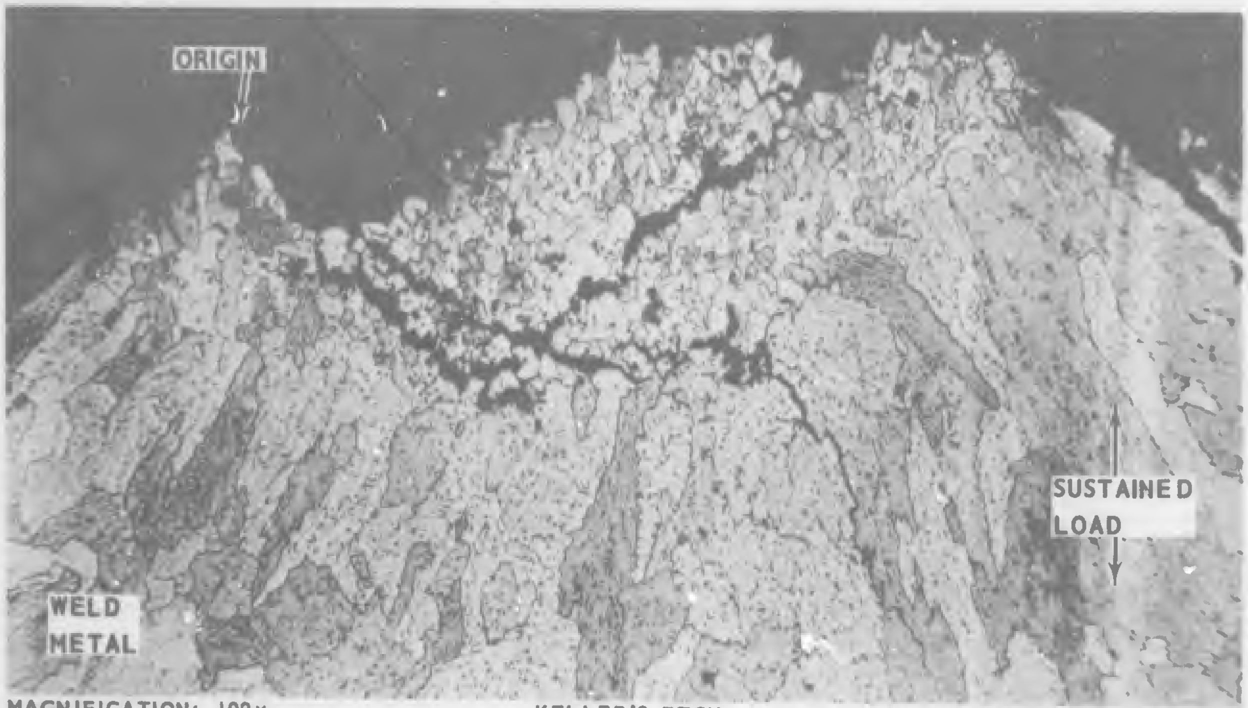
MAGNIFICATION: 100× KELLER'S ETCH SPEC NO. SWU-14-W-1

FIGURE 29. STRESS CORROSION CRACKING AT EDGE OF WELD BEAD IN 2014-T6 SHEET, AS WELDED TEMPER.



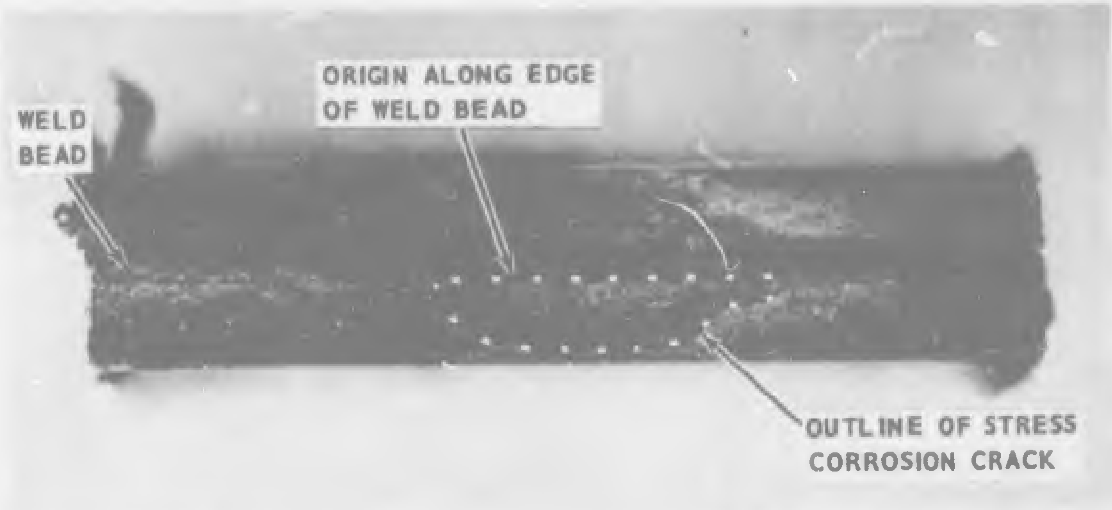
MAGNIFICATION: 250× KELLER'S ETCH SPEC NO. SWU-14-W-1

FIGURE 30. STRESS CORROSION CRACK AT EDGE OF WELD BEAD IN 2014-T6 SHEET, AS WELDED TEMPER.



MAGNIFICATION: 100× KELLER'S ETCH SPEC NO. SWU-14-S-3

FIGURE 31. ORIGIN OF STRESS CORROSION FAILURE OF UNNOTCHED 2014-T6 SHEET, WELD AND STA TEMPER.



MAGNIFICATION: 5×

SPEC NO. SWU-14-W-1

FIGURE 32. FRACTURE SURFACE OF UNNOTCHED 2014-T6 SHEET, AS WELDED TEMPER, THAT FAILED, DURING SCC TESTING.

MAGNIFICATION: 5×

SPEC NO. SWU-14-A-5

FIGURE 33. FRACTURE SURFACE OF UNNOTCHED 2014-T6 SHEET, WELD AND AGE TEMPER, THAT FAILED DURING SCC TESTING.

MAGNIFICATION 4.7× AS WELDED TEMPER SPEC NO. SWX-14-W-3-3

MAGNIFICATION 5.1× WELD + AGE TEMPER SPEC NO. SWX-14-A-2

MAGNIFICATION 5.0× WELD + STA TEMPER SPEC NO. SWX-14-5-1

FIGURE 34. FRACTURE SURFACES OF PRE-CRACKED 2014-T6 SHEET THAT FAILED DURING SCC TESTING.

Because the gross section stress of 7.7 ksi did not cause SCC with the notched specimens and 13.4 ksi did not cause failure but caused SCC to initiate in the unnotched specimens, the unnotched threshold is approximated at 10.6 ksi for the as-welded temper.

Fracture surfaces of the susceptible as-welded temper are shown in Figure 35, and the typical line of failure in Figure 36. All failures occurred through the cold side of the heat-affected zone, including the precrack specimens. Although fatigue cracks at the edge of the weld bead and minor crack extension was observed, stress corrosion cracking occurred principally out of the fatigue crack plane, as indicated above, and joined the fatigue crack tips with through-the-thickness cracks parallel to the sustained load prior to sudden failure.

Cracking was predominately intergranular. However, there was evidence of transgranular cracking (see Figures 37 and 38). Because of the severe intergranular cracking observed, the transgranular cracking may be due to mechanical failure of metal posts left behind by a rapidly advancing intergranular network-type crack front.

ALLOY 2024-T81 SHEET

The only temper found susceptible to SCC was the as-welded temper notched and unnotched. These tempers were found highly resistant to SCC: (1) basic unwelded, (2) weld plus age, and (3) weld plus STA, the former unnotched and the latter two notched and unnotched.

The step-loaded unnotched specimen for the weld plus STA temper (specimen SWU-24-S [illegible]) did fail on loading to 38.8 ksi but no evidence of SCC was observed on fracture surface and failure was considered mechanical. Replicate specimens of this temper, constant-load tested for 500 hours in alternate immersion at 38.8 ksi and 41.6 ksi, did not have evidence of SCC and the residual ultimate strengths were 96 and 102 percent of unexposed strength.

For the susceptible as-welded temper, the step-loaded unnotched specimen failed at 34.8 ksi, and a constant-load replicate failed at 40.2 ksi in 33 hours of alternate immersion. Additional replicate specimens did not fail in 500 hours at 32.2 ksi or 37.5 ksi sustained stress. Unfailed specimens exhibited 99 and 96 percent of unexposed strength. No evidence of SCC was noted on tension fracture surfaces.

Notched specimens for the as-welded temper also failed during test, the step-loaded specimen at 24.5 ksi (net section) sustained stress and constant-load specimens at 26.0 ksi (58 hours) and 25.1 ksi (118 hours). The final replicate specimen for constant-load tests did not fail in 513 hours at 21.2 ksi, and residual strength was 96 percent of unexposed strength.

Typical fracture surfaces of failed specimens of the as-welded temper are shown in Figure 39. The SCC fracture zone was more easily distinguished on the fracture surface of this alloy compared to other alloys evaluated because of the characteristic gross, flat dimples of the sudden failure zone compared to the flatter featureless zone of SCC (see

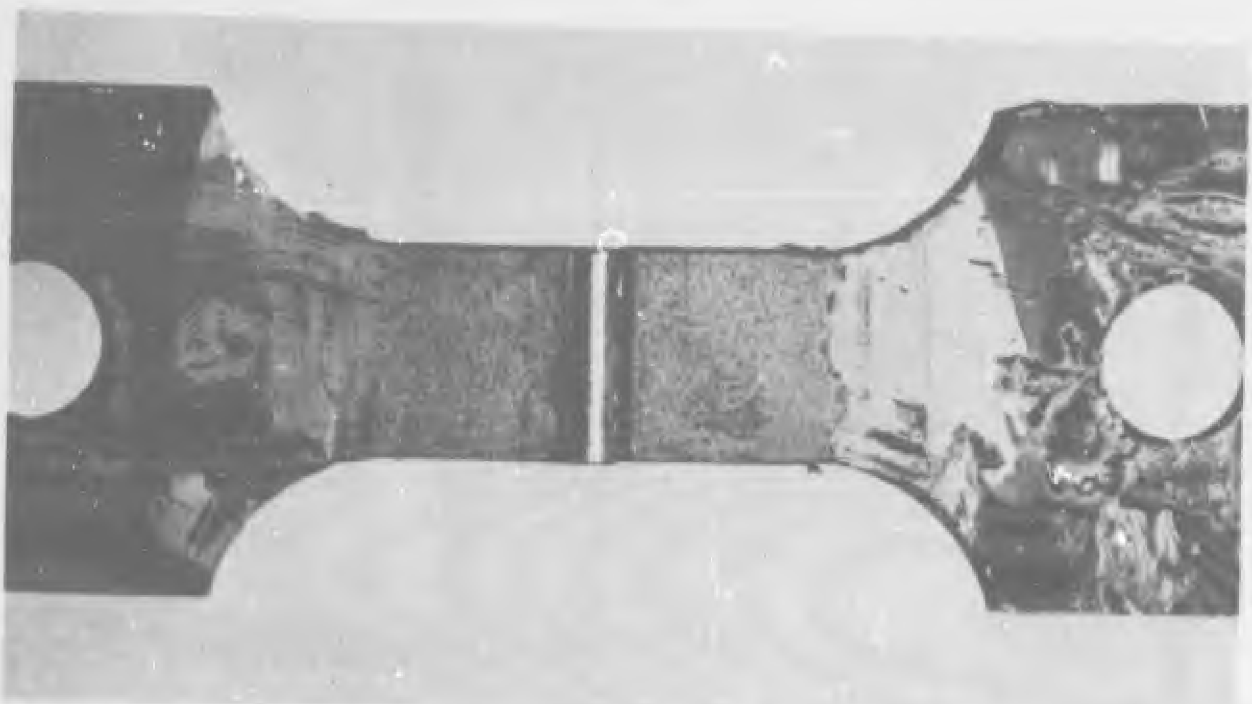
MAGNIFICATION 5×

SPEC NO. SWU-21-W-1

MAGNIFICATION 5×

SPEC NO. SWU-21-W-2

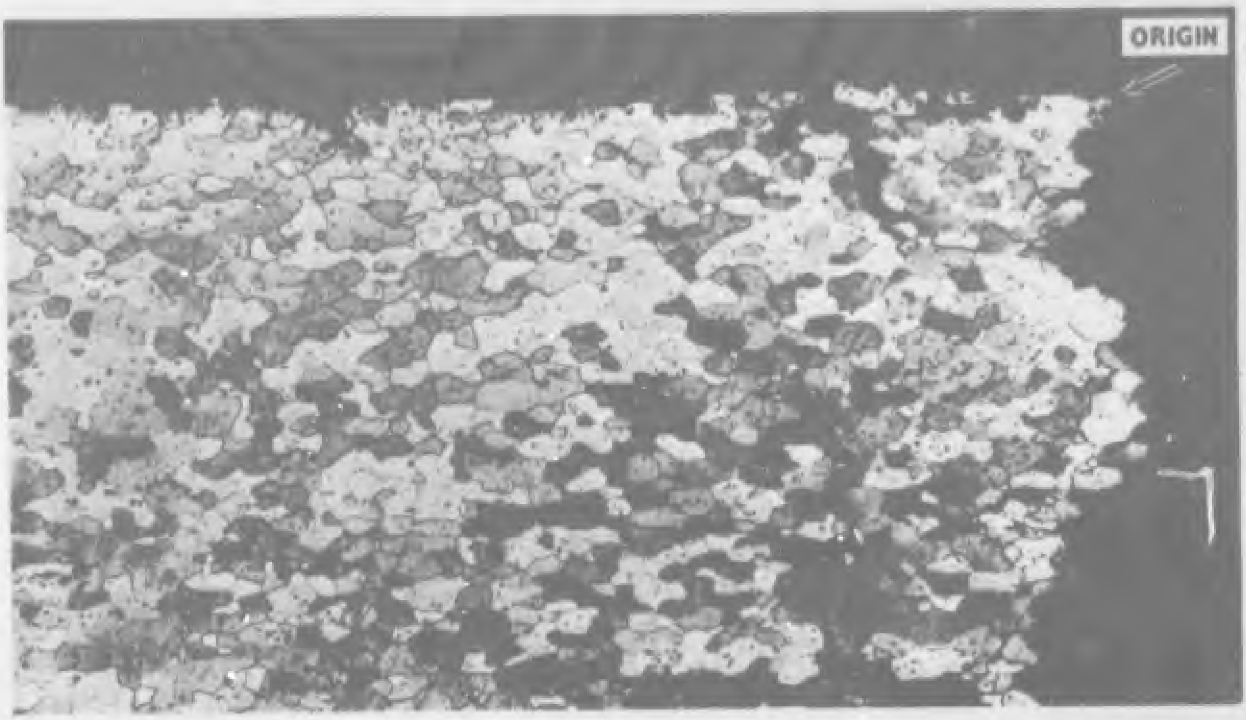
FIGURE 35. TYPICAL SCC FRACTURE SURFACES OF UNNOTCHED X2021-T8E31 SHEETS, AS WELDED TEMPER.



MAGNIFICATION 1×

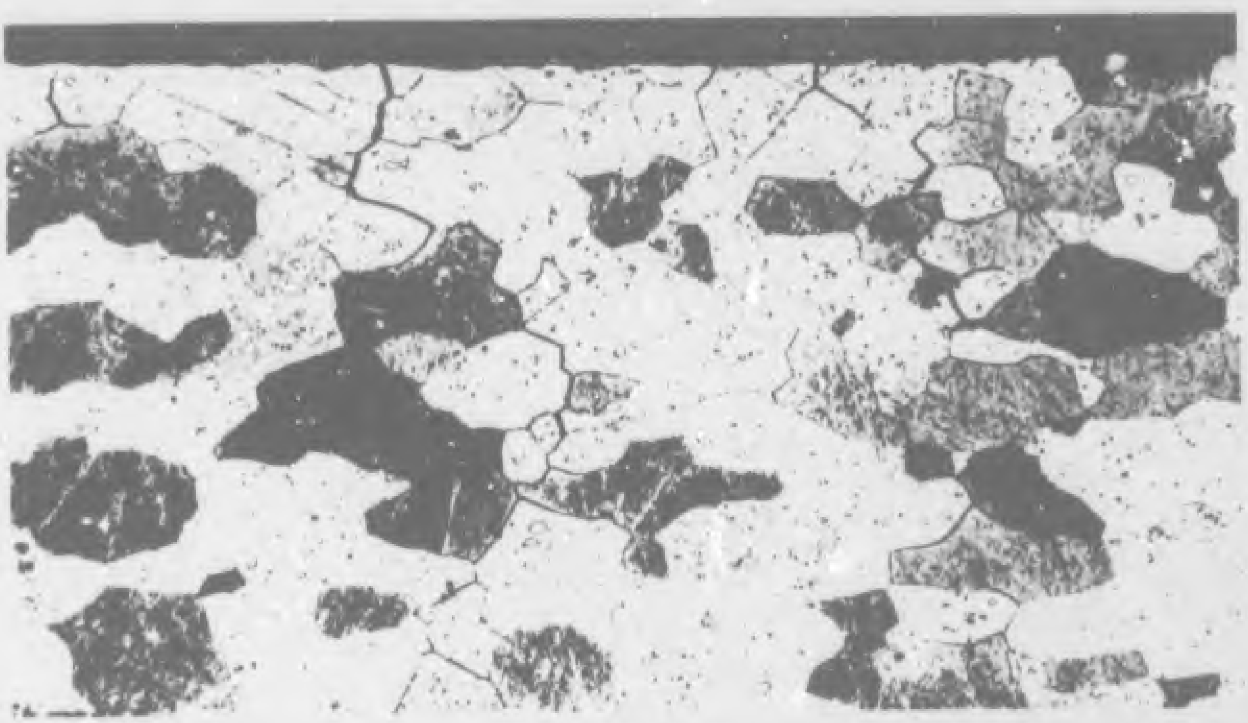
SPEC NO. SWU-21-W-1

FIGURE 36. TYPICAL LINE OF SCC FAILURE THROUGH COLD SIDE OF HEAT AFFECTED ZONE OF X2021-T8E31 SHEET, AS WELDED TEMPER.



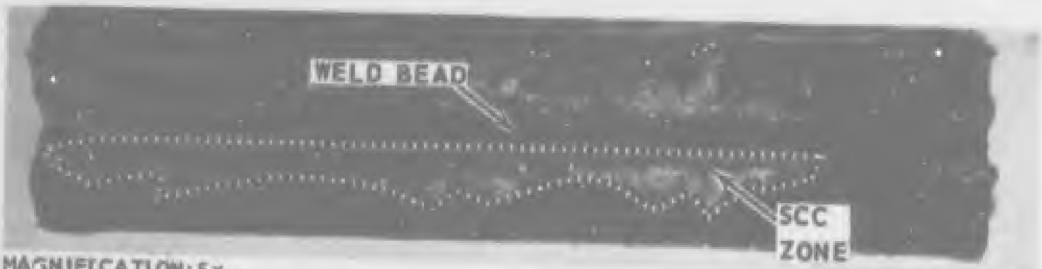
MAGNIFICATION 100× KELLER'S ETCH SPEC NO. SWU-21-W-2

FIGURE 37. MICROSTRUCTURE AT SCC FRACTURE PROFILE OF X2021-T8E31 SHEET, AS WELDED TEMPER.



MAGNIFICATION 250× KELLER'S ETCH SPEC NO. SWU-21-W-2

FIGURE 38. INTERGRANULAR AND TRANSGRANULAR CRACKING IN SCC SUSCEPTIBLE HEAT AFFECTED ZONE OF X2021-T8E31 SHEET, AS WELDED TEMPER.

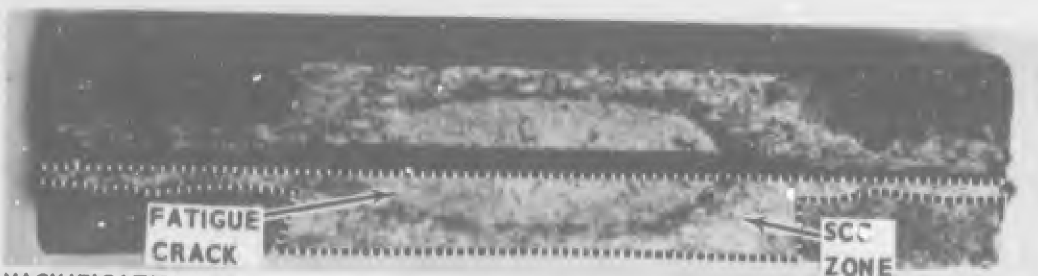


MAGNIFICATION: 5×

SPEC NO. SWU-24-W-1

MAGNIFICATION: 5×

SPEC NO. SWU-24-W-4



MAGNIFICATION: 5×

SPEC NO. SWX-24-W-1

MAGNIFICATION: 5×

SPEC NO. SWX-24-W-2

FIGURE 39. FRACTURE SURFACES OF NOTCHED AND UNNOTCHED 2024-T81 SHEET, AS WELDED TEMPER, THAT FAILED DURING SCC TESTING.

Figure 40). The appearance of the instantaneous fracture appeared independent of post-weld heat treat or the presence of a stress corrosion crack or fatigue crack.

Microscopic examination of unnotched failed specimens indicated origins to be at the edge of the weld bead. Propagation in the flat featureless zone was intergranular into the weld bead or along the edge of the weld bead. The main line of failure exhibited very few branching cracks (see Figure 41).

ALLOY 2219-T87 SHEET

Stress corrosion cracking was not observed for tempers: (1) basic unwelded unnotched, (2) as-welded, notched or unnotched, and (3) weld plus age, notched or unnotched. Crack extension was observed after 606 hours exposure for the step-loaded, notched as-welded temper but was examined microscopically and attributed to corrosion (see Figure 42).

Susceptibility to SCC was incurred with notched and unnotched weld plus STA temper. For the unnotched condition, step-load alternate immersion tests produced SCC failure at 29.0 ksi after accumulating 395 hours of alternate immersion and 30 hours in air between steps. Failure occurred in air prior to loading to next step. Subsequent constant load of 500 hours alternate immersion did not produce failures at 29.0 ksi or 34.2 ksi. The third constant-load specimen failed at 39.5 ksi through the weld bead. Examination of the fracture surface revealed incomplete weld penetration (0.27-inch long) on the bottom side of the weld bead from which the SCC initiated (see Figures 43 and 44).

Metallographic examination of the failed step-load specimen (SWU-19-S-1) confirmed intergranular cracking at the origin of failure (Figures 45 and 46) typical of SCC. The lack of confirmation of the SCC failure with subsequent constant-load tests indicates air exposure and handling may have accelerated the SCC.

Weld plus STA temper step-load tests for notched specimens produced failure at 32.7 ksi (net section stress). Subsequent constant-load tests produced failure at 32.7 ksi (197 hours) but not at 27.3 ksi or 21.8 ksi (500 hours).

Typical SCC fracture of notched, weld plus STA temper is shown in Figure 47. Because fracture surface was similar to the stress corrosion fracture of the unnotched specimen SWU-19-S-4-4, which displayed intergranular cracking below the line of incomplete penetration, metallographic examination was not conducted on notched specimens. Fracture originated at and followed the edge of the weld bead.

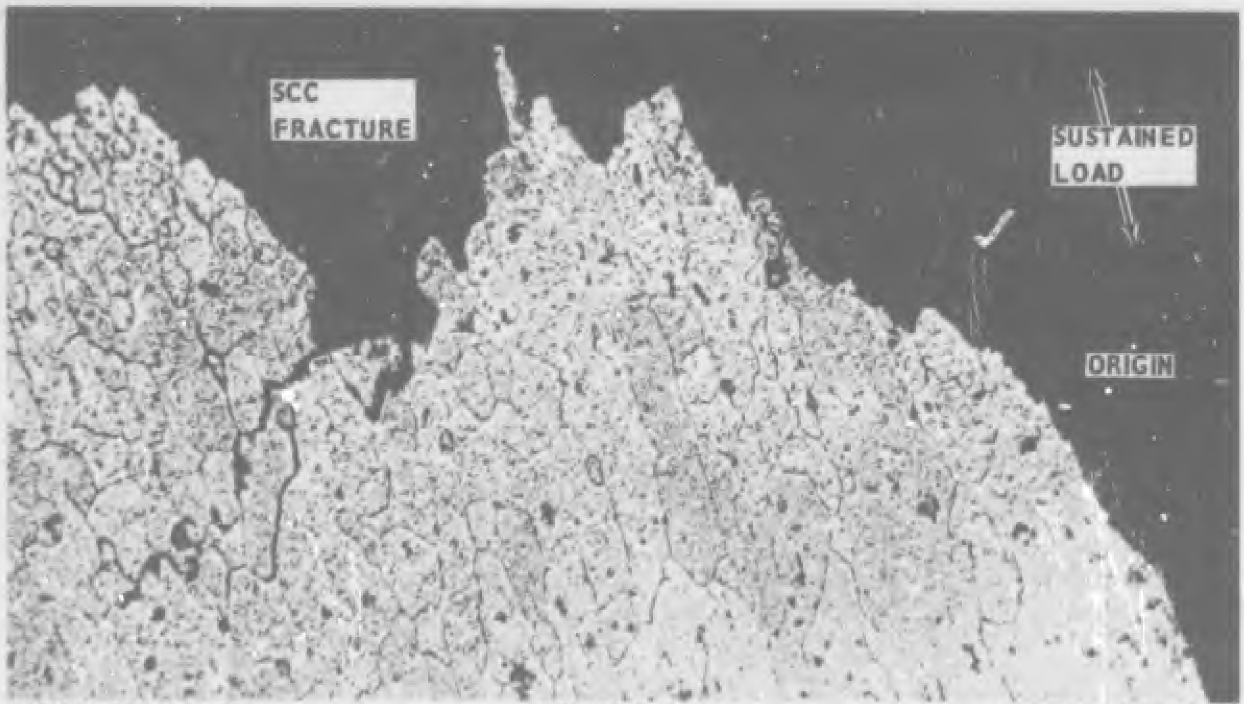
ALLOY X7002-T6 SHEET

Stress corrosion was not observed with unnotched specimens for the tempers evaluated on this program: (1) basic unwelded, (2) as-welded, (3) weld plus age, and (4) weld plus STA.

MAGNIFICATION: 5× WELD + AGE SPEC NO. SWX-24-A-1

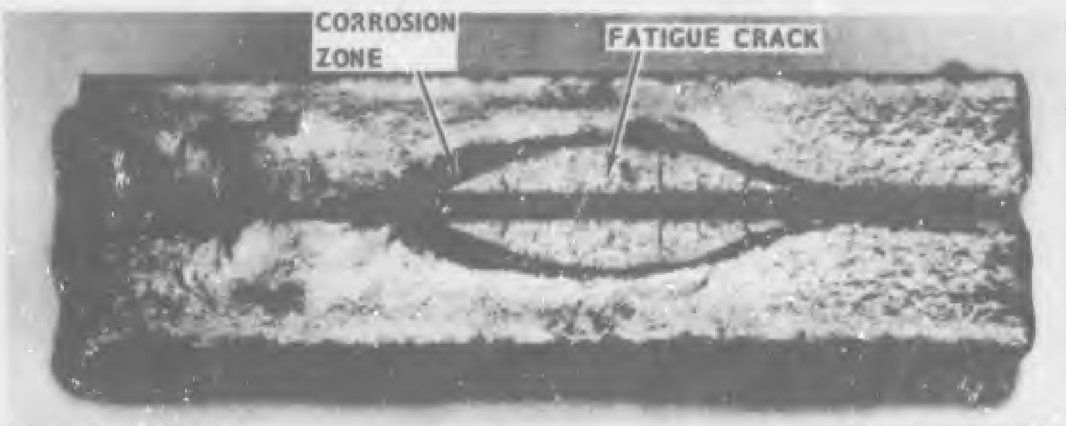
MAGNIFICATION: 5× WELD + STA SPEC NO. SWX-24-S-2

FIGURE 40. FRACTURE SURFACES OF NOTCHED 2024-T81 SHEET, TENSION TESTED AFTER ALTERNATE IMMERSION EXPOSURE.



MAGNIFICATION: 250× KELLER'S ETCH SPEC NO. SWU-24-W-1

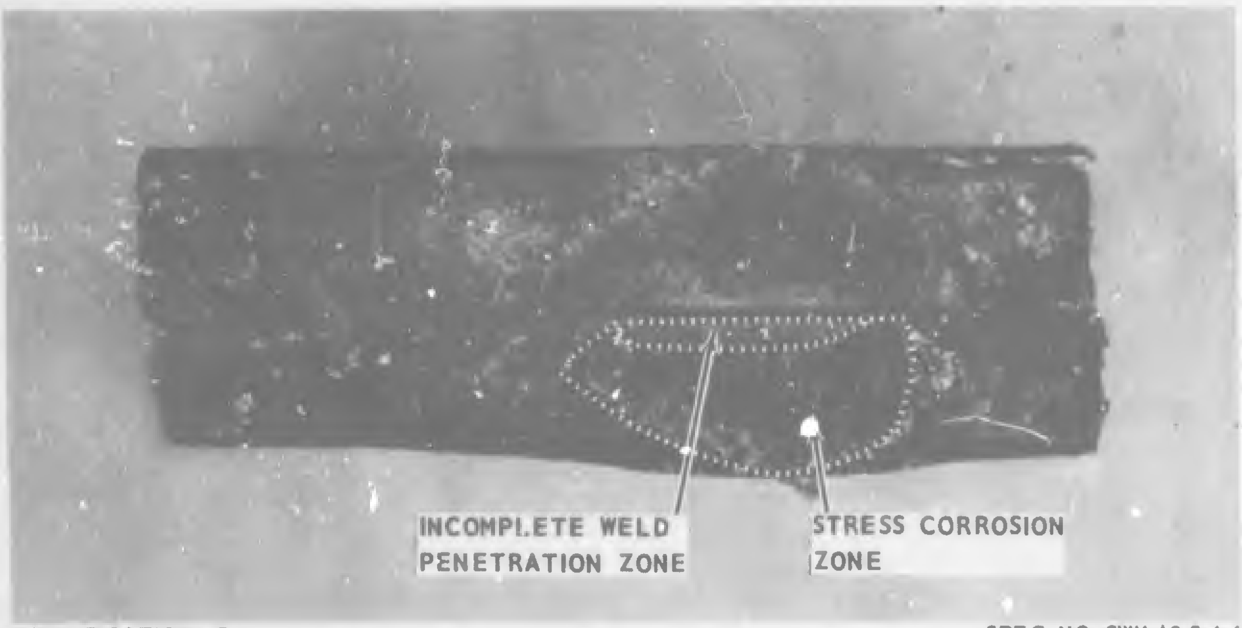
FIGURE 41. MICROSTRUCTURE AT ORIGIN OF SCC FAILURE OF UNNOTCHED 2024-T81 SHEET, AS WELDED TEMPER.



MAGNIFICATION: 5x

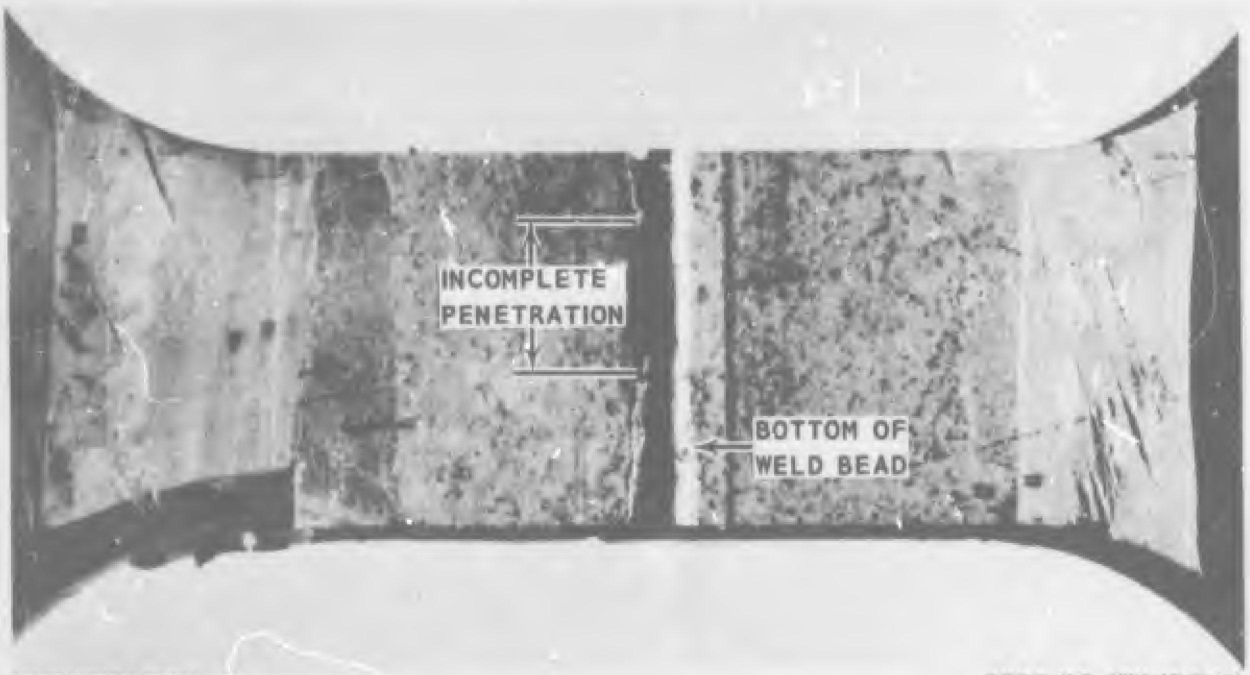
SPEC NO. SWX-19-W-1

FIGURE 42. FRACTURE SURFACE OF NOTCHED 2219-T81 SHEET, WELD + AGE TEMPER, TENSION TESTED AFTER STEP LOAD ALTERNATE IMMERSION EXPOSURE.



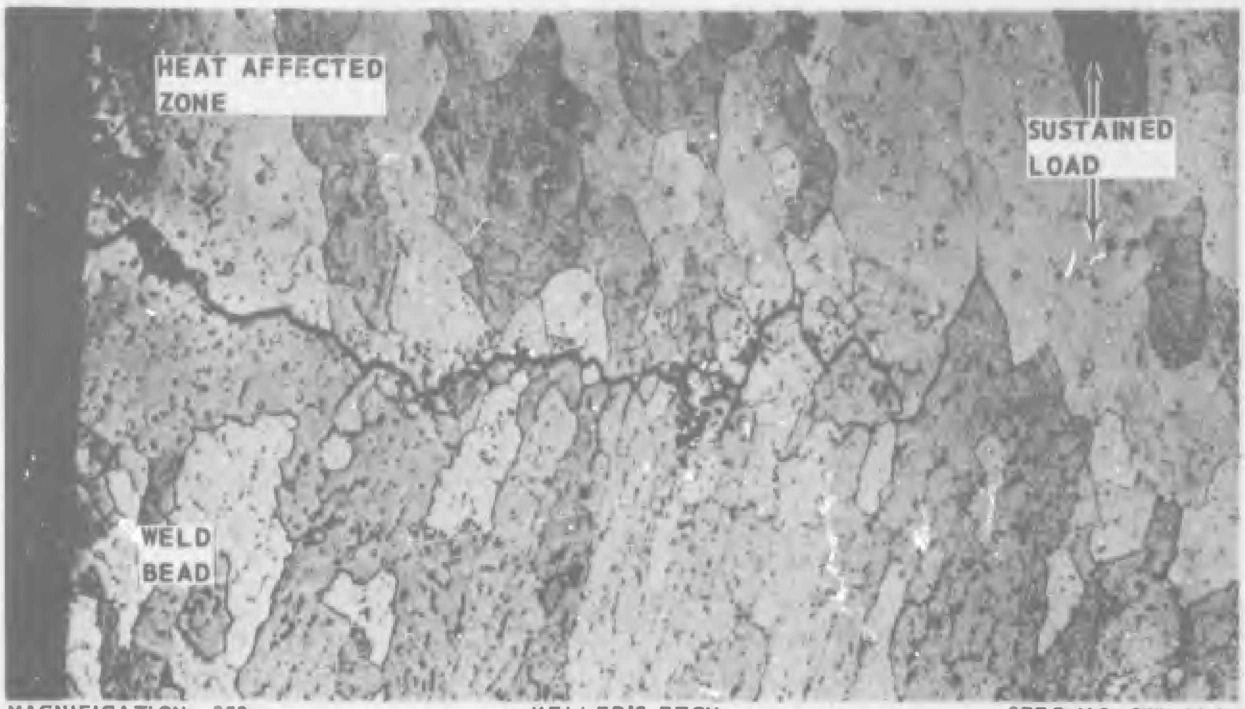
MAGNIFICATION: 5× SPEC NO. SWU-19-S-4-4

FIGURE 43. FRACTURE SURFACE OF 2219-T81 SHEET, WELD + STA TEMPER, THAT FAILED DURING ALTERNATE IMMERSION EXPOSURE AND EXHIBITED INCOMPLETE WELD.



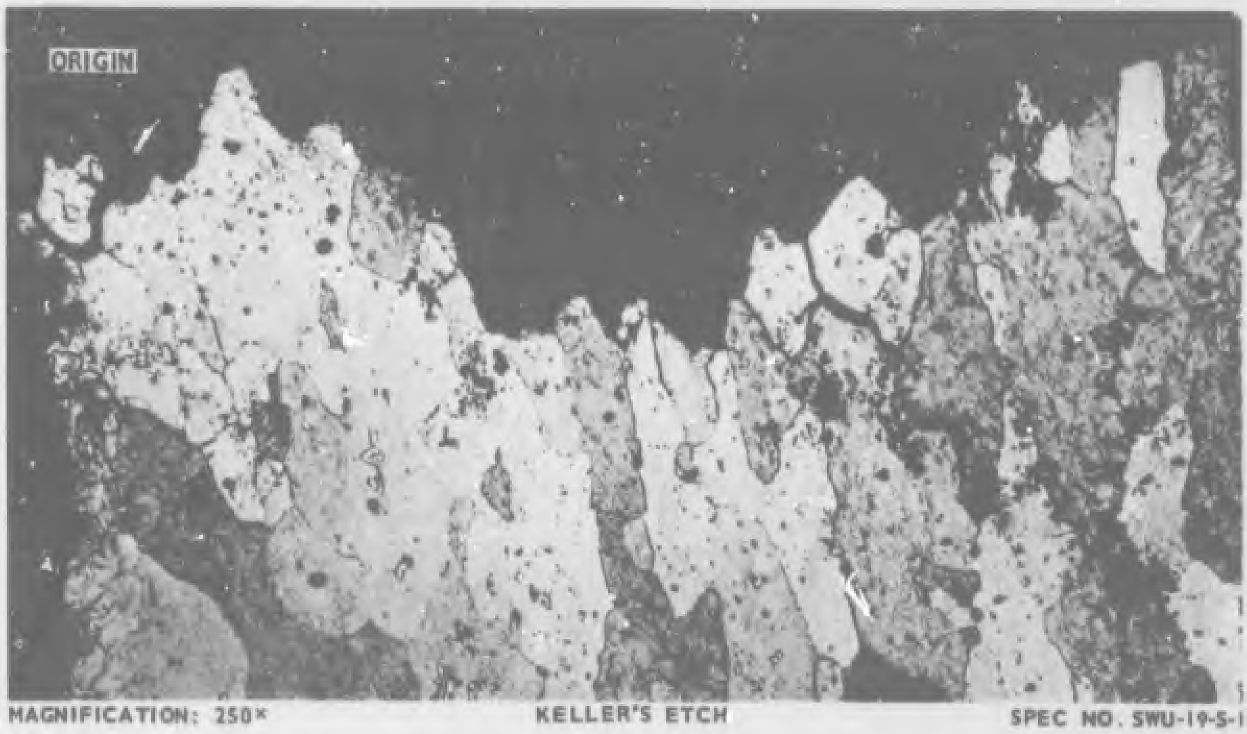
MAGNIFICATION: 2× SPEC NO. SWU-19-S-4-4

FIGURE 44. VIEW OF INCOMPLETE WELD PENETRATION FROM BOTTOM SIDE OF WELD BEAD ON 2219-T81 SHEET, WELD + STA TEMPER.



MAGNIFICATION: 250× KELLER'S ETCH SPEC NO. SWU-19-S-1

FIGURE 45. STRESS CORROSION CRACKING IN MICROSTRUCTURE AT EDGE OF WELD BEAD IN 2219-T81 SHEET, WELD + STA TEMPER, STEP LOAD ALTERNATE IMMERSION EXPOSURE.



MAGNIFICATION: 250× KELLER'S ETCH SPEC NO. SWU-19-S-1

FIGURE 46. MICROSTRUCTURE AT ORIGIN OF FAILURE, EDGE OF WELD BEAD, IN 2219-T81 SHEET, WELD + STA TEMPER, STEP LOAD ALTERNATE IMMERSION EXPOSURE.

The as-welded step-load specimen, unnotched, did fail during step-load alternate immersion testing at 29.1 ksi. This failure occurred through the severely corroded heat-affected zone. A replicate specimen did not fail at 29.1 ksi in 500 hours alternate immersion, and residual strength was 100 percent of unexposed strength. The severely corroded step-load specimen had accumulated 1000 hours alternate immersion, including 284 hours at the last step, to determine if extended exposure would initiate SCC. Microscopic examination revealed severe pitting corrosion at the periphery and transgranular shear in the sudden failure zone which is typical of a corrosion-tensile failure.

SCC was not incurred for notched specimens with as-welded temper with either step-load or constant-load tests.

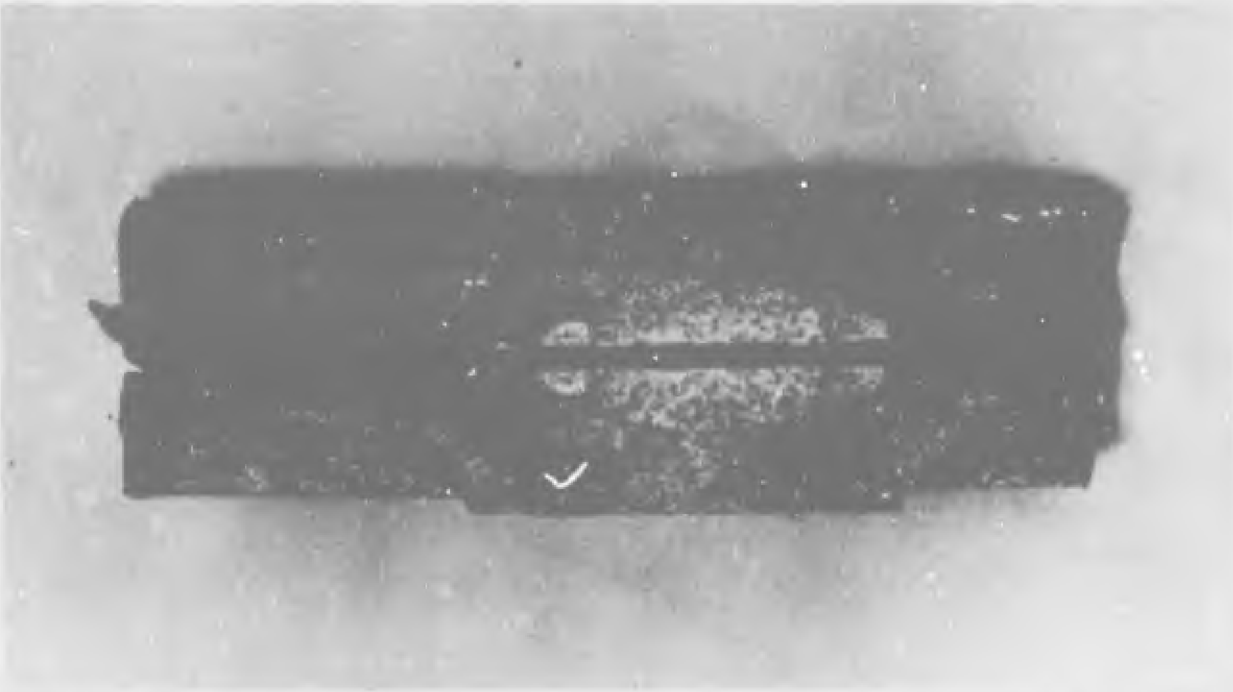
The step-load specimen for notched weld plus age temper displayed environmental crack extension when tension-tested under sustained stresses after exposure up to 38.3 ksi (net section) and 550 hours accumulated alternate immersion. Subsequent constant-load tests produced failures at 42.4 ksi in 139 hours and at 37.2 ksi in 278 hours. The third specimen for constant-load testing failed during loading.

Fracture surface of the step-load specimen is shown in Figure 48, and is also typical of the failed constant-load specimens. The dark zone extended from and 90° to the tip of fatigue crack and the edge of the weld bead into the weld bead.

Microsections through this dark zone revealed intergranular cracking of columnar grains of the weld bead with transgranular steps through the grains as the crack front progressed through the thickness. Because the intergranular cracking was not random and the step-load specimen did not fail after longer exposure hours than the constant-load specimens, which would promote failure if corrosion was the primary mode, the dark zone is attributed to SCC.

Although the constant-load alternate immersion threshold stress for no failure in 500 hours was not well defined for the notched, weld plus age temper, based on the general relationship of step-load threshold to constant-load threshold for other notched sheet specimens (i.e., step-load failure threshold being either below constant-load threshold or not more than 7.8 ksi above, Table VII), it is considered that the constant-load threshold for notched, weld plus age temper is not lower than 38.3 ksi (step-load stress) - 7.8 ksi = 30.6 ksi.

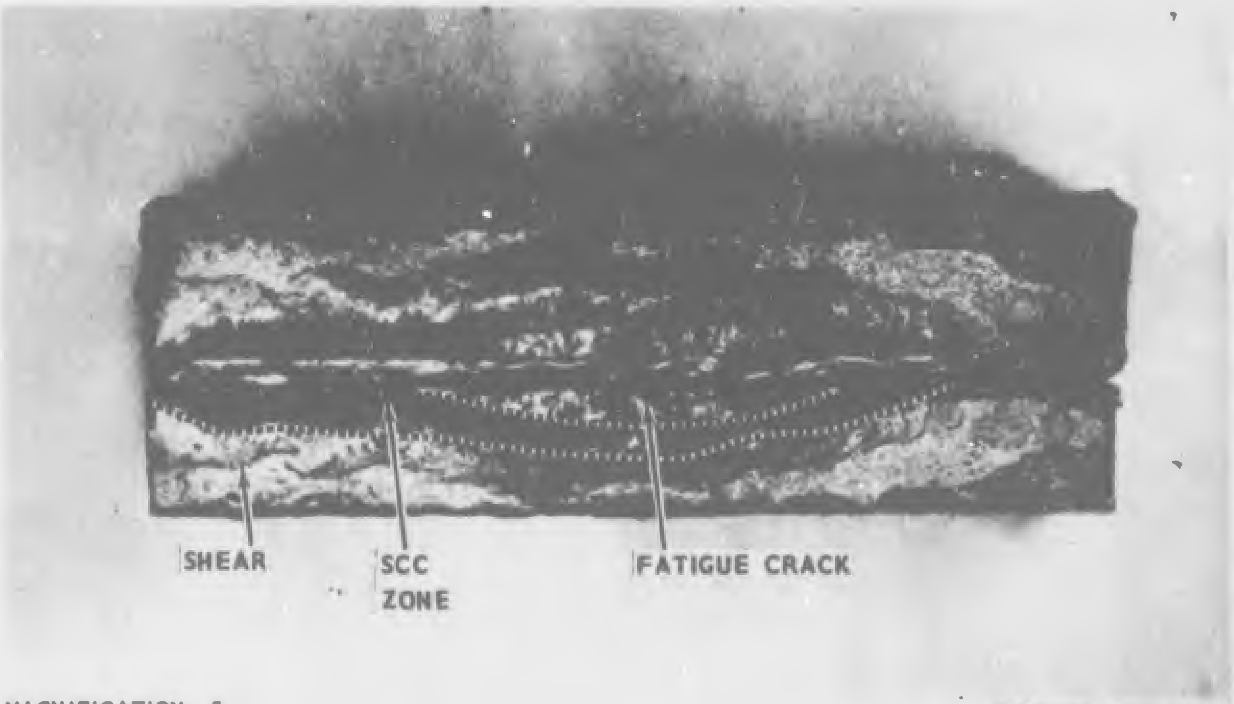
For the weld plus STA temper, notched, the step-load specimen failed in 316 hours at 40.5 ksi (net section stress) after crack extension was indicated by X-ray at 34.7 ksi. Fracture appearance was similar to that of the weld plus age temper. Constant-load tests did not confirm step-load results with specimens at 35.1 ksi, 41.9 ksi, and 47.8 ksi surviving 500 hours alternate immersion displaying residual strengths 94 to 1.07 percent of unexposed strength.



MAGNIFICATION: 5×

SPEC NO. SWX-19-S-1

FIGURE 47. FRACTURE SURFACE OF NOTCHED 2219-T81 SHEET, WELD + STA TEMPER, THAT FAILED DURING STEP LOAD ALTERNATE IMMERSION EXPOSURE.



MAGNIFICATION: 5×

SPEC NO. SWX-02-A-1

FIGURE 48. TYPICAL FRACTURE APPEARANCE OF NOTCHED 7002-T6 SHEET, WELD + AGE TEMPER, FAILED DURING ALTERNATE IMMERSION EXPOSURE.

ALLOY 7039-T64 SHEET

Stress corrosion cracking was not observed for the following tempers: (1) basic unwelded, unnotched, and (2) as-welded notched or unnotched. Corrosion-tensile-failure did occur through the heat-affected zone for the step-load tests for both notched and unnotched as-welded temper after accumulating 694 hours and 616 hours in alternate immersion, respectively. Subsequent constant-load 500-hour alternate immersion tests did not produce SCC at 24.9 ksi (75-percent yield strength) for the unnotched condition and 40.9 ksi (76-percent of net section notch strength) for the notched condition.

Stress corrosion cracking was observed for weld plus age unnotched condition at 39.7 ksi (89-percent yield strength) when unintentionally loaded according to the higher yield strength of the weld plus STA temper. Since loads above 75-percent yield strength were beyond the scope of the program subsequent constant-load tests were run at 75-percent yield strength of the weld plus age temper, 33.4 ksi, and stress corrosion was not incurred in 500 hours of exposure.

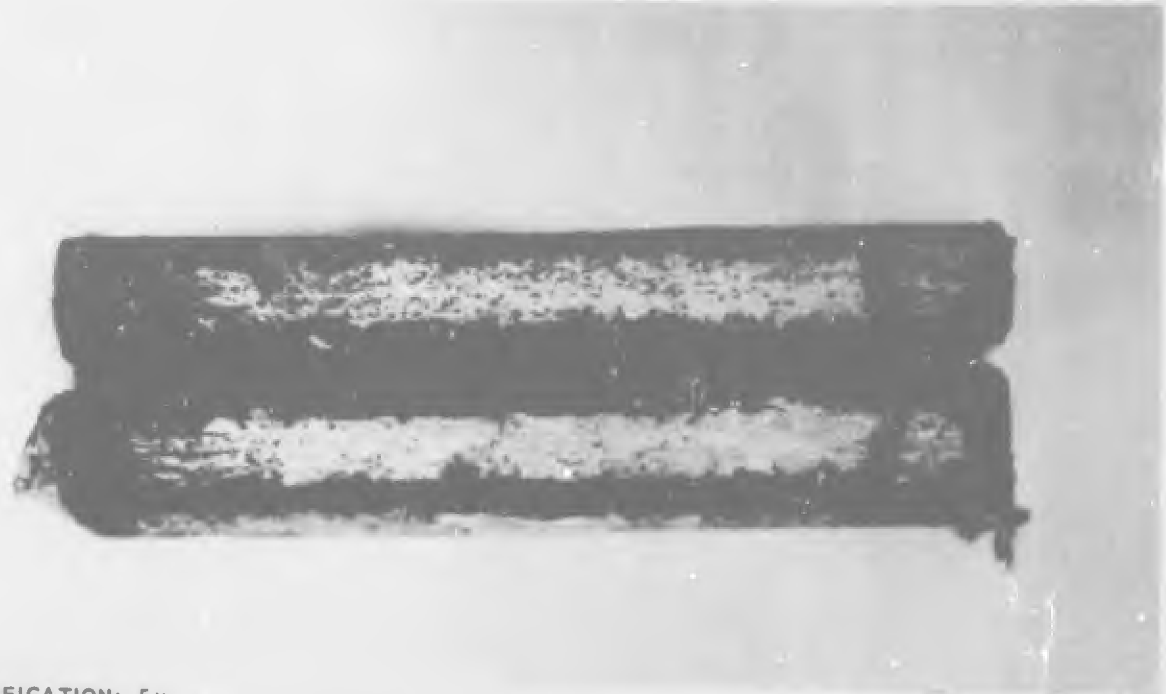
Stress corrosion did not occur with weld plus age notched condition during step-load tests up to 37.6 ksi (73-percent net section notch strength) but subsequent constant-load test at 39.4 ksi (75.9-percent net section notch strength) failed in 389 hours. Constant-load failure did not occur at 34.6 ksi.

The unnotched step-load specimen for the weld plus STA temper did not fail at stresses up to 33.4 ksi. Constant-load specimens did not fail at 29.0 ksi and 34.4 ksi but did at 39.7 ksi (75-percent yield strength). The notched step-load weld plus STA specimen failed at 39.1 ksi (60-percent net section notch strength) after 560 accumulated hours of alternate immersion, but constant-load specimens did not fail at 39.4 ksi, 41.7 ksi, or 43.0 ksi in 500 hours.

Failure of the step-loaded notched weld plus STA temper at lower stress levels may indicate (1) an accelerating effect of stress corrosion by air exposure, during handling for step loading, or (2) a mechanical rupture of surface films at the crack tip during handling and step loading which exposes fresh metal to the corrodent.

Fracture and surface appearance of the corrosion-tensile failed step load, notched, as-welded temper are shown in Figures 49 and 50. Failure occurred out of the plane of the fatigue crack through the heat-affected zone. Metallographic examination confirmed pitting corrosion followed by tensile failure.

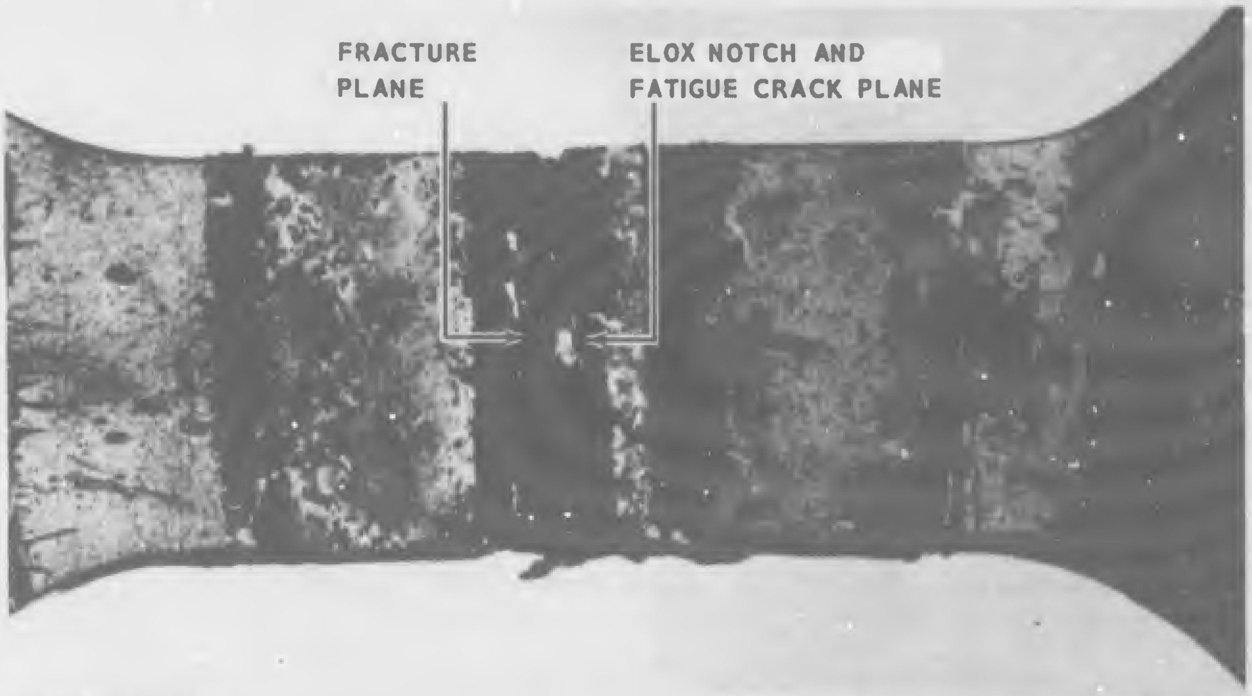
Typical fracture surfaces of specimens that failed during stress corrosion testing weld plus age, and weld plus STA are shown in Figure 51. Regardless of temper or notch stress, corrosion-failed specimens exhibited dark fracture at the edge of the weld bead which was followed by striations and terminated in shear. Fracture surface of a specimen tension-tested after 500 hours alternate immersion exposure is shown in Figure 52, illustrating a full shear failure which was typical of specimens that did not fail during SCC testing. Dark tears along the edge of and 90° to the fatigue



MAGNIFICATION: 5×

SPEC NO. SWX-39-W-1

FIGURE 49. FRACTURE APPEARANCE OF 7039-T64 SHEET, AS WELDED TEMPER, EXHIBITING CORROSION-TENSILE FAILURE THROUGH HEAT AFFECTED ZONE.



MAGNIFICATION: 2×

SPEC NO. SWX-39-W-1

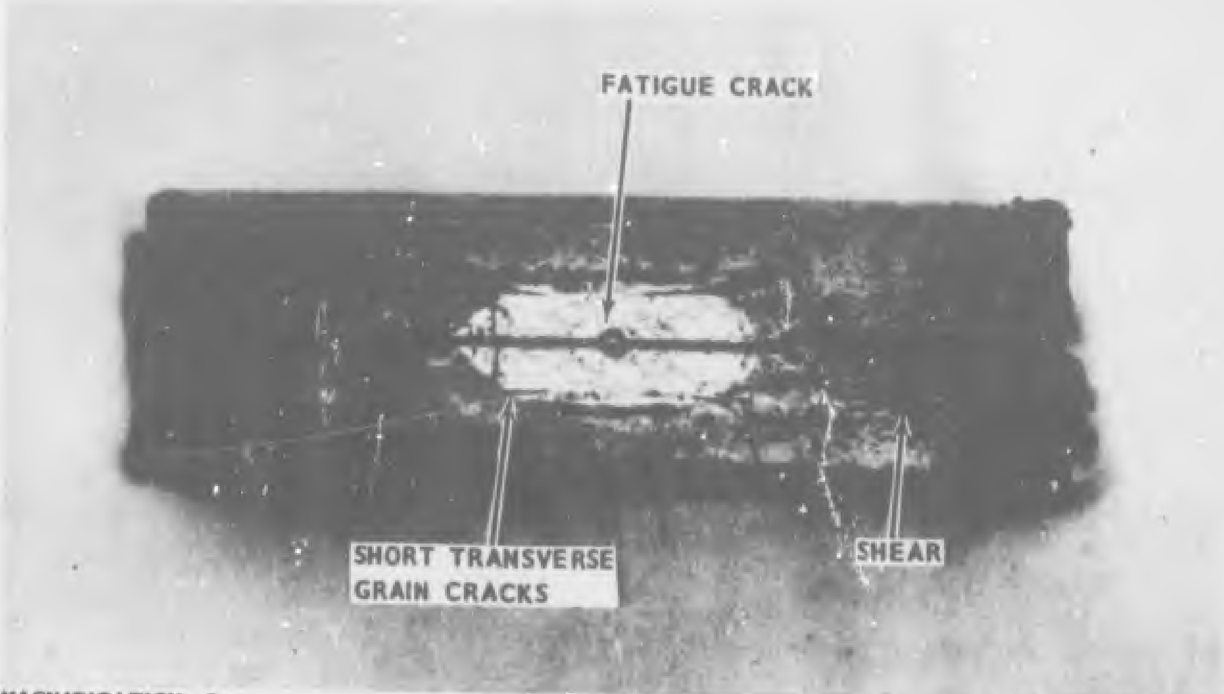
FIGURE 50. SURFACE APPEARANCE OF NOTCHED 7039-T64 SHEET, AS WELDED TEMPER, EXHIBITING CORROSION-TENSILE FAILURE THROUGH HEAT AFFECTED ZONE.

MAGNIFICATION: 5× NOTCHED, WELD + AGE SPEC NO. SWX-39-A-3

MAGNIFICATION: 5× NOTCHED, WELD + STA SPEC NO. SWX-39-S-1

MAGNIFICATION: 5× UNNOTCHED, WELD + STA SPEC NO. SWX-39-S-2

FIGURE 51. TYPICAL FRACTURE APPEARANCE OF 7039-T64 SHEET, WELD + POST WELD HEAT TREAT, FAILED DURING ALTERNATE IMMERSION EXPOSURES.



MAGNIFICATION: 5×

SPEC NO. SWX-39-S-4

FIGURE 52. FRACTURE APPEARANCE OF NOTCHED 7039-T64 SHEET, WELD + STA TEMPER, TENSION TESTED AFTER ALTERNATE IMMERSION EXPOSURE.

crack plane are considered evidence of short transverse SCC since they were not evident on unexposed, tension-test specimens.

Microstructures, at the edge of the weld bead through the dark fracture zone, exhibited pitting corrosion and short transverse cracking as shown in Figures 53 and 54.

ALLOY 7106-T6 SHEET

Stress corrosion cracking was not observed for the basic unwelded temper, unnotched, or the as-welded temper, unnotched.

Step-load, as-welded temper, unnotched, did fail through the heat-affected zone at 26.8 ksi, after accumulating 503 hours of alternate immersion and 73 hours in air between steps. Constant-load replicate specimens did not fail at 21.1 ksi, 27.5 ksi, and 31.7 ksi in 500 hours of alternate immersion, and residual ultimate strengths were 99, 97, and 87 percent, respectively. Fracture surface of the failed step-load specimen exhibited severe periphery corrosion followed by shear in the sudden failure zone. Failure was considered a corrosion-tensile failure.

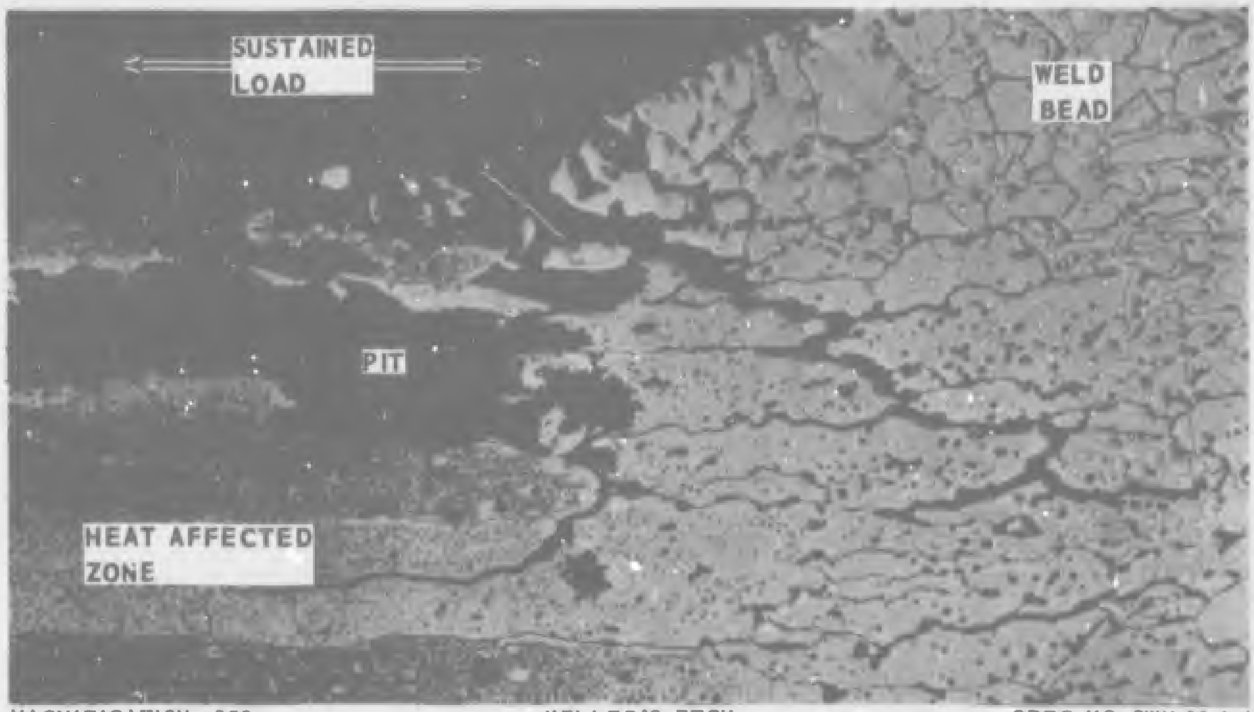
Step-load, as-welded temper, notched, failed at 29.8 ksi (net section stress) after accumulating 493 hours of alternate immersion and 54 hours in air between steps. Three replicate specimens did not fail under constant-load testing at 31.9 ksi, 36.3 ksi, or 38.7 ksi in 500 hours of alternate immersion, and residual net section strengths were 76 percent, 95 percent, and 88 percent of unexposed strength, the reduction in strength being attributed to corrosion at the edge of the weld bead.

Fracture surface of the as-welded, step-load, notched, specimen is shown in Figure 55, and is typical of specimens that failed during SCC testing of this alloy. It is visually different from unfailed specimens tension-tested after SCC testing, which exhibited full shear fracture regardless of temper and whether notched or unnotched.

Because constant-load alternate immersion did not confirm step-load alternate immersion, stress corrosion may occur at a faster rate in air for 7106-T6 as-welded temper with an existing crack. Also, handling of specimens or increasing load by steps may cause rupture of surface films at the crack tip allowing corrodent to attack fresh metal thus accelerating stress corrosion. Stress corrosion cracking was observed for weld plus age and weld plus STA tempers in both notched and unnotched conditions.

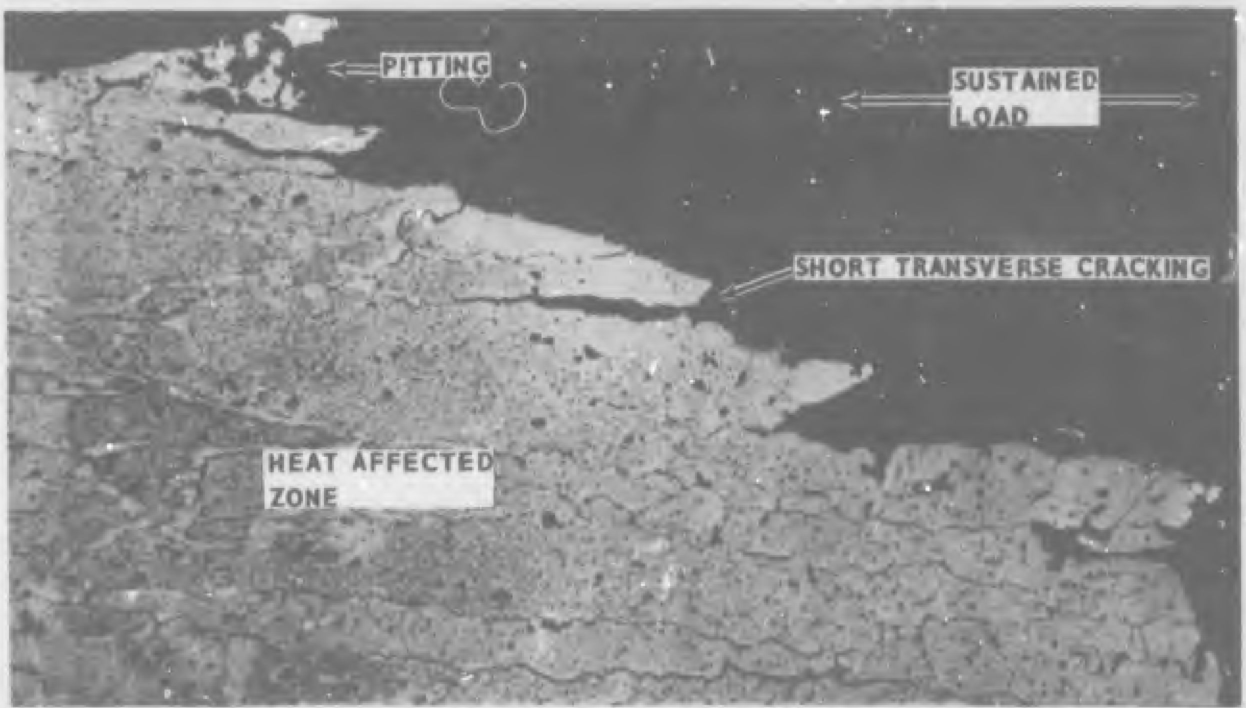
For the weld plus age temper, unnotched, failure occurred at 29.4 ksi during step-load tests. Subsequent constant-load tests produced failures at 29.4 ksi and 26.7 ksi, but not at 24.0 ksi. For notched specimens, the step-loaded specimen failed at 15.3 ksi (net section stress). Subsequent constant-load tests produced failure at 15.3 ksi and 13.8 ksi but not at 10.1 ksi.

For weld plus STA temper, step-load and constant-load failures occurred at 39.3 ksi for unnotched condition. Additional constant-load specimens did not fail at 36.3 ksi and 33.2 ksi. Step-load failure with notched



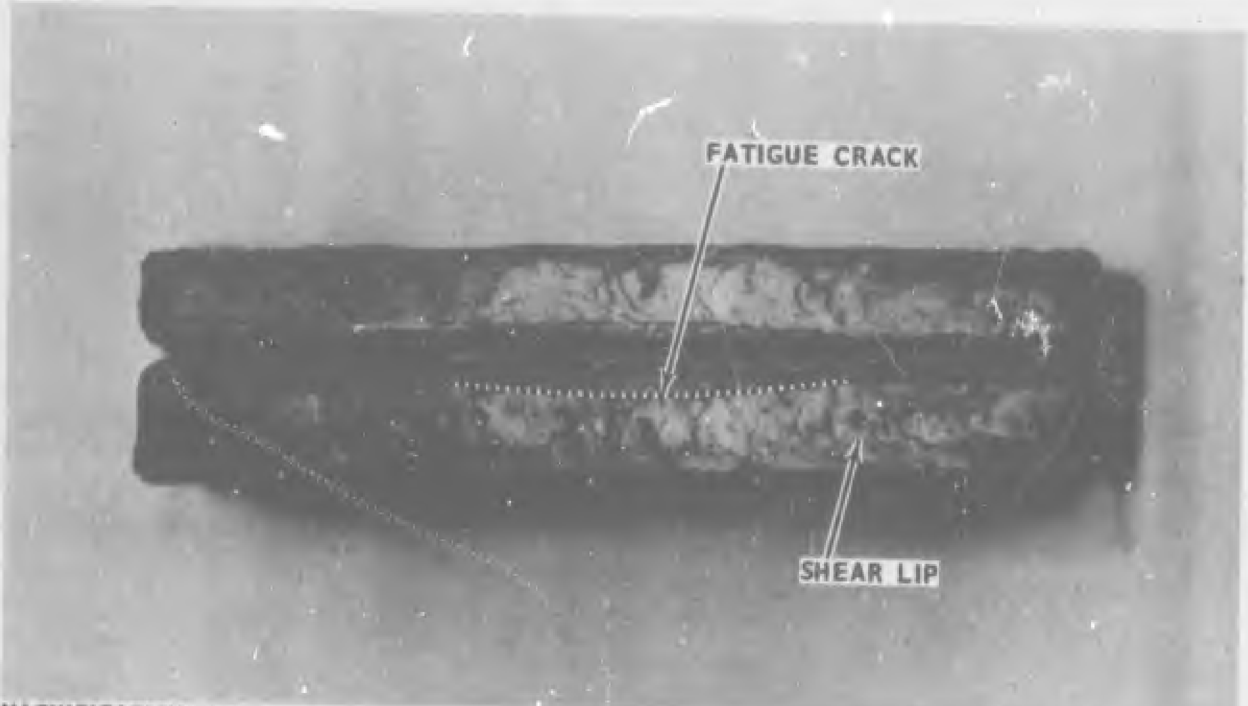
MAGNIFICATION: 250× KELLER'S ETCH SPEC NO. SWU-39-A-1

FIGURE 53. PITTING AT EDGE OF WELD BEAD IN 7039-T64 SHEET, WELD + AGE TEMPER, FAILED DURING STEP LOAD ALTERNATE IMMERSION EXPOSURE.



MAGNIFICATION: 250× SPEC NO. SWU-39-S-2

FIGURE 54. PITTING AND CRACKING AT SCC ORIGIN, EDGE OF WELD BEAD, IN 7039-T64 SHEET, WELD + STA TEMPER, FAILED DURING ALTERNATE IMMERSION EXPOSURE.



MAGNIFICATION: 5×

SPEC NO. SWX-06-W-1

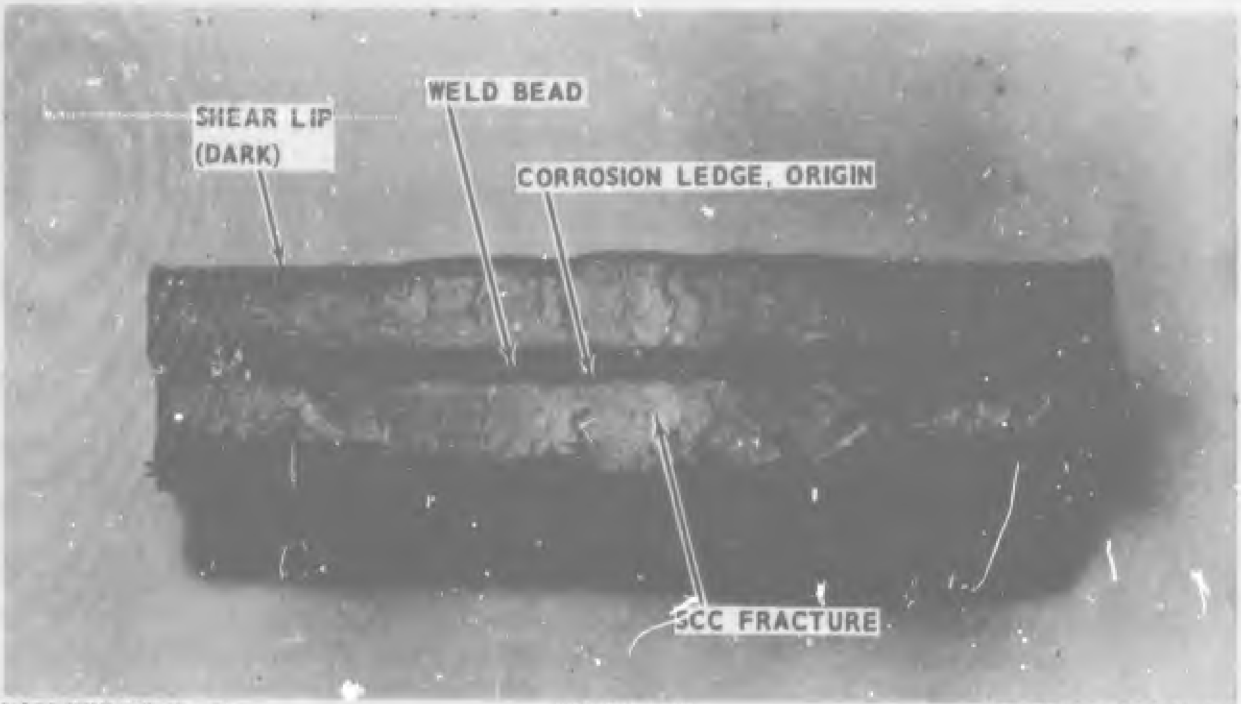
FIGURE 55. FRACTURE SURFACE OF NOTCHED 7106-T6 SHEET, AS WELDED TEMPER, THAT FAILED DURING STEP LOAD ALTERNATE IMMERSION EXPOSURE.

specimens occurred at 16.7 ksi (net section stress) and constant-load failure occurred at 16.4 ksi. Additional constant-load specimens did not fail at 13.6 ksi and 10.1 ksi.

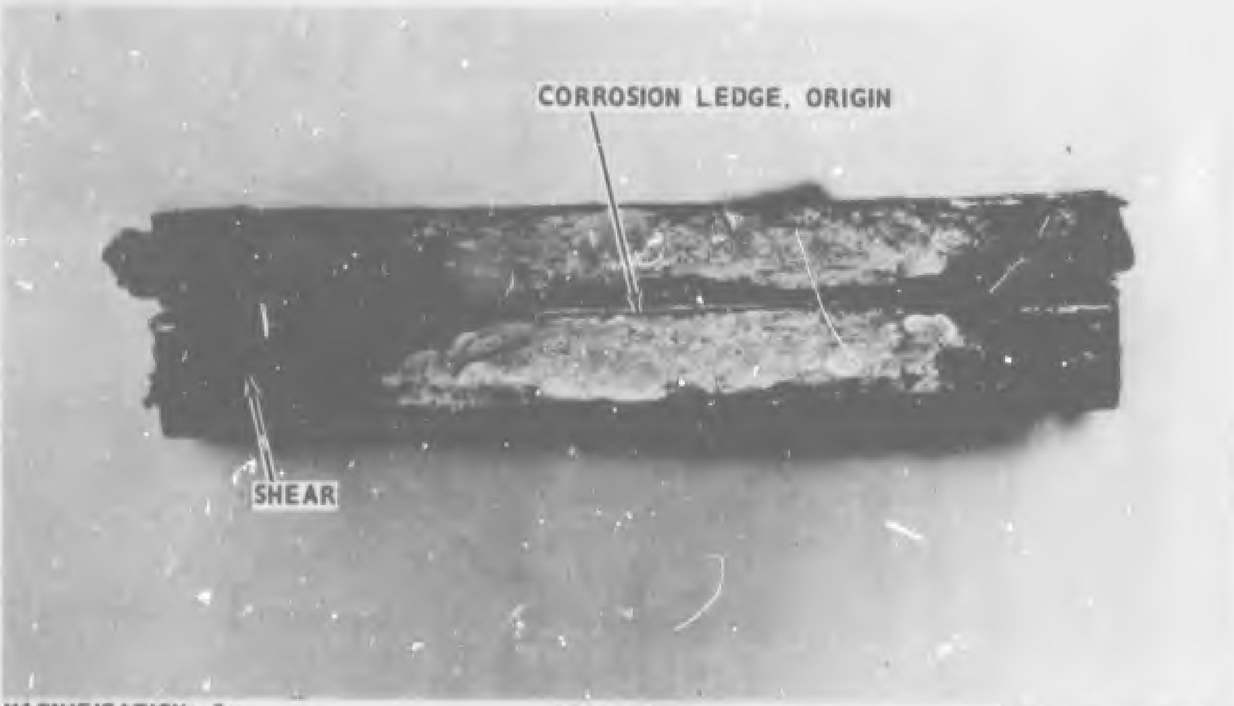
Fracture surfaces of unnotched weld plus age and weld plus STA specimens which failed during SCC testing are shown in Figure 56. The origin of failure appeared as a thin corrodent ledge at the edge of the weld bead with the main fracture at 90° to and behind the ledge following the edge of the weld bead through the thickness as a curve-linear surface.

Metallographic examination revealed pitting corrosion at the edge of the weld bead and intergranular cracking into the weld bead approximately parallel to sustained load. At this point, crack direction changed abruptly and continued through the specimen thickness along the edge of the weld bead. Figure 57 illustrates the severe pitting corrosion observed at the edge of the weld bead (origin) for weld plus age temper specimen that failed during step-load alternate immersion test. Figure 58 illustrates the ledge formation to be corrosion pitting and intergranular cracking that progressed toward the weld bead, in this case viewed at the edge of the weld bead on the unfailed side. Short transverse grain direction cracks were also found approximately 5 to 10 grains below the surface in this specimen.

Typical fracture surfaces of notched specimens which failed during SCC testing are shown in Figure 59. Because fracture appearance was similar to unnotched stress-corrosion failed specimens and did not display the full shear fracture of notched, unfailed specimens tension-tested after exposure, failures were considered due to stress corrosion. It was observed that the fatigue crack did not extend in its plane but rather stepped out of the plane, parallel to sustained load, and then continued along the edge of the weld bead through the thickness. In some cases, the full fatigue crack was not visible on the fracture surface (see Figure 59). This may be due to susceptibility of the short transverse grain direction or a more susceptible region adjacent to the fatigue crack.

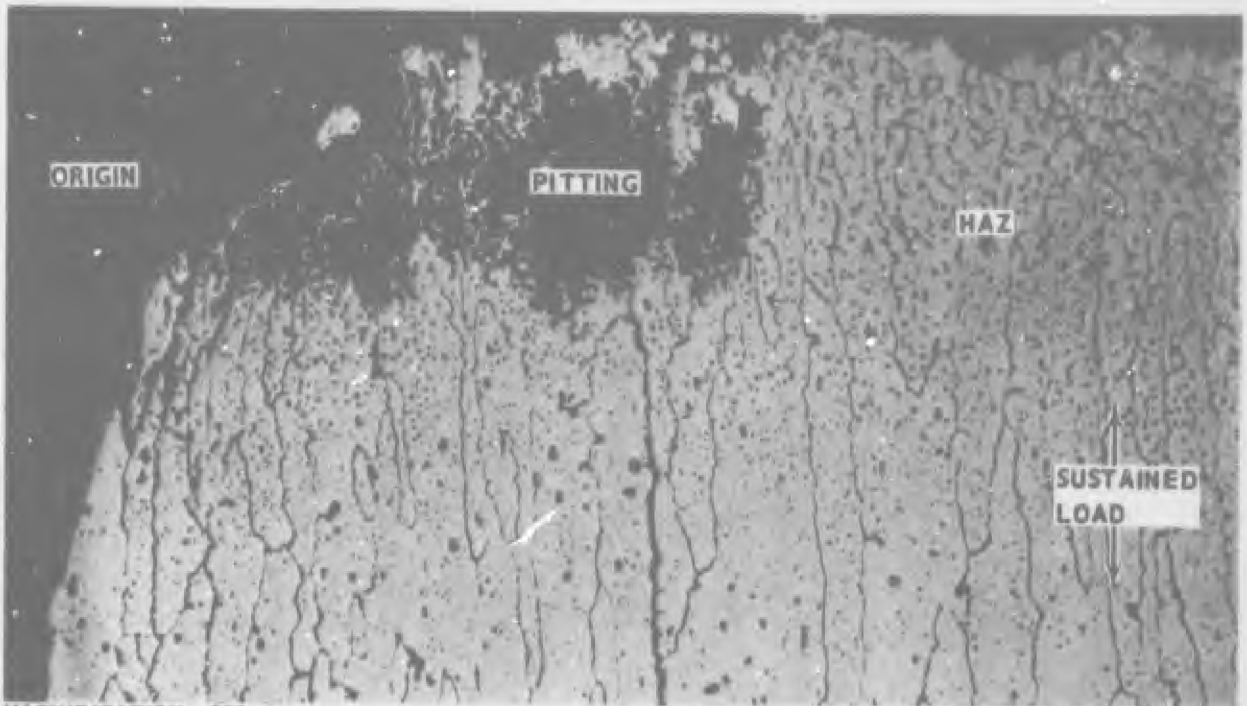


MAGNIFICATION: 5× WELD + AGE SPEC NO. SWU-06-A-4



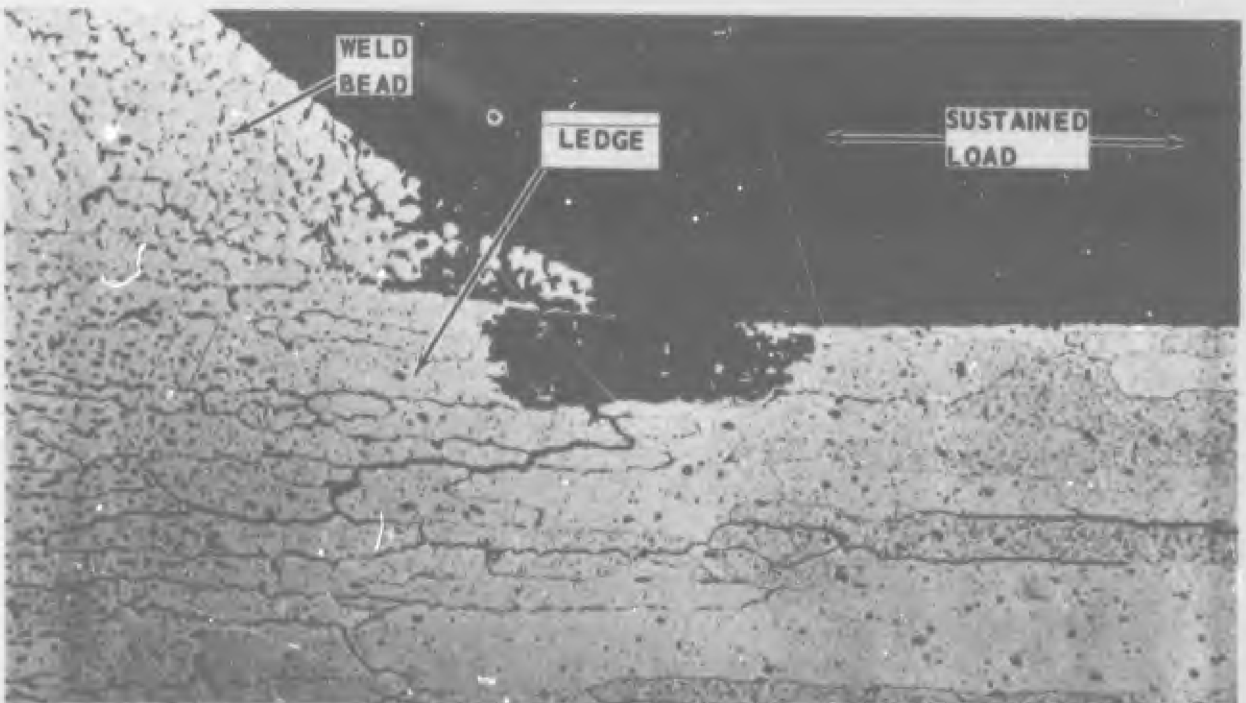
MAGNIFICATION: 5× WELD + STA SPEC NO. SWU-06-S-2

FIGURE 56. FRACTURE SURFACES OF UNNOTCHED 7106-T6 SHEET THAT FAILED DURING ALTERNATE IMMERSION EXPOSURE.



MAGNIFICATION: 250×　　SPEC NO. SWU-06-A-1

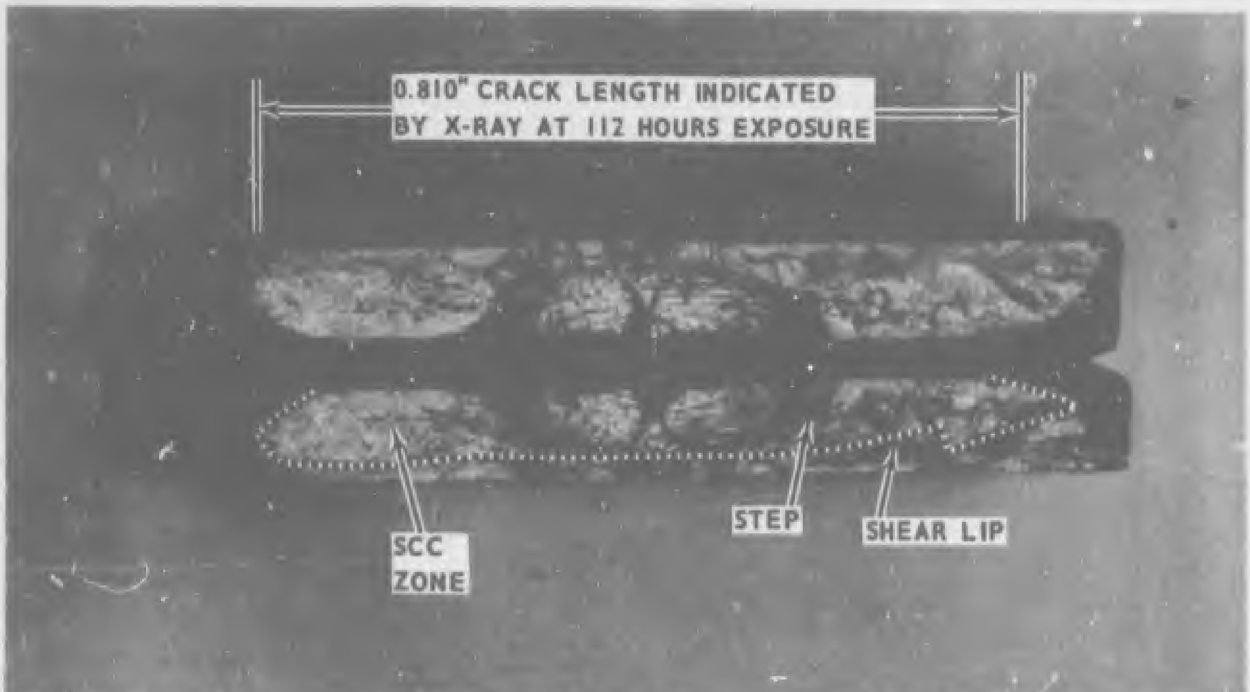
FIGURE 57. PITTING CORROSION AT ORIGIN OF FAILURE, UNNOTCHED 7106-T6 SHEET, WELD + AGE TEMPER.



MAGNIFICATION: 250×　　SPEC NO. SWU-06-A-1

FIGURE 58. PITTING CORROSION AND STRESS CORROSION CRACKING AT EDGE OF WELD BEAD IN 7106-T6 SHEET, WELD + AGE TEMPER.

MAGNIFICATION: 5× WELD + AGE SPEC NO. SWU-06-A-1



MAGNIFICATION: 5× WELD + AGE SPEC NO. SWU-06-S-1

FIGURE 59. FRACTURE SURFACE APPEARANCE OF NOTCHED 7106-T6 SHEET THAT FAILED DURING STEP LOAD ALTERNATE EXPOSURE.

SECTION VIII

RESULTS OF SCC TESTS – PLATE

Step-load tests and constant-load tests were conducted on plate alloy-weld-tempers in a manner similar to sheet specimens. Results and discussion of the plate tests concern the data in Tables A-18 through A-27 in the Appendix. The test data are first summarized and then discussed in detail in this section.

SUMMARY

Stress-Corrosion Thresholds

The following plate alloy-weld-tempers were found susceptible to SCC below 75-percent weldment yield strength: 2014-T6 weld plus STA, notched and unnotched; X2021-T8E31 weld plus STA, notched only; and 7039-T64 weld plus STA, notched and unnotched. Other alloy-weld-tempers and basic unwelded tempers as illustrated in Figure 60 had SCC thresholds indicated above 75-percent yield strength.

From Figure 60, the alloy-weld-tempers are ranked in the following order of unnotched SCC threshold as indicated by SCC tests up to 75-percent yield strength test level for the unnotched and 75-percent notch strength for the notched specimens. (Net section notched thresholds are shown in parentheses.)

Basic – Unwelded

Material	Threshold (ksi)
2024-T851	>50.4
2014-T6	>49.1
X2021-T8E31	>48.2
2219-T87	>42.7
X7002-T6	>41.5
7106-T6	>40.6
7039-T64	>40.6

As-Welded

Material	Threshold (ksi) Unnotched	Threshold (ksi) Notched (net)
2024-T851	>28.7	(>19.1)
7039-T64	>23.9	(>35.1)
2014-T6	>21.4	(>11.1)
X2021-T8E31	>17.5	(>20.8)
2219-T87	>15.5	(>23.5)

Weld + Age

Material	Threshold (ksi)	
2024-T851	>33.1	(>15.7)
X2021-T8E31	>27.0	(>17.4)
7039-T74	>26.3	(>33.5)
2014-T6	>24.2	(>16.8)
2219-T87	>23.9	(>28.2)

Weld + STA

Material	Threshold (ksi)	
X2021-T8E31	>46.8	(13.7)
2014-T6	44.2	(18.3)
2024-T851	>42.1	(>21.2)
2219-T87	>32.1	(>35.3)
7039-T64	31.3	(17.9)

>= no failure at maximum test level

These data illustrate a higher probable SCC threshold will be achieved with post-weld age and post-weld solution heat treat and age for the alloys studied. However, with alloys X2021-T8E31, 2014-T6, and 7039-T64 solution heat treated and aged after welding, the SCC threshold is significantly lower in the presence of a fatigue crack.

Comparison of Step-Load and Constant-Load Data

Although relatively few cases of stress corrosion occurred with the plate tests, it was observed that during step-load tests SCC initiated near or below the subsequent constant-load threshold in five out of five cases and, in three out of five cases, final failure occurred above the threshold. This agrees with the relationship indicated in sheet material tests: (1) step-load specimens that failed above the constant-load threshold may have incurred SCC at lower stress but were not detected by X-ray, and (2) step-load testing indicates a lower SCC threshold for some alloy-weld-tempers than constant-load testing.

Crack Initiation and Propagation

Time for crack initiation and propagation rates was studied from plate specimen data. In several cases of fatigue cracked specimens, environmental crack extension was observed to occur at slow rates without failure and independent of stress.

Subsequent metallographic examination confirmed extension due to corrosion. It is evident that with testing procedures devised to monitor SCC initiation and propagation, sufficient tests and evaluation of specimens must be included to confirm the mode of cracking.

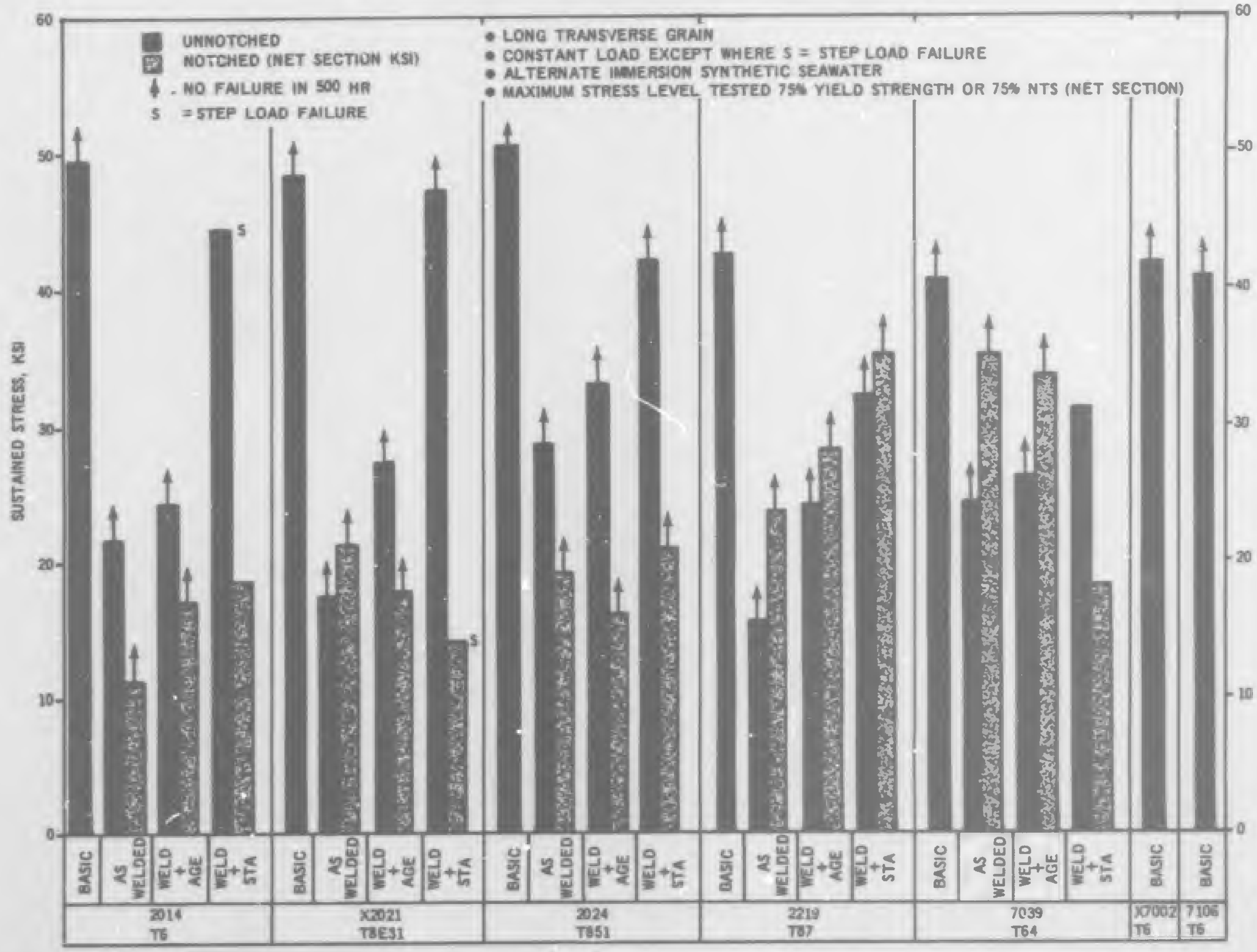


FIGURE 60. COMPARISON OF SCC THRESHOLD STRESS FOR NOTCHED AND UNNOTCHED, AS WELDED AND POST WELD HEAT TREATED ALUMINUM ALLOY PLATE.

All stress-corrosion cracks initiated at the edge of the weld bead and, in general, followed the fusion line with branches extending into the weld bead and into the heat-affected zone. Short transverse grain-direction cracks were also found accompanying the main crack front.

Inspection of step-load data and constant-load data for notched plate indicates the stress-corrosion crack moves in jumps rather than with a gradually increasing rate of propagation, and that corrosion consumes a major part of the exposure time-to-failure. Considering discrete loads and exposure times (continuous monitoring was not performed on this program) stress-corrosion crack propagation rates were observed as high as 3.20×10^{-3} in/hr during exposure. Corrosion rates were observed as low as 0.12×10^{-3} in/hr. Because these data are limited by discrete observations and inspection of data indicates time-to-failure is a spectrum of corrosion and stress-corrosion modes, stress-corrosion crack propagation could have achieved considerably higher rates than those observed.

COMPARISON OF PLATE STEP-LOAD AND CONSTANT-LOAD SCC THRESHOLDS

Stress-corrosion test data for step-load and constant-load unnotched plate are shown in Figure 61, and for the notched plate in Figure 62.

Few failures occurred for the unnotched plate as illustrated in Figure 61; these being for 2014-T6 weld plus STA and 7039-T64 weld plus STA. For 2014-T6 weld plus STA, the step-load specimen was first observed to have a stress-corrosion crack at 44.2 ksi and failed on loading to 47.4 ksi. This specimen had accumulated 456 hours in alternate immersion testing. The subsequent constant-load specimen did not fail in 501 hours at 47.4 ksi, thus the step-load threshold was below the constant-load threshold. For 7039-T64 weld plus STA, the step-load failure stress was 39.1 ksi (above constant-load threshold of 31.3 ksi). However, the initial stress-corrosion crack was observed at 31.3 ksi during step-load tests.

Alloys 2014-T6 weld plus STA and 7039-T64 weld plus STA failed in edge notch specimen tests. In addition, X2021-T8E31 weld plus STA notched also failed. Inspection of the SCC data presented for notched specimens in Figure 62 also demonstrates that several specimens exhibited crack extension from corrosion rather than SCC and did not fail during test. As a result, in stress-corrosion tests of aluminum alloys, crack extension data can be misleading if considered SCC without verification by additional tests including microscopic studies.

Considering the three notched alloy tempers that failed during test, step-load failure occurred above constant-load threshold for two out of three cases (2014-T6 weld plus STA and 7039-T6 weld plus STA); step-load crack initiation was observed below the constant-load threshold in two out of three cases (2014-T6 weld plus STA, X2021-T8E31 weld plus STA) and in the third case, 7039-T64 weld plus STA, the first crack extension was within limits of test in close proximity to the constant-load threshold.

These data are in general agreement with the results from the sheet step-load constant-load data. That is: (1) step-load specimens that failed above the constant-load threshold may have crack initiation at lower stresses which

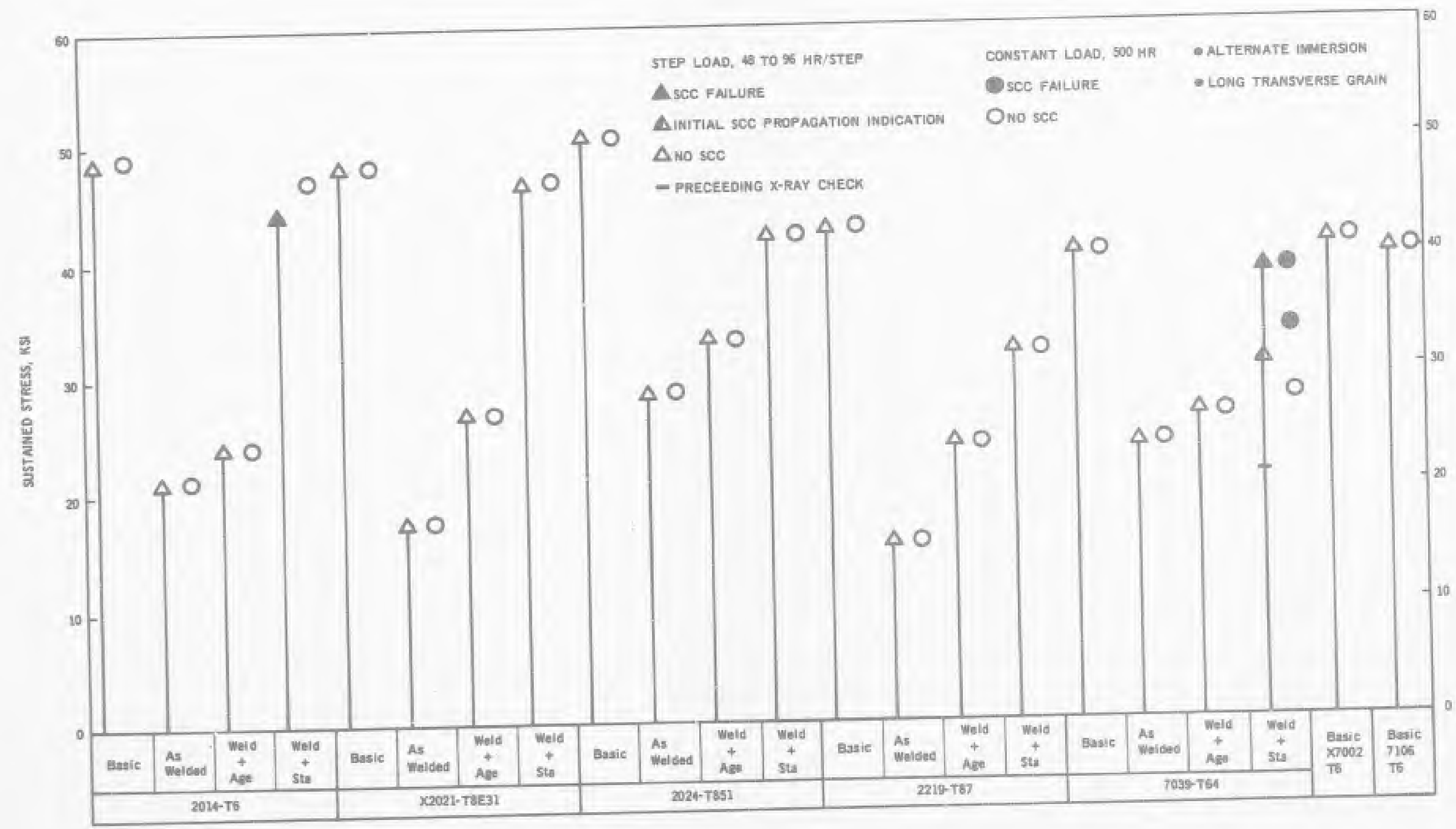


FIGURE 61. COMPARISON OF STEP LOAD AND CONSTANT LOAD SCC DATA FOR UNNOTCHED ALUMINUM ALLOY PLATE

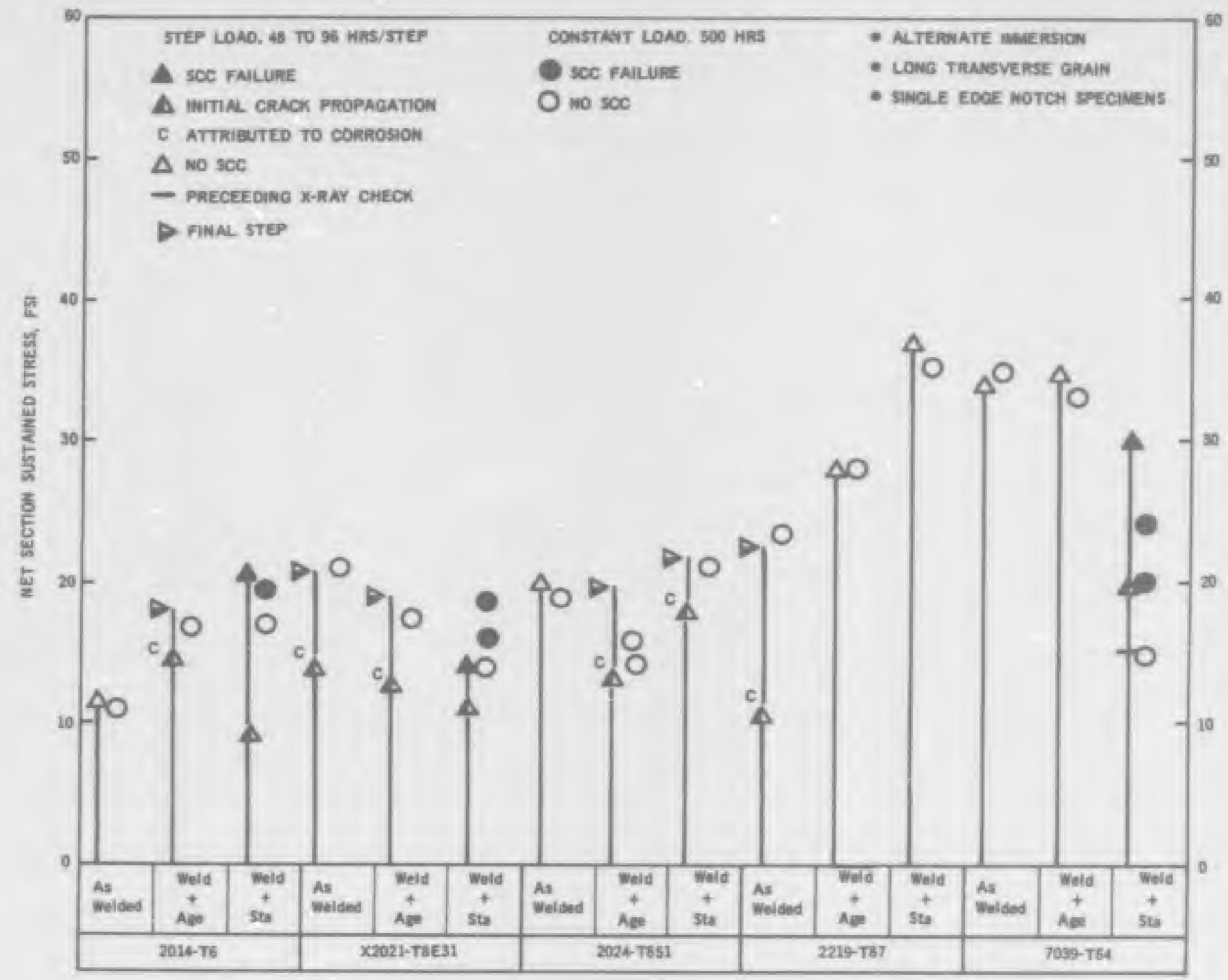


FIGURE 62. COMPARISON OF STEP LOAD AND CONSTANT LOAD SCC DATA FOR NOTCHED ALUMINUM ALLOY PLATE

could not be accurately detected by X-ray (in the case of sheet), and (2) the step-load test tends to produce a threshold below the constant-load threshold; in this case considering plate stress levels where crack extension was first observed.

EFFECT OF STRESS INTENSITY ON SCC

Stress intensity values were calculated from selected step-load and constant-load test specimens, showing best fit to recommended practice, considering stress and crack length at initiation stage and stress and crack length at final stage of SCC. Calculation data are shown in Table A-26 for step-load specimens and in Table A-27 for constant-load specimens.

The formula for calculating K_I stress intensity from the tension test of a single-edge notch specimen in Reference 15 is:

$$K_I^2 = \frac{\sigma^2_{gross}}{(1-\nu^2)} W \left[7.59 \frac{a}{W} - 32\left(\frac{a}{W}\right)^2 + 117 \left(\frac{a}{W}\right)^3 \right]$$

where:

σ_{gross} = gross section stress at pop-in (psi)

W = specimen width (inches)

ν = Poisson's ratio = 0.33

a = crack depth at pop-in (inches)

Crack length, a, is generally considered

$$a = a_o + \frac{K_I^2 (1-\nu^2)}{6\pi\sigma^2_{ys}}$$

which corrects for the plastic zone ahead of the crack, and

a_o = fatigue crack depth (inches)

σ_{ys} = 0.2-percent offset yield strength (psi)

Calculations from stress-corrosion specimens were made using these equations considering

σ_{gross} = gross section sustained stress (psi)

a_o = fatigue crack length (inch) in SCC initiation stage or fatigue crack length plus stress corrosion crack length in final stage

In all cases, a_o was corrected for plastic zone to give a. The numerical solution to the equation for K_I was obtained on a digital computer by use of an iterative method. Stress intensity values are considered nominal values because of high fatigue cracking stresses and gross branching of the stress-corrosion crack which was often blunted by a short transverse grain direction stress-corrosion crack, as is discussed later for the various alloy-weld-tempers.

Stress intensity level required to initiate SCC for susceptible tempers and the highest level tested for resistant tempers are summarized in Figure 63 and illustrate increase in susceptibility to SCC of 2014-T6, X2021-T8E31, and 7039-T64 when solution heat treated and aged after welding.

Stress intensity levels at final stage of SCC failure are shown for the constant-load test specimens in Table A-27 and step-load specimens in Table A-26 and illustrate stress intensity increased as the crack propagated, reaching a critical value and sudden failure. Few specimens were satisfactory for these calculations because of wide divergence of the stress-corrosion crack from the fatigue crack plane and indistinguishable final stress-corrosion crack lengths. It was also noted that there was no solution to the K_I equation when net section sustained stress approached yield strength.

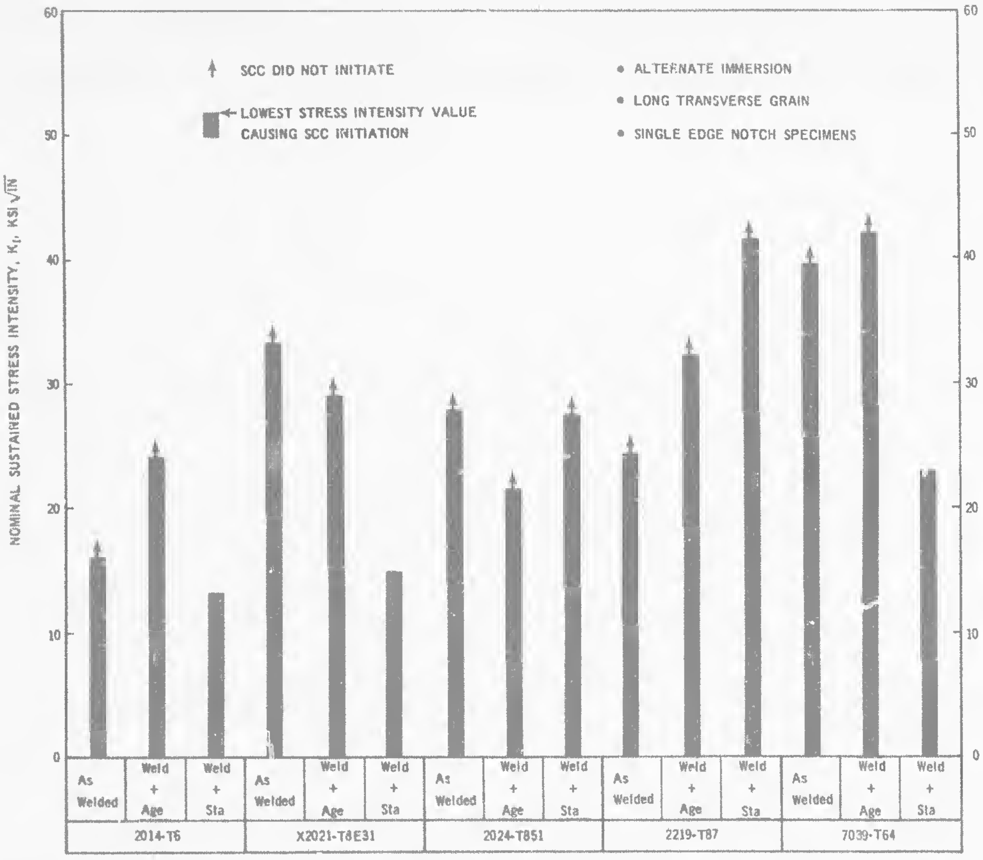


FIGURE 63. STRESS INTENSITY LEVELS REQUIRED TO INITIATE SCC IN NOTCHED ALUMINUM ALLOY PLATE.

ALLOY 2014-T6 PLATE

Stress-corrosion cracking was not observed on unnotched specimens step-loaded up to 75-percent yield strength or held under constant-load at 75-percent yield strength for 500 hours alternate immersion for the tempers: (1) basic unwelded, (2) as-welded, and (3) weld plus age.

The step-loaded weld plus STA temper specimen, SWU-14-S-5, did display a crack originating at the edge of the weld bead, propagating 0.050-inch deep along the fusion line and then an additional 0.050 inch directly into the weld bead parallel to the sustained load. This crack was first observed by X-ray after 64 hours exposure at the sixth step, 44.2 ksi (accumulated 456 hours alternate immersion and 40 hours in air between steps) and the specimen subsequently failed during loading to the last step, 47.4 ksi. A replicate specimen, constant-loaded at 47.4 ksi, did not have any evidence of SCC after 500 hours of alternate immersion and residual ultimate strength was 96 percent of unexposed strength.

The fracture surface of SWU-14-S-5 is shown in Figure 64, and the line of failure along the edge of the weld bead is shown in Figure 65. Metallographic examination at the origin in Figure 66 revealed intergranular cracking, typical of stress-corrosion cracking, and also micro-porosity. This porosity could have contributed to the failure, although cracks are not shown emitting from the porosity in the plane of the micro section.

Notched specimens did not show SCC for the as-welded temper or weld plus age temper. Crack extension was indicated in X-ray of the step-load, weld plus age temper, SWX-14-A-5, but microscopic examination revealed random, wide intergranular corrosion at the precrack tip suggesting corrosion to be the cause of extension (as viewed by the X-ray). The fracture surface of this specimen after tension testing is shown in Figure 67, and illustrates an irregular extension of the crack tip. Crack extension was also observed on the replicate specimen constant-loaded in alternate immersion for 500 hours. In this case, the fatigue crack tip extended parallel to the sustained load, 0.070-inch deep into the weld bead. Failure did not occur and residual strength was 97 percent of the unexposed strength.

Stress-corrosion cracking was observed with notched specimens of 2014-T6 weld plus STA temper. Failure occurred for the step-load specimen, SWX-14-S-5, at 20.8 ksi (net section stress) and 19.4 ksi for the constant-load specimen, SWX-14-S-7. Failure did not occur for a second constant-load specimen, SWX-14-S-8, at 17.1 ksi and residual strength was 1.04 percent of unexposed strength. The step-load specimen did fail in air during handling but considerable crack extension was observed prior to failure.

MAGNIFICATION: 5×

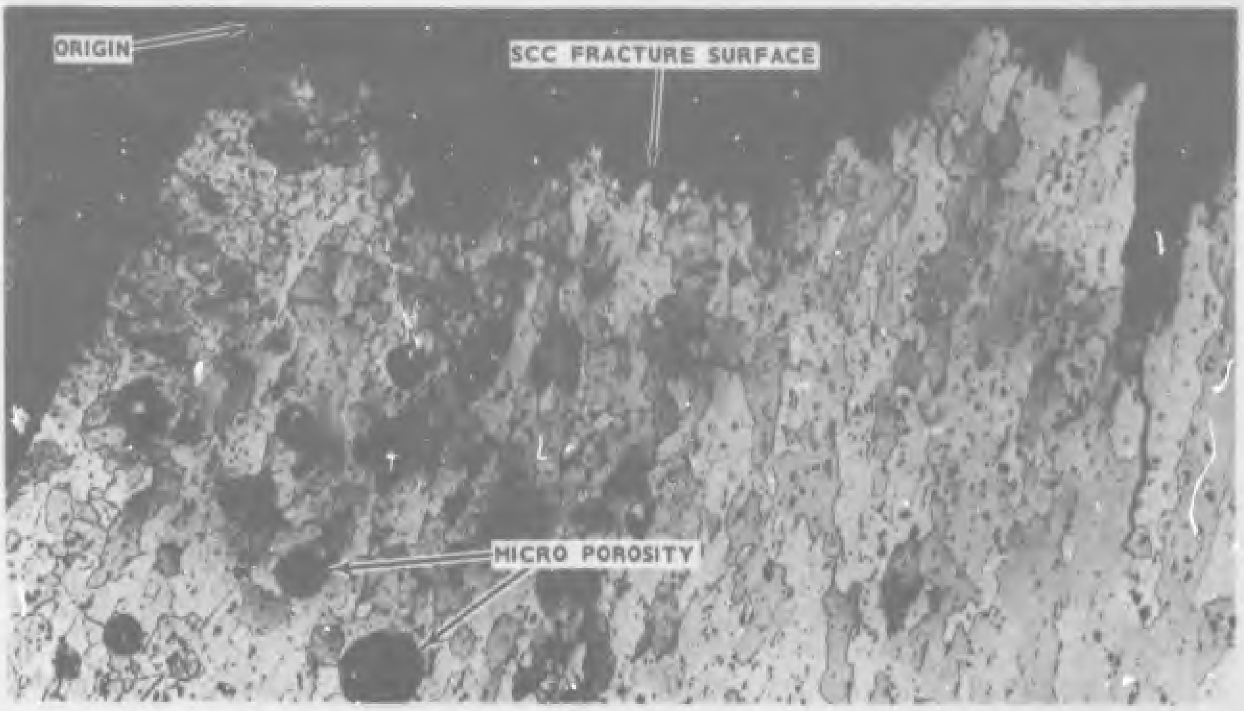
SPEC NO. SWU-14-S-5

FIGURE 64. FRACTURE SURFACE OF 2014-T6 PLATE, WELD + STA TEMPER, FAILED DURING SCC TESTING.

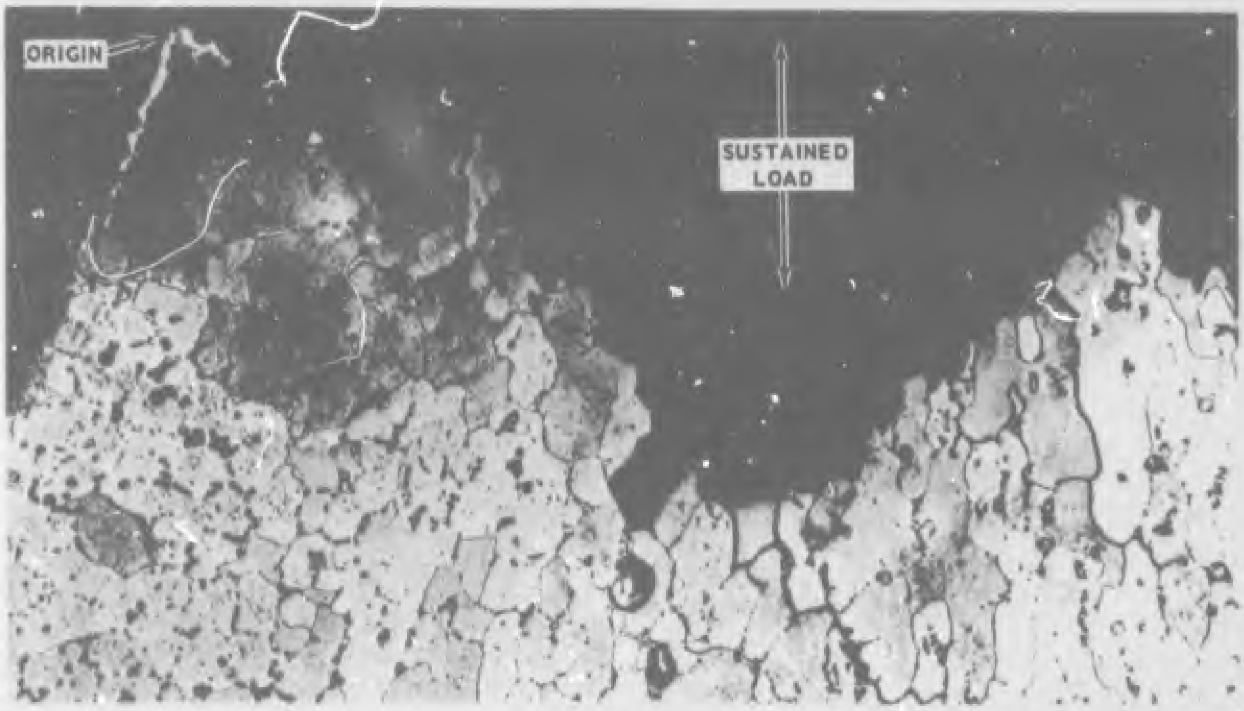
MAGNIFICATION: 3×

SPEC NO. SWU-14-S-5

FIGURE 65. LINE OF FAILURE OF 2014-T6 PLATE, WELD + STA TEMPER, FAILED DURING SCC TESTING

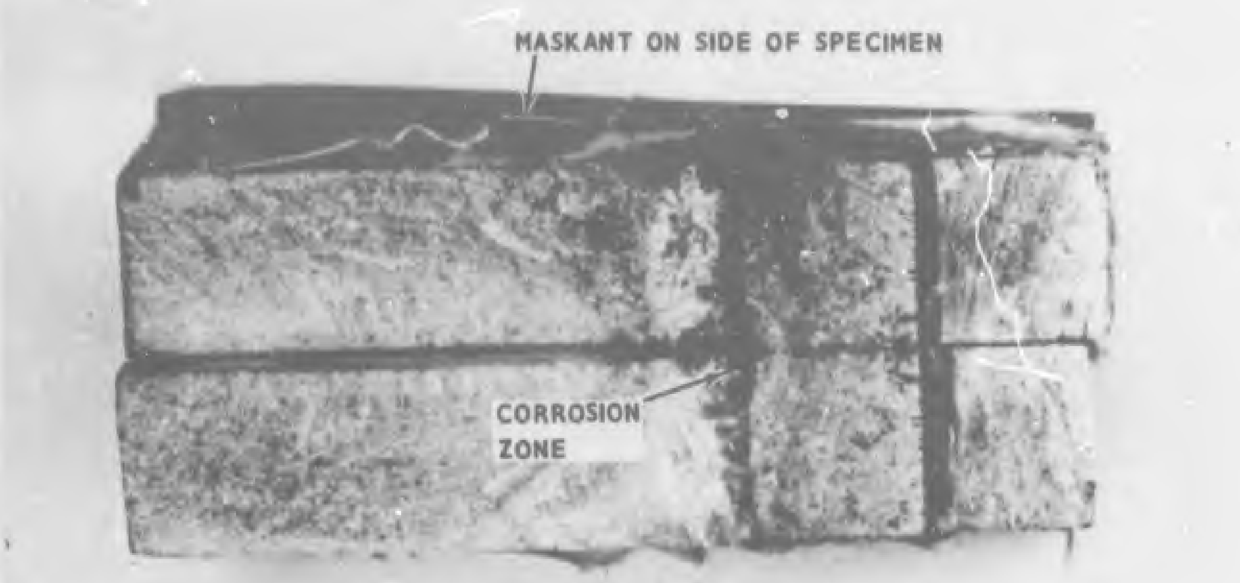


MAGNIFICATION: 100× KELLER'S ETCH SPEC NO. SWU-14-S-5



MAGNIFICATION: 250× KELLER'S ETCH SPEC NO. SWU-14-S-5

FIGURE 66. MICROSTRUCTURE AT ORIGIN OF FAILURE OF 2014-T6 PLATE, WELD + STA TEMPER, FAILED DURING SCC TESTING.



MAGNIFICATION: 5×

SPEC NO. SWX-14-A-5

FIGURE 67. FRACTURE SURFACE OF PRE-CRACKED 2014-T6 PLATE, WELD + AGE TEMPER, THAT DID NOT FAIL DURING SCC TESTING BUT DISPLAYED CRACK EXTENSION DUE TO CORROSION.

A series of pictures made directly from the X-ray negatives from the step-load specimen illustrating the stages of crack propagation are shown in Figure 68. The crack appears to have several fronts, branching into the heat-affected zone initially and finally turning 90° into the weld bead just prior to final failure.

The fracture surface and line of failure are shown in Figures 69, and displaying an erratic dog-leg that terminated in final failure through the weld bead. Corrosion products on the side of the specimen at the SCC area in Figure 70 confirm the corrodent was transported through the notch and fatigue crack to the crack tip. Sides of all plate specimens were masked to prevent SCC away from the fatigue crack tip.

Microscopic examination of the step-load specimen did not reveal any branching cracks along the main fracture but intergranular cracking was evident along the leg extending directly into the weld bead.

ALLOY 2021-T8E31 PLATE

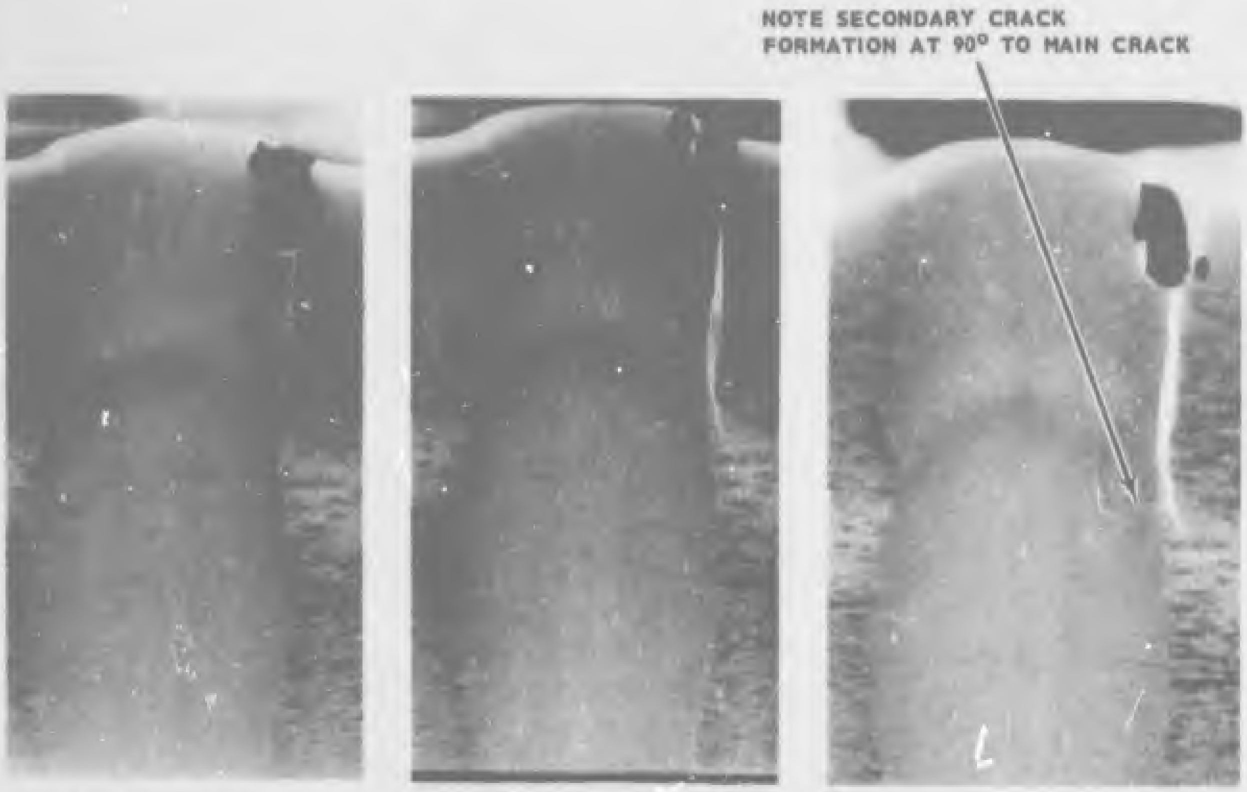
Stress-corrosion cracking was not observed on unnotched specimens step-loaded up to 75-percent yield strength or held under constant load at 75-percent yield strength for 500 hours alternate immersion for the tempers: (1) basic unwelded, (2) as-welded, (3) weld plus age, and (4) weld plus STA.

Crack extension for notched specimens was observed by X-ray during step-load alternate immersion for the tempers: (1) as-welded, (2) weld plus age, and (3) weld plus STA, the latter failing prior to completion of the step-load tests.

Subsequent constant-load tests of replicate specimens did not produce crack extension during exposure or failures for either as-welded or weld plus age tempers but did for the weld plus STA temper. Weld plus STA specimens failed at 18.9 ksi (net section) in 122 hours, at 16.2 ksi in 226 hours, but did not fail at 14.0 ksi in 498 hours.

It was difficult to verify mode of crack extension for the step-loaded, as-welded and weld plus age tempers because of short crack extension lengths for viewing. Considerable corrosion products were observed on fracture surfaces of these two specimens, SWX-21-W-5 and SWX-21-A-5, as illustrated in Figure 71, and wide grain boundary corrosion was observed microscopically at the fatigue crack tip on SWX-21-W-5. It is considered likely that both crack extensions were due to corrosion.

The nature of crack extension for the weld plus STA temper was also difficult to verify with microscopic examination. Branching or distinct intergranular cracks were not observed along the fracture surface. Since the fracture surfaces displayed fewer corrosion products than the former two tempers, failure times were a function of sustained stress (lower stress — longer times) and a significant degree of rapid crack extension was observed, the failures of the weld plus STA temper are considered attributable to SCC. The stages of crack propagation as viewed by X-ray are shown for SWX-21-S-5 in Figure 72, and the relatively clean surface of the crack-extended area in Figure 73.

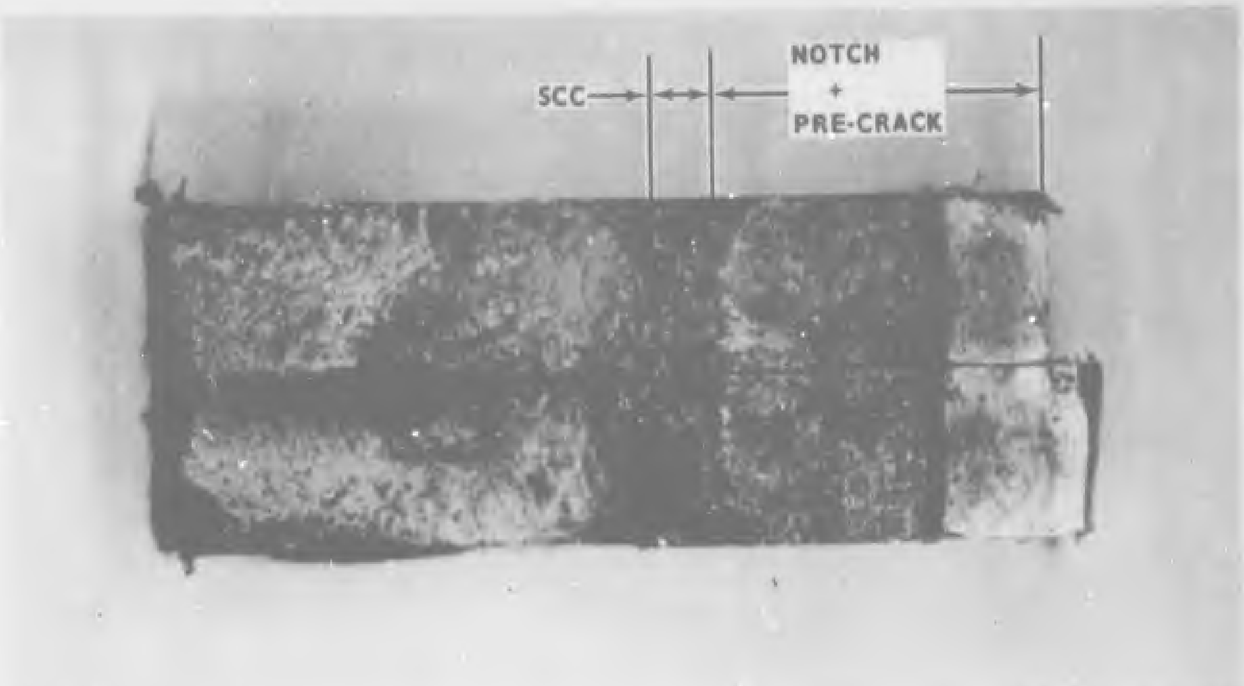


MAGNIFICATION: 2.9× MAGNIFICATION: 2.9× MAGNIFICATION: 3.2×

SPEC NO. SWX-14-5-5

	STEP 1	STEP 2	STEP 5
SUSTAINED STRESS (KSI)	5.93	8.90	17.81
HOURS AT STEP	90	41	113
ACCUM. HOURS ALTERNATE IMMERSION	90	131	394
ACCUM. HOURS, AIR (BETWEEN STEPS)	0	6	31
NOTCH + CRACK DEPTH (INCH)	0.393	0.503	0.518

FIGURE 68. STAGES OF STRESS CORROSION CRACK PROPAGATION IN PRE-CRACKED 2014-T6 PLATE, WELD + STA TEMPER, AS VIEWED BY X-RAY.



MAGNIFICATION: 4.4×

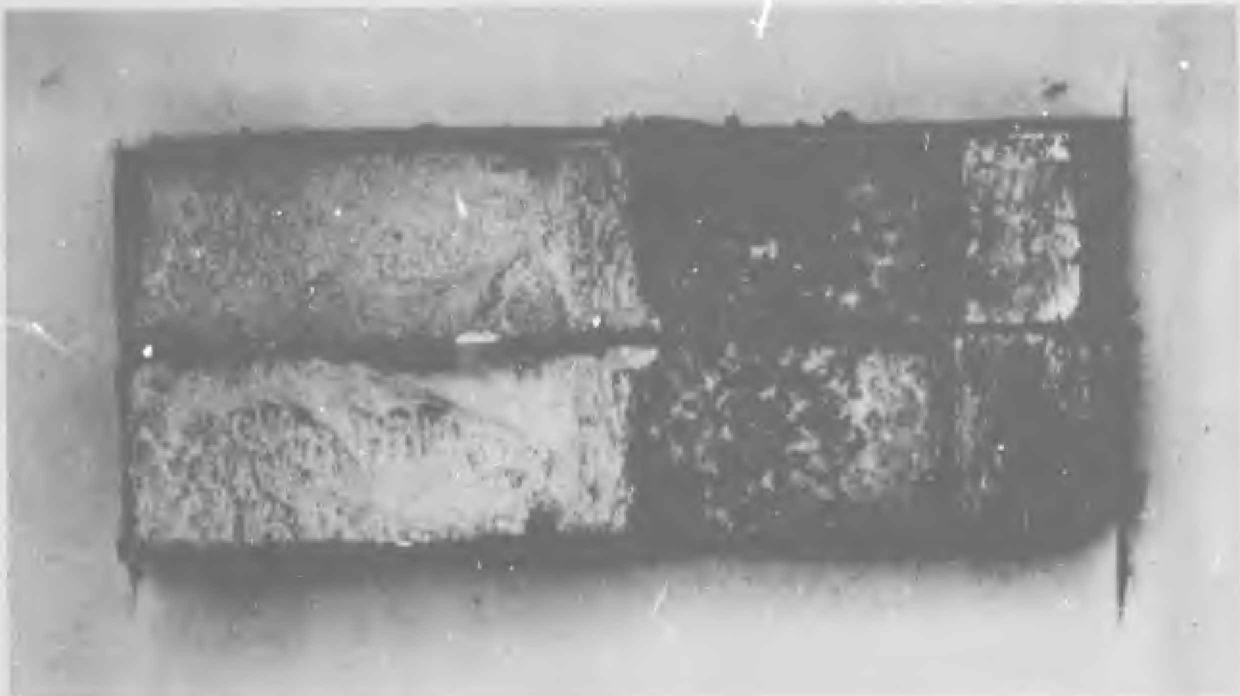
SPEC NO. SWX-14-S-5

FIGURE 69. FRACTURE SURFACE OF PRE-CRACKED 2014-T6 PLATE, WELD + STA TEMPER, THAT FAILED DURING SCC TESTING.

MAGNIFICATION: 2.7×

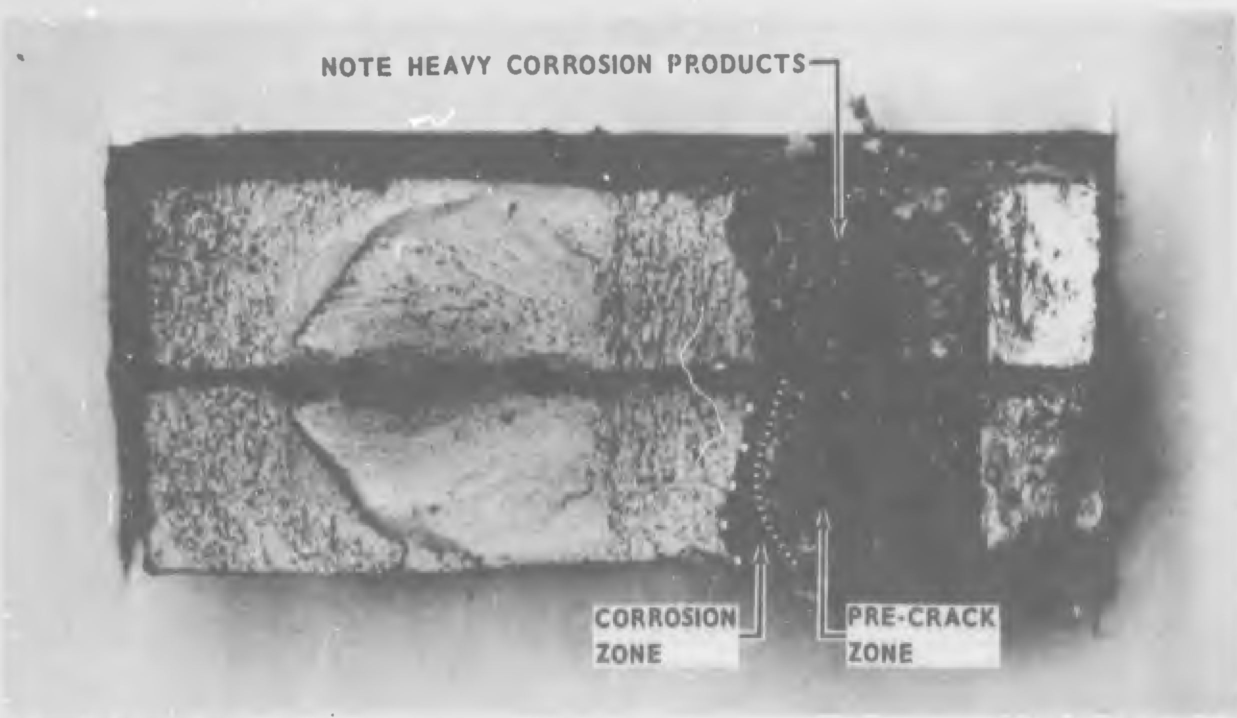
SPEC NO. SWX-14-S-5

FIGURE 70. LINE OF FAILURE OF 2014-T6 PLATE, WELD + STA TEMPER, THAT FAILED DURING SCC TESTING.



MAGNIFICATION: 5×

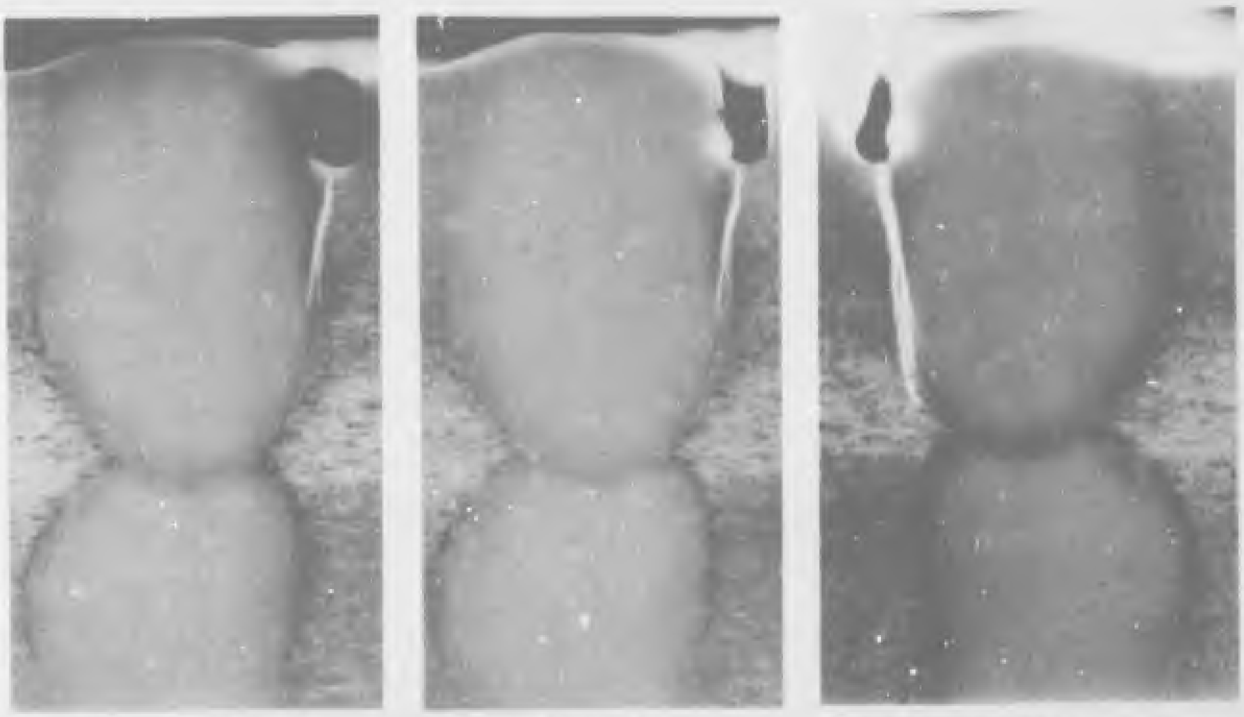
SPEC NO. SWX-21-W-5



MAGNIFICATION: 5×

SPEC NO. SWX-21-A-5

FIGURE 71. FRACTURE SURFACES OF PRE-CRACKED X2021-T8E31 PLATE THAT DID NOT FAIL DURING SCC TESTING BUT DISPLAYED CRACK EXTENSION ATTRIBUTED TO CORROSION.

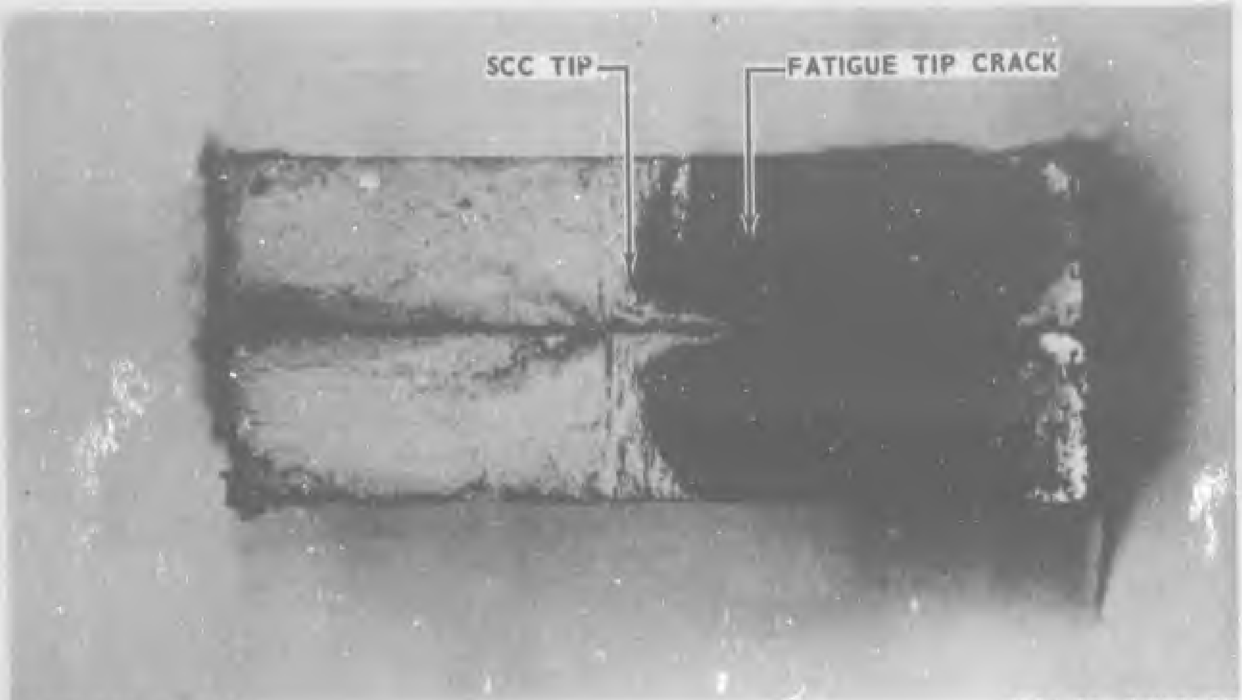


MAGNIFICATION: 3.4× MAGNIFICATION: 3.5× MAGNIFICATION: 3.1×

SPEC NO. SWX-21-S-5

	STEP 2	STEP 3	STEP 4
SUSTAINED STRESS (KSI)	8.3	11.0	13.7
HOURS AT STEP	88	41	41
ACCUM. HOURS ALTERNATE IMMERSION	129	170	211
ACCUM. HOURS AIR (BETWEEN STEPS)	8	15	22
NOTCH + CRACK DEPTH (INCH)	0.348	0.373	0.558

FIGURE 72. STAGES OF STRESS CORROSION CRACK PROPAGATION IN PRE-CRACKED X2021-T8E31 PLATE, WELD + STA TEMPER, AS VIEWED BY X-RAY.



MAGNIFICATION: 4.5×

SPEC NO. SWX-21-S-5

FIGURE 73. FRACTURE SURFACE OF PRE-CRACKED X2021 - T8E31 PLATE, WELD + STA TEMPER, THAT FAILED DURING SCC TESTING.

ALLOY 2024-T851 PLATE

Stress-corrosion cracking was not observed in unnotched specimens step-loaded up to 75-percent yield strength or held under constant-load at 75-percent yield strength for 500 hours alternate immersion for the tempers: (1) basic unwelded, (2) as-welded, (3) weld plus age, and (4) weld plus STA.

No failures occurred during step-load tests or constant-load tests for notched specimens of the three tempers: (1) as-welded, (2) weld plus age, and (3) weld plus STA. Crack extensions were observed by X-ray, however, during step-loading for weld plus age temper (0.080-inch increase) and weld plus STA (0.020-inch increase) and for constant-load as-welded temper, the latter displaying very irregular crack extension on the fracture after post-exposure tension testing such as that illustrated for 2014-T6 weld plus age temper, specimen SWX-14-A-5, in Figure 67, and is considered due to corrosion.

Fracture appearance of the step-loaded weld plus age temper specimen, SWX-24-A-5, which displayed crack extension, is shown in Figure 74. Metallographic examination of the 0.080-inch extended area did not reveal intergranular cracking and it is considered that the crack extension was due to corrosion rather than SCC. The minor extension (0.020-inch) on the weld plus STA specimen is also considered due to corrosion.

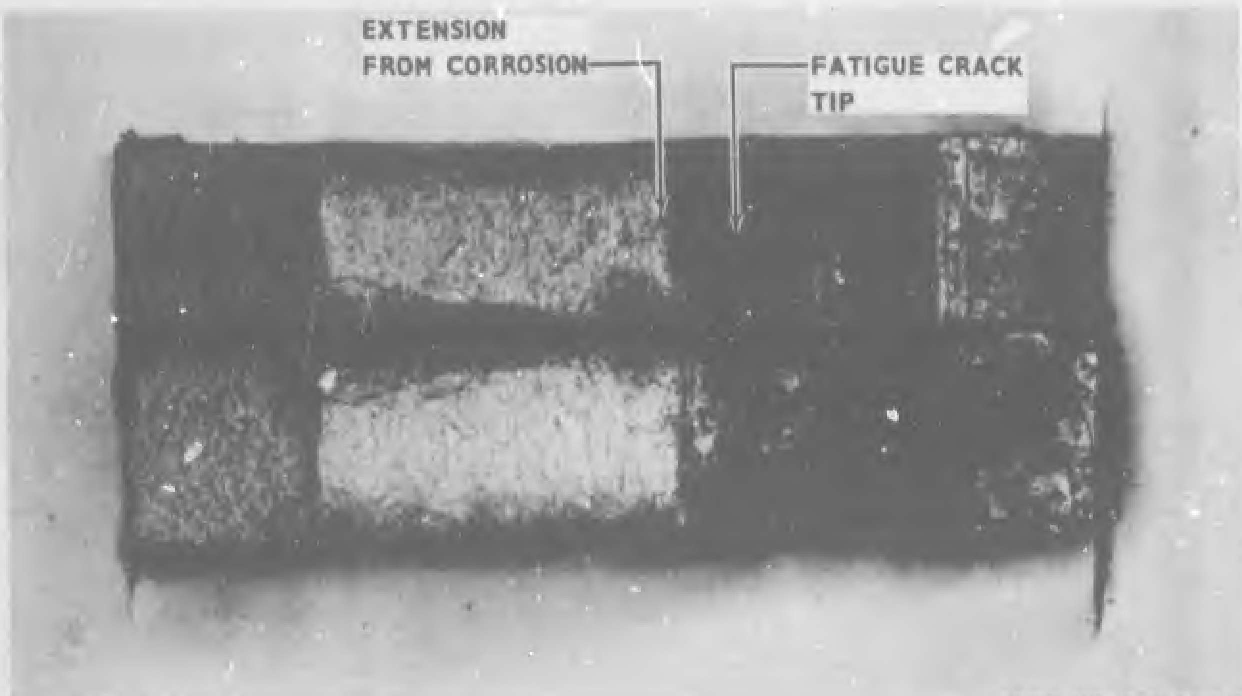
The residual net section strengths of the weld plus age stress-corrosion specimens, SWX-24-A-5 (step-load) and SWX-24-A-6 (constant-load) confirmed the wide scatter in notch specimen ultimate strength exhibited by the notched unexposed specimens. Unexposed notch strengths varied from 22.2 ksi to 34.5 ksi (net section) specimen SWX-24-A-6 failed on loading to 16.8 ksi, and SWX-24-A-5 had residual strength of 35.7 ksi (net section).

ALLOY 2219-T87 PLATE

Stress corrosion cracking was not observed with unnotched specimens step-load or constant-load tested at 75-percent yield strength in alternate immersion for 500 hours for the tempers: (1) basic unwelded, (2) as-welded, (3) weld plus age, and (4) weld plus STA, nor was SCC observed with notched specimens for the tempers: (1) as-welded, (2) weld plus age, and (3) weld plus STA.

Although SCC was not observed for the notched as-welded temper, branching of the fatigue tip was observed for both step-load and constant-load specimens. For the step-load specimen, SWX-19-W-5, branching was first observed by X-ray at 10.6 ksi sustained stress (net section). The branch extended slowly and, after 843 hours, accumulated alternate immersion with stress increased to 22.7 ksi, the branch leg was 0.070 inch long. No failure occurred and the specimen was tension tested. Residual strength was 1.07 percent of the unexposed strength.

A replicate specimen, SWX-19-W-6, constant-load tested in alternate immersion at 23.5 ksi showed forking of the fatigue crack tip into 0.030-inch-long and 0.100-inch-long legs. After 530 hours exposure,



MAGNIFICATION: 5×

SPEC NO. SWX-24-A-5

FIGURE 74. FRACTURE SURFACE OF PRE-CRACKED 2024-T851 PLATE, WELD + AGE TEMPER, THAT DID NOT FAIL DURING SCC TESTING BUT DISPLAYED CRACK EXTENSION.

the specimen was tension-tested and residual strength was 78 percent of unexposed strength. The fracture exposed one leg of the fork 0.140-inch long and a second crack in the unnotched edge of the specimen at the edge of the weld bead. The final fracture line connected these crack zones with a diagonal through-the-weld bead.

Microscopic examination was conducted on the constant-load specimen to determine nature of cracking. Random intergranular cracking, associated with the eutectic melt zone, was observed along the edge of the fatigue crack and along the fork leg, as shown in Figures 75 through 77. Similar cracking was observed along the crack formed on the unnotched side of the specimen.

Because the extension of the crack in the step-load specimen was relatively independent of stress in the step-load test and random intergranular cracking was found, it is considered that the primary mode of failure was intergranular corrosion through the eutectic melt zone and that the sustained stress acted in a secondary manner mechanically joining corrosion-deteriorated grain boundaries.

ALLOY 7039-T64 PLATE

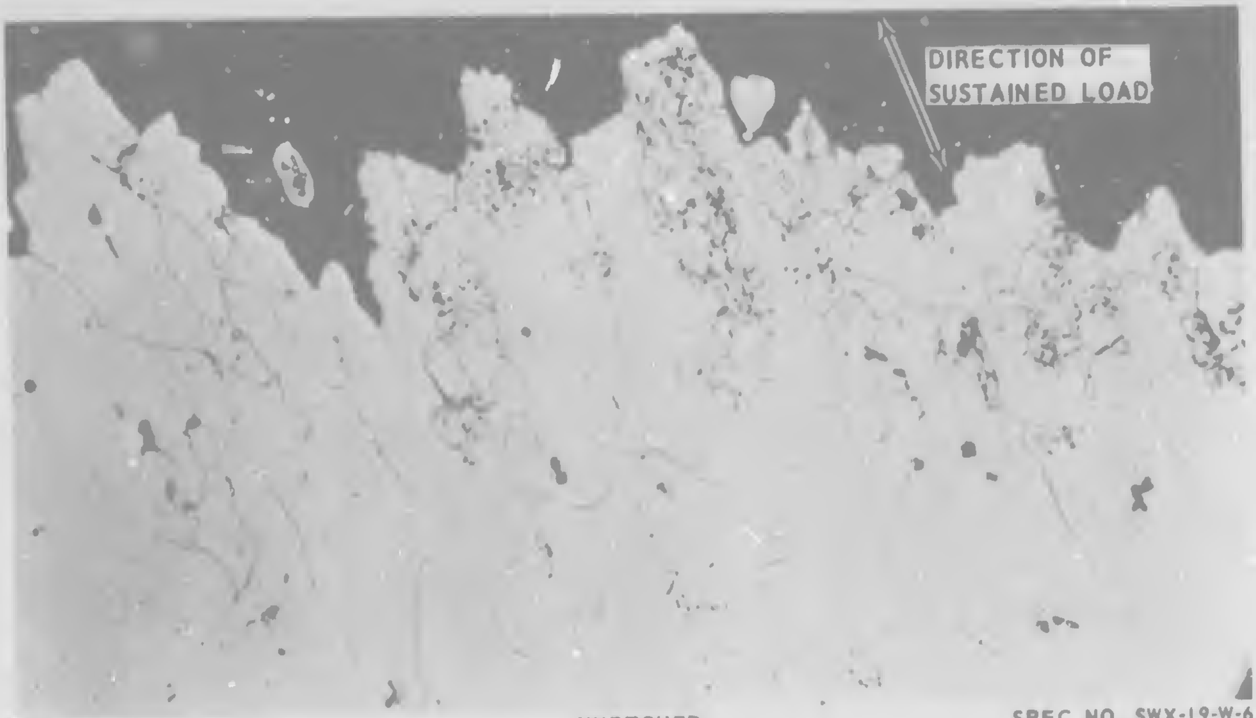
Stress-corrosion cracking was not observed on unnotched specimens step-loaded up to 75-percent yield strength or held under constant load at 75-percent yield strength for 500 hours alternate immersion for the tempers: (1) basic unwelded, (2) as-welded, and (3) weld plus age.

For the unnotched weld plus STA temper, SCC occurred at the edge of the weld bead in three locations prior to failure with the step-load specimen SWU-39-S-5 as illustrated in Figure 78, with final failure occurring through the weld bead, Figure 79. First cracks were observed at 31.3 ksi sustained stress. The fracture surface is shown in Figure 80. Microscopic examination along the line of and at the origin of failure, Figure 81, revealed intergranular cracking typical of SCC.

Replicate constant-load weld plus STA specimens exposed at stress levels in the region of step-load SCC failure failed under 39.1 ksi sustained stress (249 hours) and 33.9 ksi (416 hours) and the third did not have evidence of SCC at 28.7 ksi in 500 hours alternate immersion. Microscopic examination of failed constant-load specimen SWU-39-S-6 revealed intergranular cracking at the origin of failure, edge of weld bead, as shown in Figure 82.

Fracture surface and line of failure through the weld bead are shown in Figures 83 and 84.

The microstructure at the origin, as shown in Figures 81 and 82, includes what is considered the high-zinc eutectic formed during welding. It does not appear that the eutectic contributed a significant part to SCC because (1) it was present on as-welded and weld plus age tempers that did not fail, and (2) notched specimens of the weld plus STA temper (the notch removing the eutectic area) still were susceptible, as discussed in the following paragraphs.



MAGNIFICATION: 250× UNETCHED SPEC NO. SWX-19-W-6

FIGURE 75. INTERGRANULAR CORROSION AND EUTECTIC MELTING ALONG FRACTURE SURFACE IN HEAT AFFECTED ZONE OF 2219-T87 PLATE AS WELDED TEMPER, TESTED IN ALTERNATE IMMERSION.

MAGNIFICATION: 100× UNETCHED SPEC NO. SWX-19-W-6

FIGURE 76. INTERGRANUL R CORROSION AND EUTECTIC MELTING ALONG FATIGUE CRACK SURFACE OF .2'4-T87 PLATE, AS WELDED TEMPER, TESTED IN ALTERNATE IMMERSION.

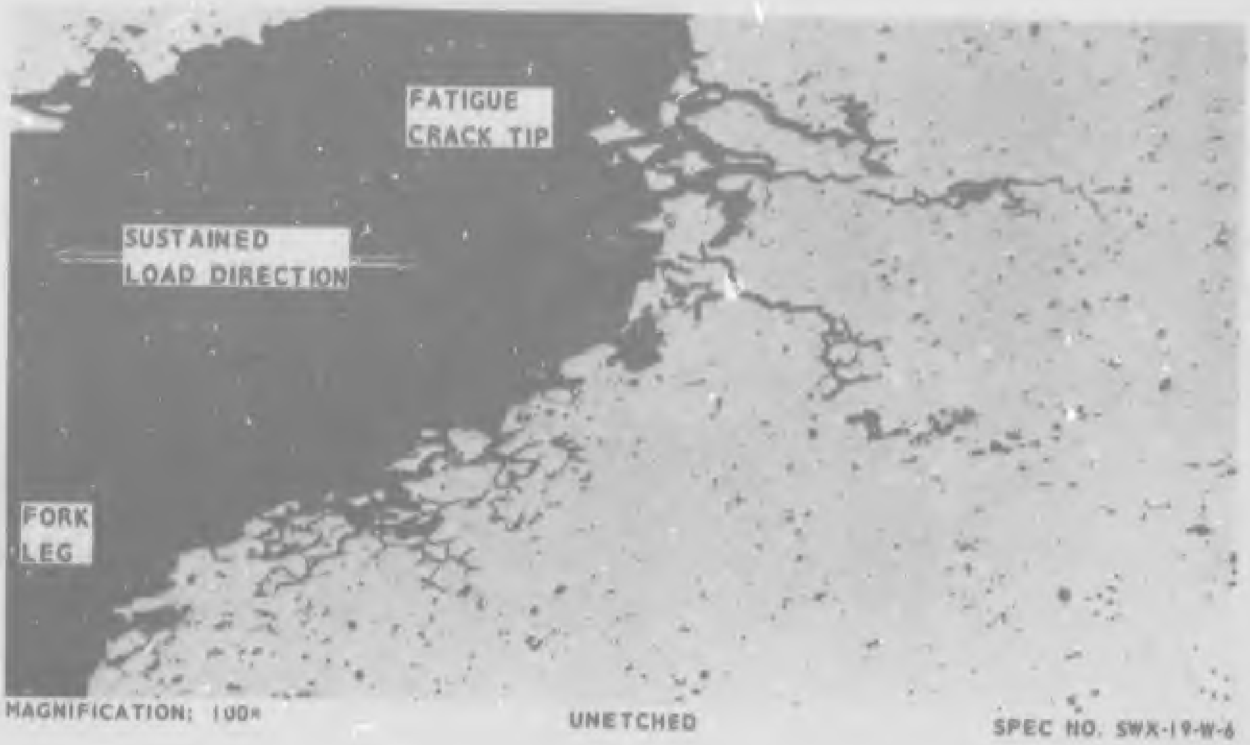
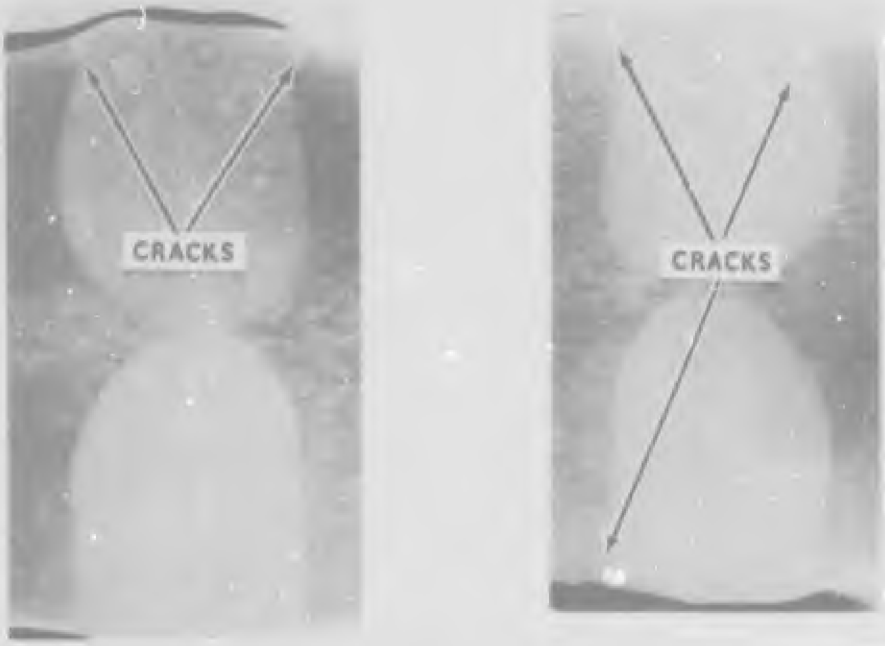
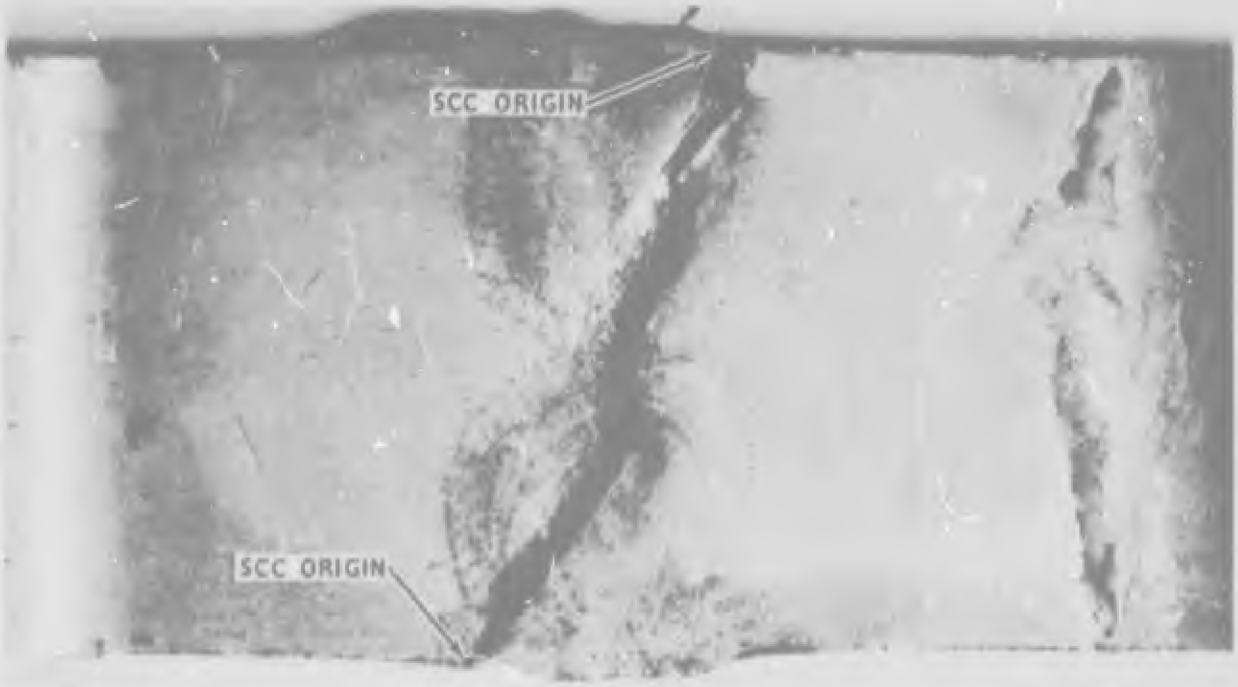


FIGURE 77. INTERGRANULAR CORROSION AT TIP OF FATIGUE CRACK IN 2219-T87 PLATE, AS WELDED TEMPER, TESTED IN ALTERNATE IMMERSION.



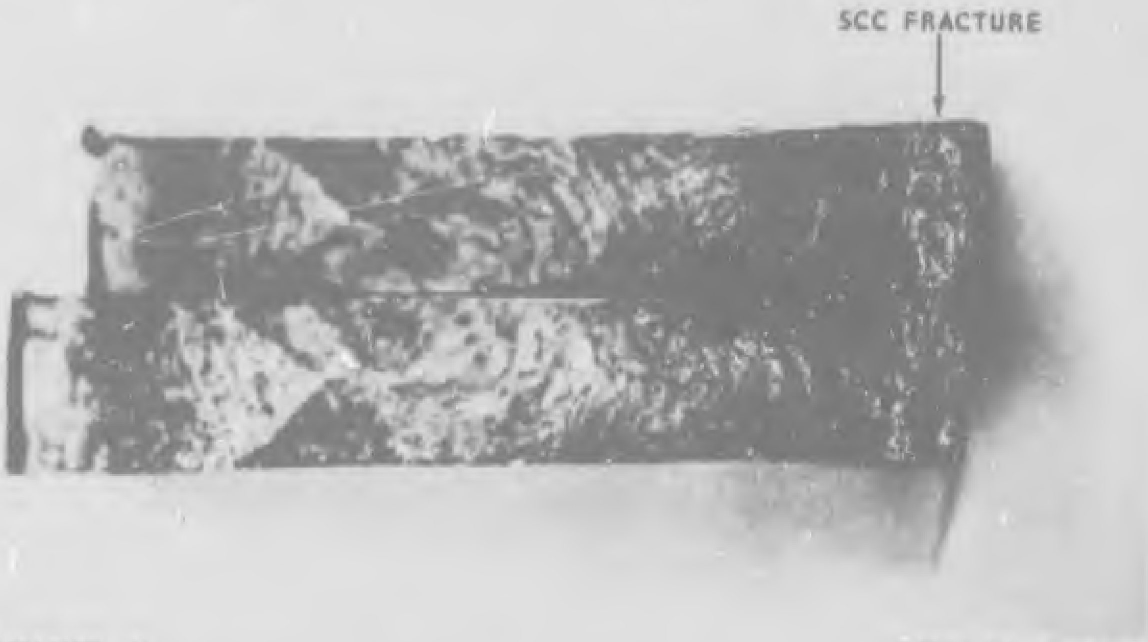
	STEPLOAD 5	STEPLOAD 6
SUSTAINED STRESS (KSI)	31.3	36.5
HOURS AT STEP	113	24
ACCUM. HOURS ALTERNATE IMMERSION	394	436
ACCUM. HOURS AIR (BETWEEN STEPS)	31	55
CRACK DEPTH (INCH)	0.75 0.75	0.150 0.100 0.075

FIGURE 78. STAGES OF SCC PROPAGATION IN 7039-T64 PLATE, WELD + STA TEMPER, AS VIEWED BY X-RAY.



MAGNIFICATION: 3× SPEC NO. SWU-39-5-5

FIGURE 79. LINE OF FAILURE OF 7039-T64 PLATE, WELD + STA TEMPER, THAT FAILED DURING STEP LOAD SCC TESTING.



MAGNIFICATION: 4× SPEC NO. SWU-39-5-5

FIGURE 80. FRACTURE SURFACE OF 7039-T64 PLATE, WELD + STA TEMPER, THAT FAILED DURING STEP LOAD SCC TESTING.

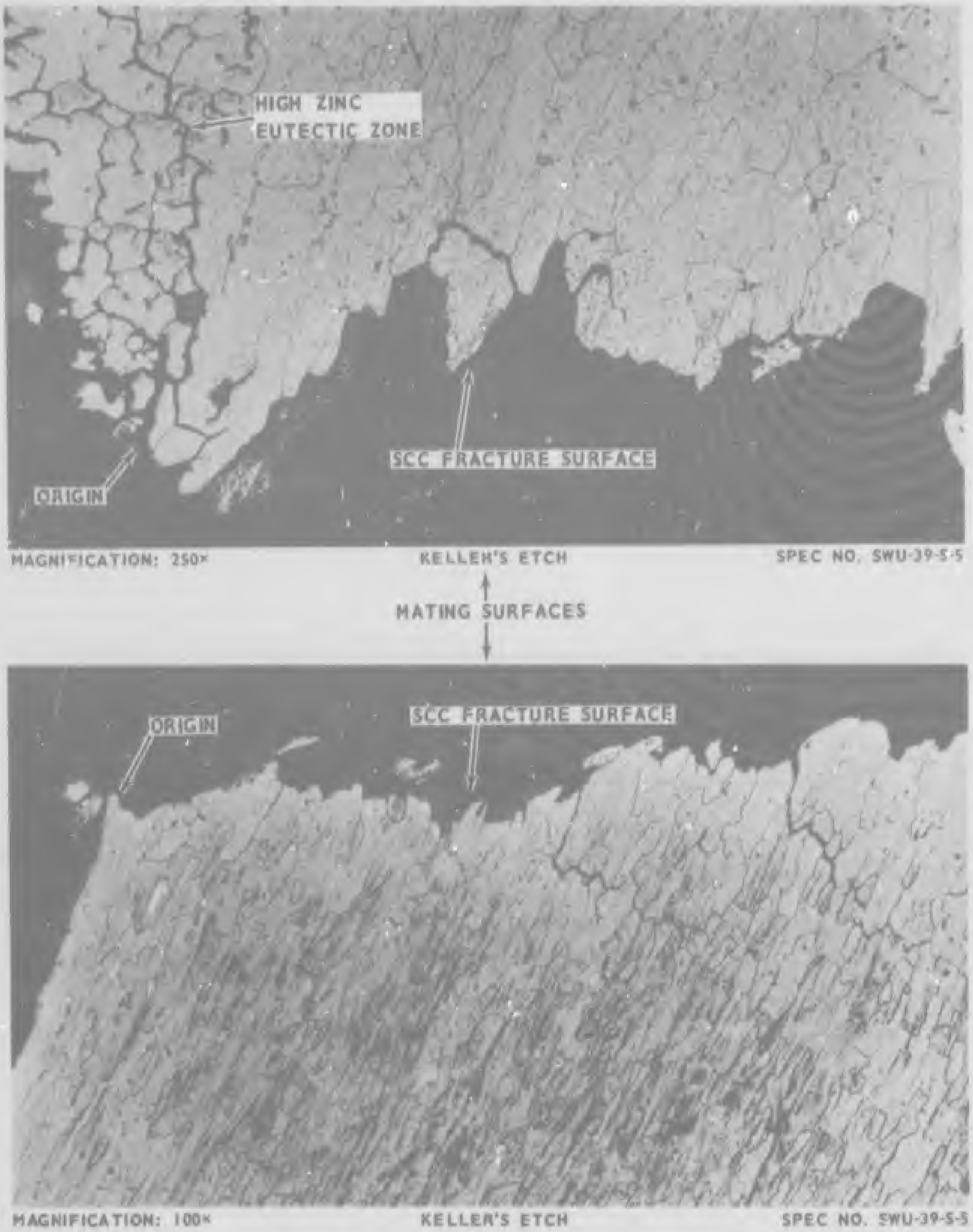
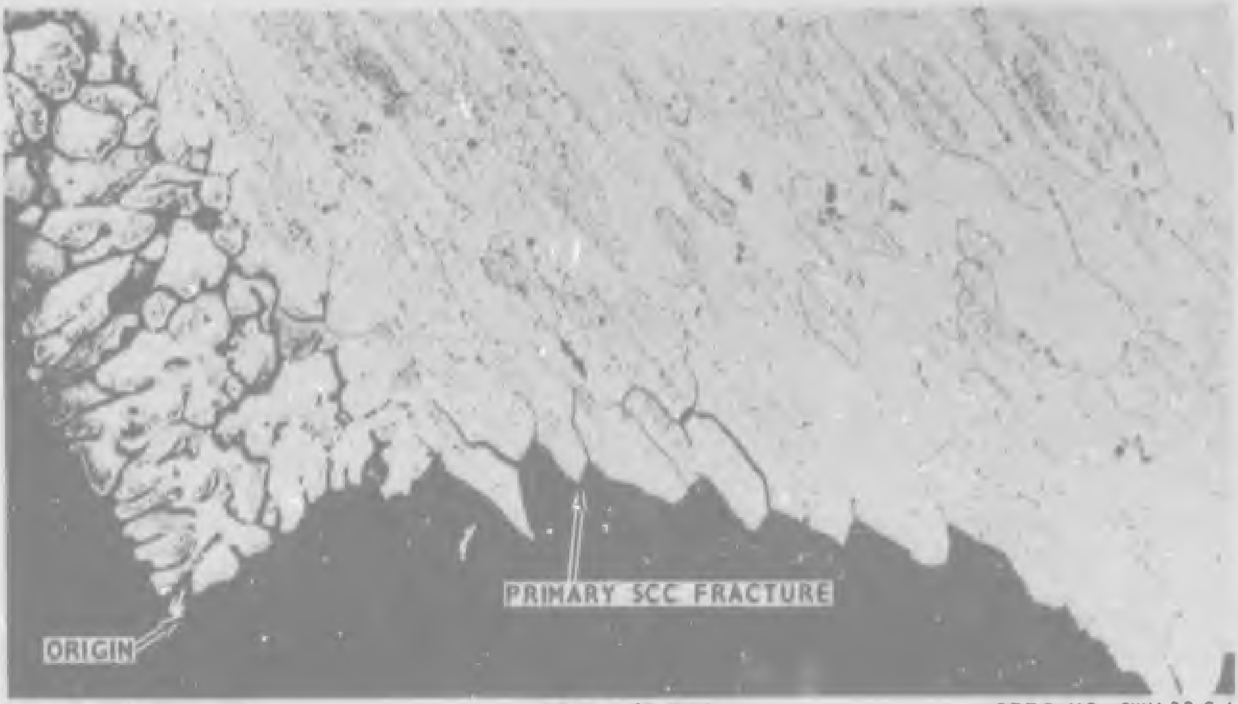
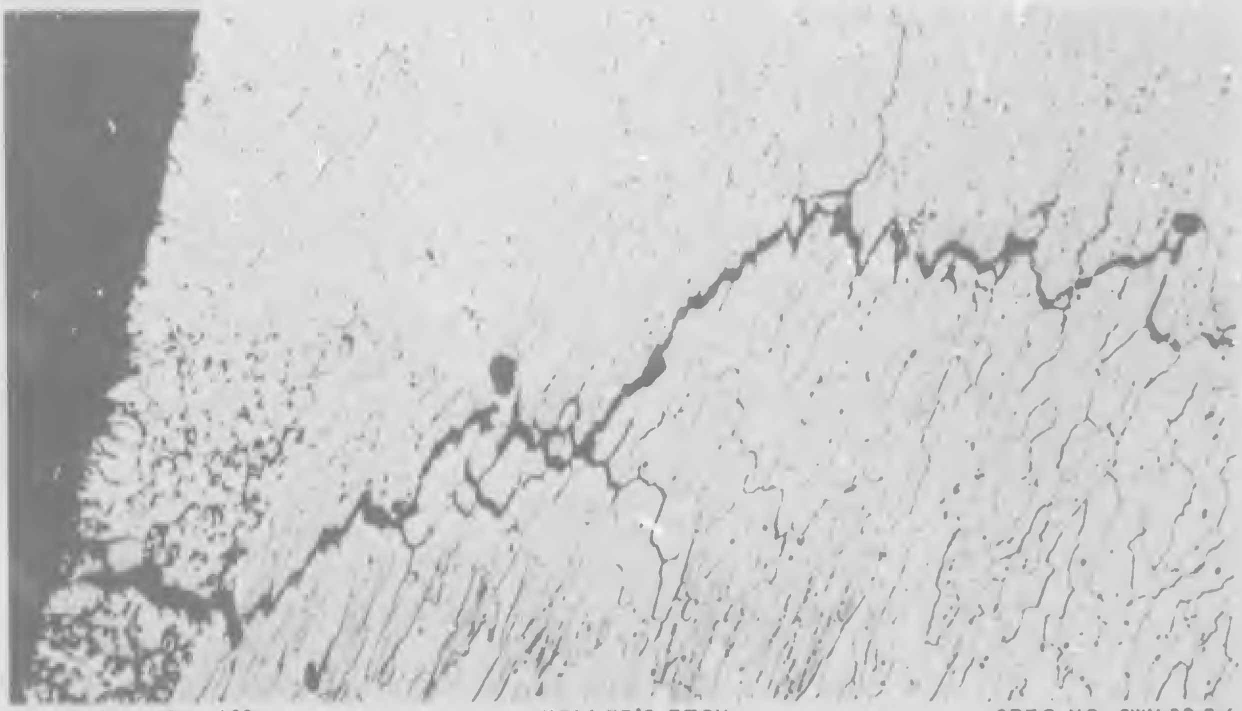


FIGURE 51. MICROSTRUCTURE AT ORIGIN OF FAILURE (EDGE OF WELD BEAD) OF 7039-T64 PLATE, WELD + STA TEMPER, FAILED DURING STEP LOAD SCC TESTING.

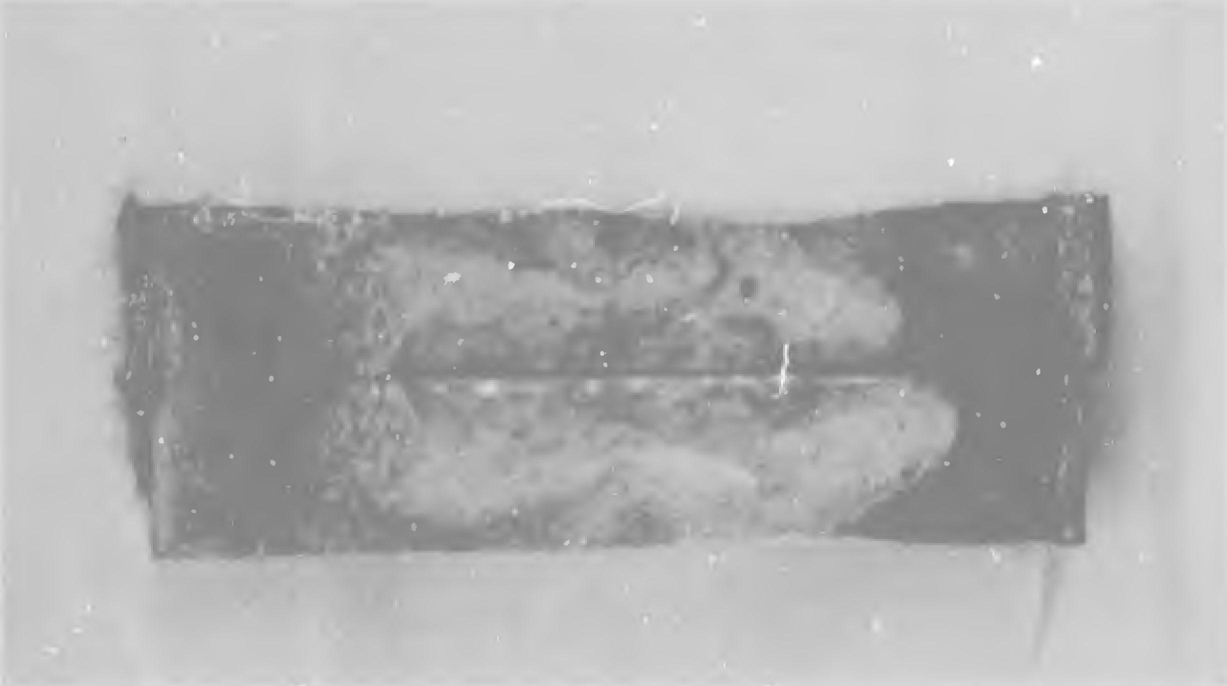


MAGNIFICATION: 250× KELLER'S ETCH SPEC NO. SWU-39-S-6



MAGNIFICATION: 100× KELLER'S ETCH SPEC NO. SWU-39-S-6

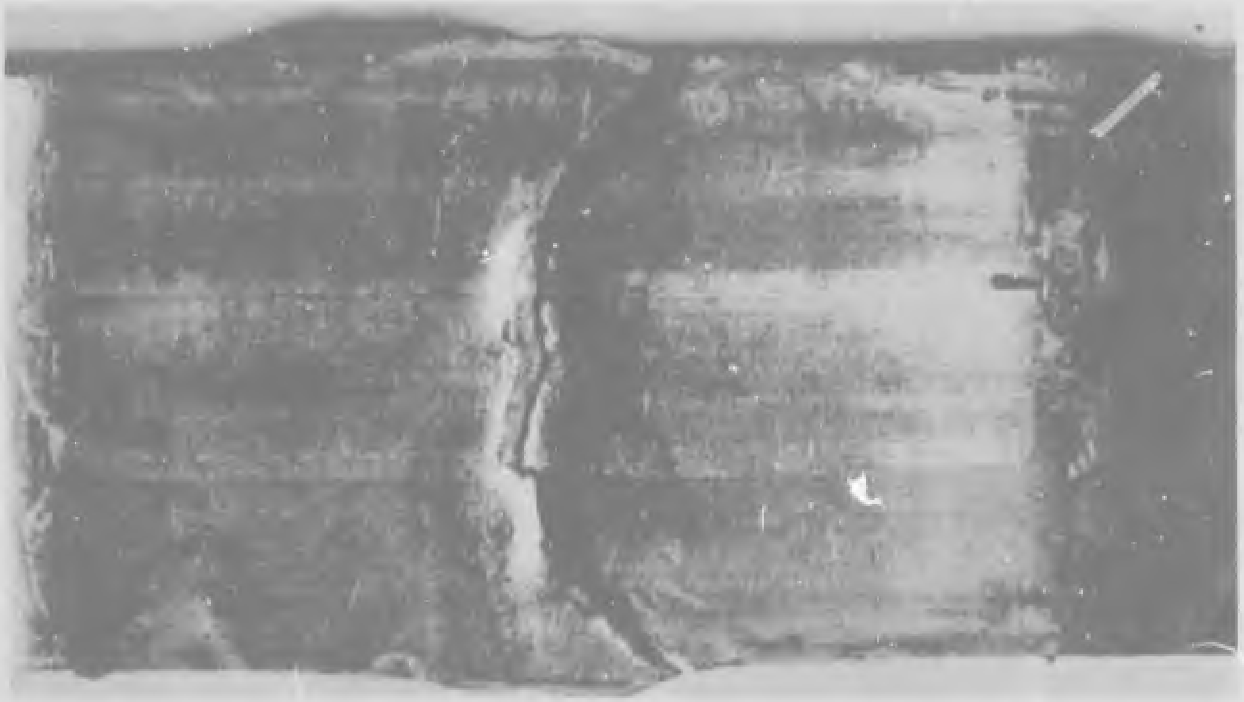
FIGURE 82. MICROSTRUCTURE AT ORIGIN OF PRIMARY AND SECONDARY CRACK IN 7039 - T64 PLATE, WELD + STA TEMPER, FAILED DURING CONSTANT LOAD SCC TESTING.



MAGNIFICATION: 5×

SPEC NO. SWU-39-S-6

FIGURE 83. FRACTURE SURFACE OF 7039 - T64 PLATE, WELD + STA TEMPER, THAT FAILED DURING CONSTANT LOAD SCC TESTING.



MAGNIFICATION: 3×

SPEC NO. SWU-39-S-6

FIGURE 84. LINE OF FAILURE OF 7039 - T64 PLATE, WELD + STA TEMPER, THAT FAILED DURING CONSTANT LOAD SCC TESTING.

Notched specimens of 7039-T64 in as-welded and weld plus age tempers did not fail in step-load or constant-load SCC tests. Short cracks were observed extending from and 90° to the precrack tip with the constant-load specimens, but residual strengths were at unexposed strength level.

Stress-corrosion cracking did occur with the notched weld plus STA temper. Crack extension was first observed by X-ray during step-load tests at 20.1 ksi sustained stress with failure occurring at 30.1 ksi sustained stress. Constant-load tests produced failures at 24.4 ksi, 272 hours and 20.5 ksi, 285 hours. The third specimen did not fail at 15.2 ksi, 500 hours.

The stages of stress-corrosion crack propagation in the step-load specimen, as viewed by X-ray, are shown in Figure 85. Initially, short cracks extended from and 90° to the precrack tip (short transverse grain direction). This was followed by extension of the main fatigue crack front along the edge of the weld bead confined to the fusion line. B anching cracks, short transverse grain direction, accompanied this progression along the edge of the weld bead. In the final stage, a mechanical crack formed on the centerline of the weld bead, disjointed from the stress-corrosion crack, and the specimen subsequently failed. Short transverse grain direction cracks are considered indicative of susceptibility in that direction and residual stress.

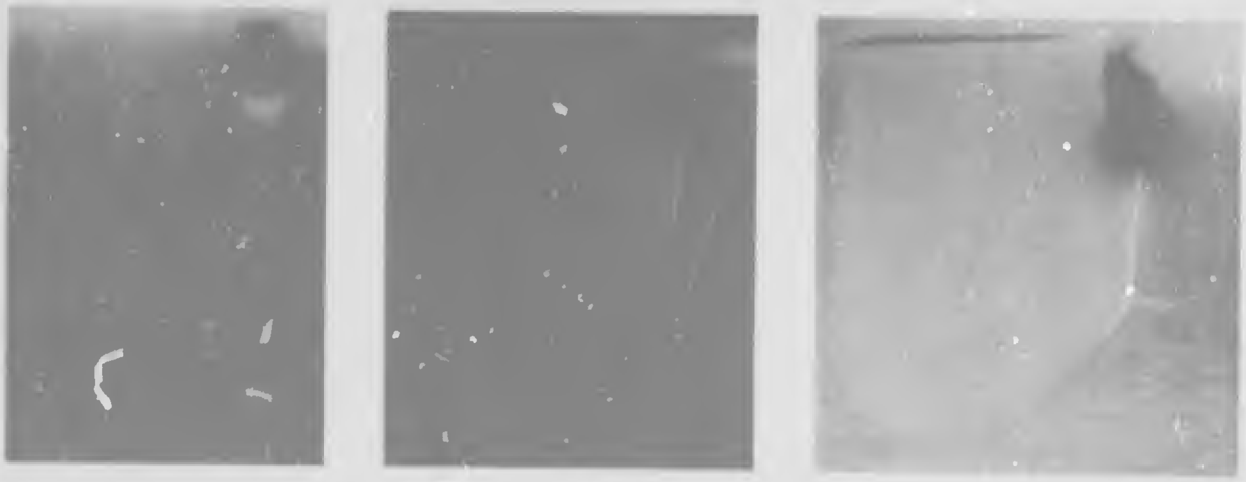
The fracture surface of the step-load specimen is shown in Figure 86 and is typical of the failures of the constant-load specimens.

Microstructure studies along the fracture profile revealed intergranular cracking typical of SCC which terminated as transgranular tearing at the base of the weld bead. Microstructure at the tip of the fatigue crack is shown in Figure 87. Both rounded and sharp tip cracks were noted indicating corrosion and stress corrosion as operating modes.

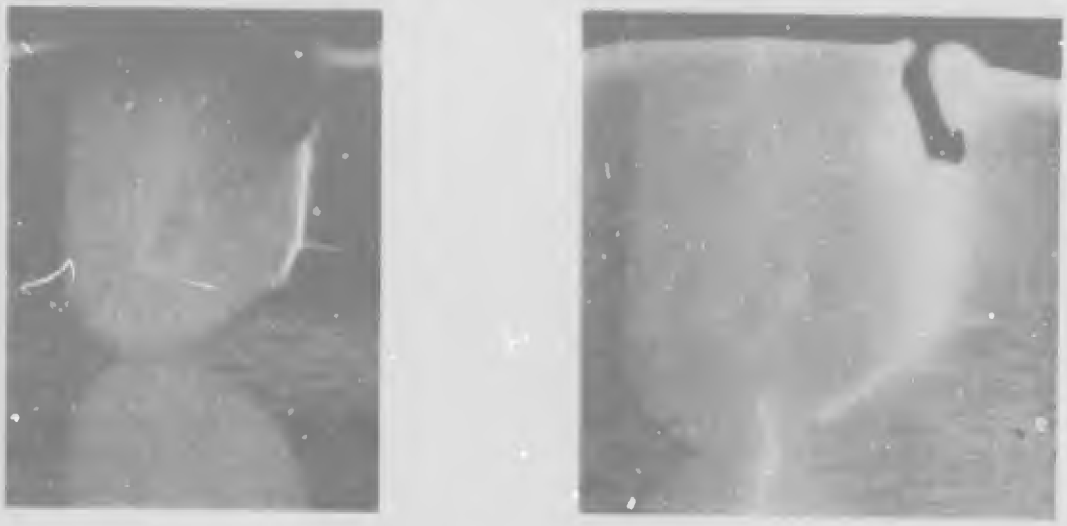
The tips of the larger short transverse cracks were sharp, typical of SCC.

Final lengths of the stress corrosion cracks for the constant-load notched specimens were difficult to determine. For the first specimen, SWX-39-S-6, the crack tip extended directly into the weld bead, 90° fatigue crack, with final failure occurring on the centerline of the lower weld bead parallel to the fatigue crack. For the second and third specimens, SWX-39-S-7 and SWX-39-S-8, cracks followed the edge of the weld bead, forking from the fatigue crack with final failure occurring through the weld bead. (SWX-39-S-7 was tension-tested after exposure but displayed prior crack extensions.)

At the fatigue crack tip, in the SCC initiation and propagation zone, the fracture was fibrous macrosopically with varying orientations and levels. Microscopic examination of this area revealed both inter- and transgranular cracks. The fibrous nature was also evident, to a lesser extent, in the sudden failure zone. This fracture is illustrated in Figure 88. It was not observed on the tension-tested unexposed specimens and is, therefore, considered related to stress-corrosion cracking in the weld bead.



STEP LOAD	1	2	3
SUSTAINED STRESS (KSI)	10.1	15.1	20.1
HOURS AT STEP	41	88	41
ACCUM. HOURS ALTERNATE IMMERSION	41	129	170
ACCUM. HOURS AIR (BETWEEN STEPS)	0	8	15
CRACK DEPTH (INCH)	0.340	0.340	0.375



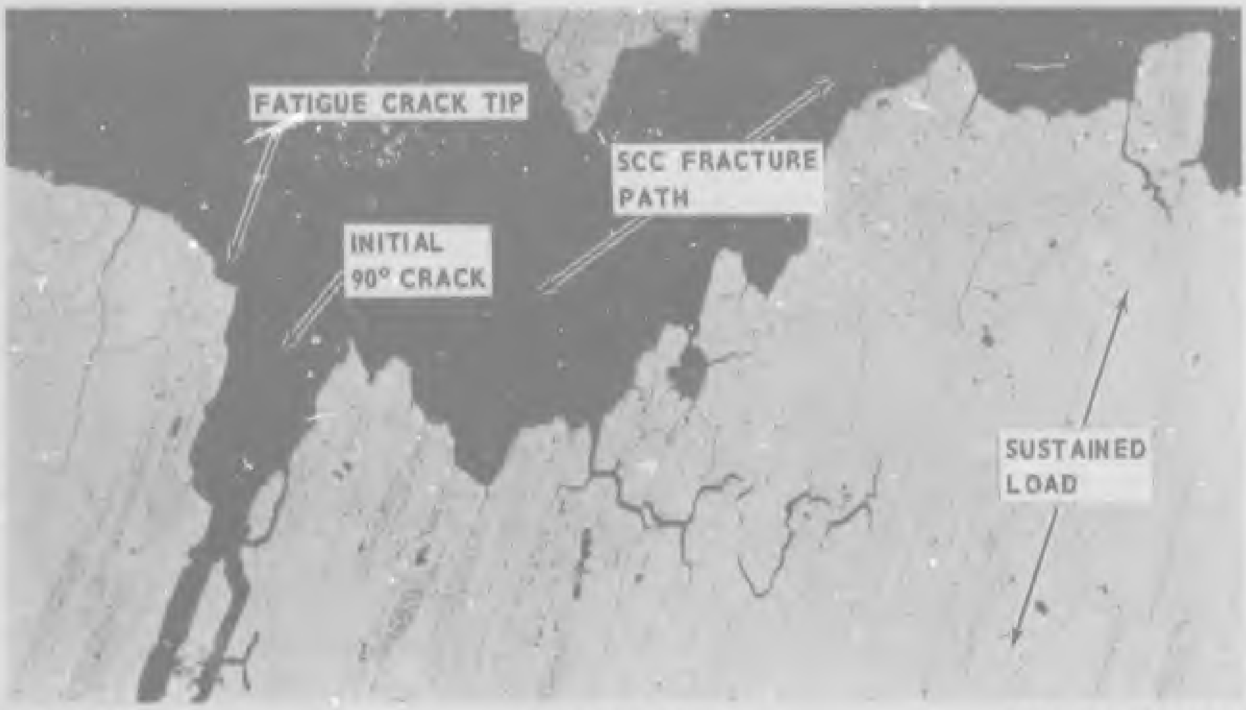
STEP LOAD	4	5
SUSTAINED STRESS (KSI)	25.2	30.2
HOURS AT STEP	41	89
ACCUM. HOURS ALTERNATE IMMERSION	211	300
ACCUM. HOURS AIR (BETWEEN STEPS)	21	27
CRACK DEPTH (INCHES)	0.415	0.510 (0.600 LINEAR)

FIGURE 85. STAGES OF SCC PROPAGATION IN 7039-T64 PLATE, WELD + STA TEMPER, AS VIEWED BY X-RAY.

MAGNIFICATION: 5×

SPEC NO. SWX-39-S-5

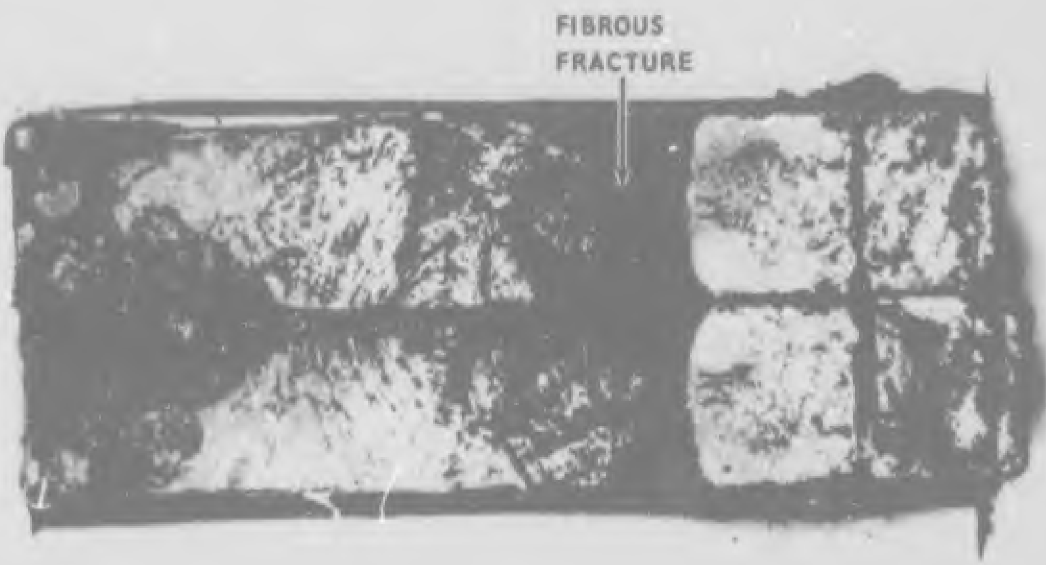
FIGURE 86. FRACTURE SURFACE OF PRE-CRACKED 7039-T64 PLATE, WELD + STA TEMPER, THAT FAILED DURING STEP LOAD SCC TESTING.



MAGNIFICATION: 250X KELLER'S ETCH SPEC NO. SWX-39-5-5

MAGNIFICATION: 250X KELLER'S ETCH SPEC NO. SWX-39-5-5

FIGURE 87. MICROSTRUCTURE AT TIP OF FATIGUE CRACK OF 7039-T64 PLATE, WELD + STA TEMPER, THAT FAILED DURING STEP LOAD SCC TESTING.



MAGNIFICATION: 5×

SPEC NO. SWX-39-S-7

FIGURE 88. FRACTURE SURFACE OF PRECRACKED 7039-T64 PLATE, WELD + STA TEMPER, THAT FAILED DURING CONSTANT LOAD SCC TESTING.

ALLOYS 7106-T6 AND X7002-T6 PLATE

Only the basic unwelded temper, unnotched, was tested in step-load and constant-load alternate immersion. No SCC was incurred with either of the alloys at sustained stresses up to 75-percent yield strength.

ENVIRONMENTAL CRACK INITIATION AND PROPAGATION

Environmental crack initiation times and propagation rates were studied from plate specimens that exhibited crack extension either from corrosion or SCC during step-load and constant-load SCC tests. Specimens selected from the tables in the Appendix are shown in Table IX for step loads, and Table X for constant loads. Notched and unnotched specimens are included.

Because of the multi-directionality of the various cracks relative to sustained stress: (1) curve-linear along the fusion line, (2) diagonal into the weld bead, (3) dog-leg into the weld bead or heat-affected zone, and (4) short transverse grain direction, the length of crack extension used for rate study is not necessarily perpendicular to the applied load but is viewed to be the main line of crack progression.

Step-load specimens were X-rayed for crack length after exposure at each step and relative hours to crack initiation and lapsed time hours during crack propagation could be distinguished. Constant-load test specimens were X-rayed at beginning of test and after 250 hours exposure, thus exposure hours for a given crack length include both initiation and propagation stages.

Analysis of the step-load data indicates the stress-corrosion crack propagates in a discontinuous manner. For example, 2014-T6 weld plus STA temper, specimen SWX-14-S-5 exhibited the initial fatigue crack length of 0.393 inch after 90 hours alternate immersion at 5.9 ksi (net section stress). After 41 hours at 8.9 ksi, the crack jumped to 0.503 inch. For the balance of exposure, 325 hours, up to failure at 20.8 ksi, the crack length increased to only 0.518 inch. As another example, specimen SWX-39-S-5, 7039-T64 weld plus STA temper, exhibited most rapid growth at the last two steps. After 41 hours exposure at 25.2 ksi the crack length was 0.415 inch and during 89 hours at the next step, 30.7 ksi, crack length jumped to 0.600 inch and failure. Initial fatigue crack length was 0.340 inch.

To generalize the step-load data and arrive at a representative crack propagation rate, total increase in crack length was divided by alternate immersion hours consumed after crack tip was observed extending. Exposure hours consumed prior to crack extension was considered hours to crack initiation. These data are shown in Table IX. Corrosion and SCC modes of crack extension have been indicated in the table as determined by metallographic examination (discussed previously in the text). Summarizing the data in Table IX, considering specimens exhibiting crack extension attributed to corrosion and then specimens exhibiting extension due to SCC, the following crack propagation rates are given:

TABLE IX

Environmental Crack Initiation and Propagation Rates for Step-Load Plates

ALLOY	TEMPER	SPECIMEN CODE[1]	CRACK INITIATION			CRACK PROPAGATION				CAUSE
			Stress Range KSI	Exposure Hours	% Total Exposure Hours	Increase in Crack Length Inch	Stress Range KSI	Exposure Hours	Rate in. /hr x 10^{-3}	
2014-T6	Weld + Age	SWX-14-A-5	4.8/12.0	281	56.2	0.040	14.4/18.0	219	0.18	Corrosion
	Weld + STA	SWU-14-S-5	12.6/31.6	304	66.5	0.100	37.9/44.2	152	0.66	SCC
		SWX-14-S-5	5.9	90	21.0	0.125	0.9/20.8	325	0.38[2]	SCC
X2021-T8E31	As Welded	SWX-21-W-5	5.6/11/2	170	39.6	0.080	16.0/21.0	259	0.31	Corrosion
	Weld + Age	SWX-21-A-5	5.0/10.1	170	39.6	0.045	12.6/18.9	259	0.17	Corrosion
	Weld + STA	SWX-21-S-5	5.5/8.3	129	61.0	0.210	11.0/13.7	82	2.50	SCC
2024-T851	Weld + Age	SWX-24-A-5	5.3/10.6	244	49.0	0.080	13.2/19.8	256	0.31	Corrosion
2219-T87	As Welded	SWX-19-W-5	6.1/9.1	242	29.1	0.070	10.6/22.7	590	0.12	Corrosion
7039-T64	Weld + STA	SWX-39-S-5	10.1/15.1	129	43.0	0.260	10.1/30.7	171	1.50[3]	SCC
		SWU-39-S-5	10.4/20.9	244	48.8	0.280	26.1/39.1	256	1.10	SCC

[1] X = Fatigue Cracked Specimen
U = Unnotched Specimen

[2] Maximum propagation rate between 5.9/8.9 KSI steps 0.110 in. in 41 hrs = 2.70 x 10^{-3} in./hr.

[3] Propagation between 25.2/30.7 KSI steps = 2.02 x 10^{-3} in./hr.

TABLE X

Damage Rate of Precracked Welded Aluminum Alloy Plate in Alternate Immersion Environment

CONSTANT LOAD TESTS — LONG. TRANS. GRAIN

Alloy	Temper	Specimen Code	Sustained Net Section Stress, KSI	Initial Stress Intensity K_I KSI $\sqrt{\text{inch}}$	Alternate Immersion Hours	Increase in Crack Length, Inch	Average Damage Rate (1) in./hr X 10^{-3}	Cause
2014 T6	Weld + STA	SWX-14-S-7	19.4	25.8	F217	0.260	1.20 (2)	SCC
X2021 T8E31	Weld + STA	SWX-21-S-6	14.0	19.5	NF498	0.065	0.13	Corrosion
		SWX-21-S-7	16.2	24.4	F226	0.150	0.66	SCC
		SWX-21-S-8	18.9	25.8	F122	0.080	0.65 (3)	SCC
2024 T851	As Welded	SWX-24-W-6	19.0	27.7	NF498	0.125	0.25	Corrosion
	Weld + Age	SWX-24-A-7	14.2	21.6	NF498	0.030	0.06	Corrosion
2219 T87	As Welded	SWX-19-W-6	23.5	-	NF530	0.140 (Fork) (4)	0.26	Corrosion
7039 T64	Weld + STA	SWX-39-S-7	20.5	26.9	NF250 (5)	0.205 (Fork)	0.82	SCC
		SWX-39-S-8	15.2	18.9	NF505	0.150 (Fork)	0.30	SCC
					NF250 (5)	0.075 (Fork)	0.30	
		SWU-39-S-7 (6)	34.0	-	F416	0.350	0.84	SCC

(1) Average Damage rate = increase in crack length/alternate immersion hours

(2) Major damage occurred in first 64 hours. Crack length increased 0.205 in. 0.205/64 = 3.20 x 10^{-3} in./hr

(3) Major damage occurred in first 18 hours. Crack length increased 0.060 in. 0.060/18 = 3.30 x 10^{-3} in./hr

(4) Crack forked. Leg length = 0.140 in.

(5) Based on X-Ray crack length @ 250 hours exposure

(6) Unnotched specimen. All others notched.

	Corrosion Crack Propagation Rate (in/hr × 10^{-3})	Stress Corrosion Crack Propagation Rate (in/hr × 10^{-3})
Maximum	0.31	2.50
Minimum	0.12	0.38
Average	0.21	1.23

As would be expected, the corrosion crack extended at a much slower rate than the stress-corrosion crack and the SCC rate exhibited considerable range between maximum and minimum.

Hours to crack initiation as a percent of the total exposure hours considering corrosion and stress-corrosion modes from Table IX can be summarized as follows:

	Corrosion Initiation (Percent Total Exposure Hours)	Stress Corrosion Initiation (Percent Total Exposure Hours)
Maximum	56.2	66.5
Minimum	29.1	21.0
Average	42.7	48.1

The similarity of these data indicates both modes require approximately the same exposure time before measurable damage occurs and suggests that the SCC initiation stage is strongly corrosion related. Also, approximately one-half of the number of hours-to-failure in the step-load stress corrosion test was consumed by the initiation stage.

Referring to the constant-load test data in Table X and summarizing in a similar manner where initial crack extension and propagation stages are inseparable and called "damage rate," gives:

	Corrosion Damage Rate (in/hr × 10^{-3})	Stress Corrosion Damage Rate (in/hr × 10^{-3})
Maximum	0.26	1.20
Minimum	0.06	0.30
Average	0.17	0.68

These damage rates are slower than the propagation rates derived from the step-load tests, as might be expected, because the hours to initial crack extension are included in determining the damage rate. Considering that approximately one-half of the time to failure is consumed before initial extension, as indicated by the step-load tests, the average stress-corrosion damage rate of the constant-load test then approximates the average stress-corrosion crack propagation rate of the step-load tests.

The discontinuous nature of crack propagation was also observed with the constant-load specimens as noted in Table X. For example, specimen SWX-14-S-7,2014-T6 weld plus STA temper, had an average damage rate of 1.20×10^{-3} in/hr over the total exposure time to failure of 217 hours. However, major damage occurred in the first 64 hours of exposure at a rate of 3.20×10^{-3} in/hr. In a similar manner, specimen SWX-21-S-8 X2021-T8E31 weld plus STA had an average damage rate of 0.65×10^{-3} in/hr over a total exposure time-to-failure of 122 hours, but exhibited major damage in the first 18 hours of exposure of 3.30×10^{-3} in/hr.

In general, then, stress-corrosion cracking data exhibit corrosion and stress corrosion stages. The stress corrosion stage exhibits varying rates from the fastest corrosion rate observed to approximately 10 times that rate. Close inspection of the data indicates that the stress-corrosion cracking process is not merely one of one-time initiation and propagation but rather a complex spectrum of initiation stages and propagation stages which must be taken into consideration in defining the stress-corrosion process by mathematical models. Additional work is recommended along these lines.

As discussed previously, the propagating stress-corrosion cracks observed in this program selected various paths. This is attributed to the heterogeneous nature of the micro structure at the edge of the weld bead and is considered cause of much of the data scatter. Nevertheless, heterogeneity exists in structural materials and may be a source of error between mathematical prediction and actual results.

SECTION IX

REFERENCES

1. B. W. Lifka and D. O. Sprowls, "Stress Corrosion Testing of Aluminum Alloy 7079-T6 in Various Environments," Paper presented at ASTM 69th Annual Meeting, June 28, 1966, Stress-Corrosion Testing Symposium.

2. Welding Handbook, Section 4, Fifth Edition, Chapter 69.

3. I. B. Robinson, F. R. Collins, and J. D. Dowd, "Welding High Strength Alumirum Alloys," Welding Journal, May 1962.

4. J. H. Dudas and F. R. Collins, "Preventing Weld Cracks in High Strength Aluminum Alloys," Welding Journal Supplement, June 1966.

5. "Weldability of High Strength Aluminum Alloys," Defense Metals Information Center, DMIC #216 of August 22, 1966.

6. D. E. Schillinger, "Welding 2014-T6 and 2024-T86 Aluminum Alloy Sheet," Report AD615-735, Frankford Arsenal, Philadelphia, Pennsylvania, March 1965.

7. Selected Welding Techniques, Part II, NASA 5009, Marshall Space Flight Center, pages 1-2 and 11-13, July 1964.

8. J. A. Liptak, "Gas Tungsten-Arc Welding Aluminum Plate," Welding Journal, June 1965.

9. "Procedure Specification for Welding Aluminum Alloy 7039 to Code Case 1363 and ASME Section IX Requirements; and for Ballistic Applications," Kaiser Aluminum and Chemical Corporation, Dept. of Metallurgical Research, Spokane, Washington, June 1966.

10. A. I. Kemppinen and G. E. Stein, Reynolds Metal Company Alloy Bulletin X7002, Metallurgical Research Division (date unknown).

11. "Radiographic Standard for Classification of Fusion Weld Discontinuities," National Aerospace Standard (NAS) 1514, June 1963.

12. R. P. Meister and D. C. Martin, "Welding of Aluminum and Aluminum Alloys," Defense Metals Information Center, DMIC Report 236, April 1, 1967.

13. C. L. Mitchell, "Out-of-Position-Gas-Shielded-Arc Welding of Heavy Aluminum Sections," Welding Journal, September 1965.

14. "Fracture Toughness Testing," a symposium presented at the 67th Annual Meeting of the American Society for Testing and Materials, Chicago, Illinois, June 21-26, 1964. ASTM Special Technical Publication No. 381, April 1965.

15. J. E. Campbell, "Current Methods of Fracture Toughness Testing of High-Strength Alloys With Emphasis on Plain Strain," Battelle Memorial Institute, Columbus, Ohio, DMIC Report 207, August 31, 1964.

16. ASTM Special Committee, "Progress in Measuring Fracture Toughness and Using Fracture Mechanics," Materials Research and Standards, March 1964.

17. Telephone conversation between Dr. T. Sumerson, Kaiser, and R. V. Turley, Douglas, May 16, 1967.

APPENDIX A

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TABLE A-1

Tension Test Data for 2XXX Series Aluminum Alloys, Unnotched Sheet Specimens

Long Trans Grain

	Temper	Specimen Code	Ultimate KSI	Yield KSI	Elongation % (2")	Fracture Zone
2014 T6 (0.080")	Basic unwelded	TCU-14-C	70.51	63.59	8.4	
		TCU-14-D	70.13	62.78	8.9	
		Average	70.32	63.19	8.7	
	As welded	TWU-14-W-1	54.30	44.50	1.0	EWB
		TWU-14-W-2	53.40	43.15	1.2	EWB
		Average	53.85	43.83	1.1	
	Weld + AGE	TWU-14-A-1	57.64	52.31	0.7	EWB
		TWU-14-A-2	61.54	54.62	0.7	EWB
		Average	59.59	53.47	0.7	
	Weld + STA	TWU-14-S-1	68.33	57.05	5.7	EWB
		TWU-14-S-2	67.64	57.95	4.0	EWB
		Average	67.99	57.50	4.9	
X2021 T8E31 (0.064")	Basic unwelded	TCU-21-1	76.04	65.94	8.2	
		TCU-21-2	76.23	66.51	8.0	
		Average	76.14	66.23	8.1	
	As welded	TWU-21-W-1	46.91	33.64	2.0	EWB
		TWU-21-W-2	46.99	33.28	2.0	EWB
		Average	46.95	33.46	2.0	
	Weld + AGE	TWU-21-A-1	55.21	51.82	0.7	EWB
		TWU-21-A-2	52.96	48.78	0.7	EWB
		Average	54.09	50.30	0.7	
	Weld + STA	TWU-21-S-1	73.87	66.67	5.8	EWB/HAZ
		TWU-21-S-2	74.85	66.16	6.0	PM
		Average	74.36	66.42	5.9	
2024 T81 (0.080")	Basic unwelded	TCU-24-C	69.27	61.96	7.0	
		TCU-24-D	70.20	63.64	7.0	
		Average	69.74	62.80	7.0	
	As welded	TWU-24-W-1	51.74	(1)	1.1	WB
		TWU-24-W-2	56.49	53.59	0.6	WB
		Average	54.12	53.59	0.9	
	Weld + AGE	TWU-24-A-1	61.84	61.08	0.2	WB
		TWU-24-A-2	61.99	60.98	0.5	WB
		Average	61.92	61.03	0.4	
	Weld + STA	TWU-24-S-1	61.50	55.39	1.1	WB
		TWU-24-S-2	62.94	55.53	1.6	WB
		Average	62.22	55.46	1.4	
2219 T87 (0.125")	Basic unwelded	TCU-19-C	67.61	53.83	9.5	
		TCU-19-D	67.71	54.45	9.5	
		Average	67.66	54.14	9.5	
	As welded	TWU-19-W-1	46.81	32.97	3.0	EWB
		TWU-19-W-2	46.89	33.30	2.1	EWB
		Average	46.85	33.14	2.6	
	Weld + AGE	TWU-19-A-1	51.57	43.48	1.3	EWB
		TWU-19-A-2	51.70	43.51	2.1	EWB
		Average	51.64	43.50	1.7	
	Weld + STA	TWU-19-S-1	69.98	52.88	12.3	PM
		TWU-19-S-2	69.86	52.41	12.0	PM
		Average	69.92	52.65	12.2	

(1) Specimen failed before 0.2% offset yield strength reached.

TABLE A-2

Tension Test Data for 7XXX Series Aluminum Alloys, Unnotched Sheet Specimens

Long Trans Grain

	Temper	Specimen Code	Ultimate KSI	Yield KSI	Elongation % (2")	Fracture Zone
X7002 T6 (0.125")	Basic unwelded	TCU-02-C TCU-02-D Average	68.41 68.26 68.34	57.78 57.26 57.52	12.0 11.1 11.6	
	As welded	TWU-02-W-1 TWU-02-W-2 Average	49.05 48.57 48.81	38.70 38.76 38.73	2.1 2.8 2.5	EWB EWB
	Weld + AGE	TWU-02-A-1 TWU-02-A-2 Average	54.21 55.62 54.92	49.68 49.05 49.37	1.3 1.0 1.2	EWB EWB
	Weld + STA	TWU-02-S-1 TWU-02-S-2 Average	64.82 64.61 64.72	52.54 52.13 52.34	11.4 9.5 10.5	PM EWB/PM
7039 T64 (0.125")	Basic unwelded	TCU-39-C TCU-39-D Average	60.02 60.05 60.04	51.15 51.48 51.32	10.0 10.0 10.0	
	As welded	TWU-39-W-1 TWU-39-W-2 Average	50.00 50.90 50.45	33.88 32.51 33.20	4.3 4.5 4.4	EWB/WB EWB/WB
	Weld + AGE	TWU-39-A-1 TWU-39-A-2 Average	55.12 54.75 54.94	44.74 44.43 44.59	4.8 5.0 4.9	EWB/WB EWB/WB
	Weld + STA	TWU-39-S-1 TWU-39-S-2 Average	62.60 62.26 62.43	53.03 52.70 52.87	11.5 11.6 11.6	PM PM
7106 T6 (0.090")	Basic unwelded	TCU-06-C TCU-06-D Average	63.70 62.73 63.22	56.16 56.36 56.26	11.1 11.0 11.1	
	As welded	TWU-06-W-1 TWU-06-W-2 Average	57.62 58.02 57.82	41.93 42.57 42.25	4.0 3.6 3.8	EWB EWB
	Weld + AGE	TWU-06-A-1 TWU-06-A-2 Average	61.06 61.76 61.41	53.27 53.50 53.39	5.2 5.5 5.4	EWB EWB
	Weld + STA	TWU-06-S-1 TWU-06-S-2 Average	66.32 66.44 66.38	60.34 60.54 60.44	8.3 8.6 8.5	PM PM

TABLE A-3

Notched Tension Test Data for Sheet Alloys

Specimens With Surface Flaw at EWB

Long Trans Grain

Alloy	Temper	Specimen Code	σ_{Gross} KSI	σ_{Net} KSI	Fatigue Crack Length/Depth In/In	Final Failure % Shear Lip @ P-C Depth/ Near Edge	Specimen Width/Thick In/In	$\frac{\sigma_{Net}}{\text{Yield Strn.}}$
2014-T6	As Welded	TWX-14-W-1	43.47	45.84	0.300/0.017	33/83	1.0014/0.0775	1.05
		TWX-14-W-2	42.97	45.87	0.310/0.020.	33/40	0.9943/0.0777	1.05
		Average	43.44	45.86				
	Weld + AGE	TWX-14-A-1	49.04	53.94	0.600/0.015	30/25	1.0002/0.0778	1.01
		TWX-14-A-2	51.61	53.98	0.290/0.015	33/25	1.0000/0.0778	1.01
		Average	50.33	53.96				
	Weld + STA	TWX-14-S-1	47.64	56.16	0.375/0.040	33/100	0.9995/0.0777	0.98
		TWX-14-S-2	46.98	59.56	0.400/0.040 & 0.200/0.030	25/100	0.9988/0.0763	1.03
		Average	47.31	57.86				
X2021-T8E31	As Welded	TWX-21-W-1	33.21	38.63	0.400/0.030	100/100	0.9931/0.0657	1.15
		ΓWX-21-W-2	24.81	36.73	0.600/0.045	100/100	0.9967/0.0655	1.10
		Average	29.01	37.68				
	Weld + AGE	TWX-21-A-1	29.08	40.30	0.460/0.050	100/100	1.0012/0.0649	0.80
		TWX-21-A-2	31.64	38.15	0.330/0.043	100/100	0.9946/0.0655	0.76
		Average	30.36	39.23				
	Weld + STA	TWX-21-S-1	39.03	50.50	0.420/0.045	100/100	0.9977/0.0654	0.76
		TWX-21-S-2	39.11	49.61	0.440/0.040	100/100	0.9947/0.0655	0.75
		Average	39.07	50.06				
2024-T81	As Welded	TWX-24-W-1	33.59	43.80	0.500/0.047	5/15	1.0011/0.0791	0.82
		TWX-24-W-2	30.70	40.77	0.500/0.050	5/10	0.9999/0.0795	0.76
		Average	32.15	42.29				
	Weld + AGE	TWX-24-A-1	19.57	26.71	0.385/0.070	5/10	0.9999/0.0792	0.44
		TWX-24-A-2	19.02	24.28	0.360/0.061	5/15	1.0002/0.0794	0.40
		Average	19.30	25.50				
	Weld + STA	TWX-24-S-1	41.44	51.78	0.410/0.050	100/100	1.0005/0.0794	0.93
		TWX-24-S-2	43.45	51.57	0.370/0.043	50/100	1.0003/0.0794	0.93
		Average	42.45	51.68				
2219-T87	As Welded	TWX-19-W-1	42.14	43.15	0.380/0.010	100/100	0.9985/0.1280	1.30
		TWX-19-W-2	38.31	43.86	0.320/0.065	33/100	1.0025/0.1284	1.32
		Average	40.23	43.51				
	Weld + AGE	TWX-19-A-1	41.25	44.78	0.430/0.030	100/100	0.9974/0.1283	1.03
		TWX-19-A-2	43.68	47.83	0.280/0.051	100/100	0.0042/0.1284	1.10
		Average	42.47	46.31				
	Weld + STA	TWX-19-S-1	46.95	58.83	0.410/0.080	100/100	1.0009/0.1277	1.12
		TWX-19-S-2	52.02	58.96	0.310/0.062	33/100	0.9996/0.1282	1.11
		Average	49.49	58.90				
X7002-T6	As Welded	TWX-02-W-1	44.42	48.67	0.460/0.030	-	1.0009/0.1238	1.26
		TWX-02-W-2	45.79	50.58	0.300/0.050	40/100	0.9985/0.1249	1.31
		Average	45.11	49.63				
	Weld + AGE	TWX-02-A-1	45.97	53.67	0.420/0.050 & (1) 0.170/0.010	100/100	1.0012/0.1239	1.09
		TWX-02-A-2	47.08	50.47	0.203/0.028 & (1) 0.203/0.025	100/100	0.9997/0.1250	1.02
		Average	46.53	52.07				
	Weld + STA	TWX-02-S-1	46.00	52.98	0.300/0.069	60/100	0.9984/0.1239	1.01
		TWX-02-S-2	48.55	58.79	0.395/0.070	100/100	1.0023/0.1243	1.12
		Average	47.28	55.89				
7039-T64	As Welded	TWX-39-W-1	51.98	53.62	0.390/0.012	100/100	1.0013/0.1210	1.62
		TWX-39-W-2	52.88	54.27	0.330/0.012	100/100	0.9974/0.1183	1.63
		Average	52.43	53.95				
	Weld + AGE	TWX-39-A-1	46.03	50.09	0.420/0.030	100/100	1.0021/0.1218	1.12
		TWX-39-A-2	40.30	53.54	0.640/0.060	100/100	1.0024/0.1218	1.20
		Average	43.17	51.82				
	Weld + STA	TWX-39-S-1	47.49	58.33	$\frac{0.400}{0.060}$ $\frac{0.160}{0.040}$ $\frac{0.100}{0.010}$ (1)	100/100	1.0025/0.1214	1.10
		TWX-39-S-2	50.17	69.98	0.880/0.050	100/100	1.0030/0.1218	1.32
		Average	48.83	64.16				
7106-T6	As Welded	TWX-06-W-1	53.47	57.04	0.250/0.028	100/100	1.0008/0.0824	1.35
		TWX-06-W-2	50.40	56.93	0.430/0.030	100/100	0.9990/0.0881	1.35
		Average	51.94	56.99				
	Weld + AGE	TWX-06-A-1	49.71	56.43	0.440/0.030	100/100	1.0027/0.0872	1.06
		TWX-06-A-2	38.86	51.67	0.460/0.060	100/100	1.0027/0.0873	0.97
		Average	44.29	54.05				
	Weld + STA	TWX-06-S-1	48.69	67.22	0.440/0.070	100/100	1.0003/0.0878	1.11
		TWX-06-S-2	49.54	66.64	0.440/0.065	100/100	0.9990/0.0878	1.10
		Average	49.12	66.93				

(1) Multiple fatigue cracks.

TABLE A-4

Tension Test Data for Unnotched Plate Alloys

Long Trans Grain

	Temper	Specimen Code	Ultimate KSI	Yield KSI	Elongation Percent (2 inches)	Fracture Zone
2014 T6 (1")	Basic unwelded	TCU-14-A	71.44	62.25	8.2	
		TCU-14-B	71.12	64.97	9.1	
		Average	71.28	65.11	8.7	
	As welded	TWU-14-W-3	44.44	28.84	1.7	WB
		TWU-14-W-4	44.93	28.20	1.7	WB
		Average	44.69	28.52	1.7	
	Weld + AGE	TWU-14-A-3	42.75	34.01	0.8	WB
		TWU-14-A-4	47.42	30.60	1.4	WB
		Average	45.09	32.31	1.1	
	Weld + STA	TWU-14-S-3	67.01	63.71	1.0	EWB
		TWU-14-S-4	67.88	62.68	1.5	EWB
		Average	67.45	63.20	1.3	
X2021 T8E31 (1")	Basic unwelded	TCU-21-3	73.27	63.76	3.7	
		TCU-21-4	74.38	64.70	3.7	
		Average	73.83	64.23	3.7	
	As welded	TWU-21-W-3	31.96	22.65	2.7	WB
		TWU-21-W-4	39.99	23.88	2.8	WB
		Average	35.98	23.27	2.8	
	Weld + AGE	TWU-21-A-3	38.43	35.82	2.3	EWB/WB
		TWU-21-A-4	44.26	36.04	2.4	EWB/WB
		Average	41.35	35.93	2.4	
	Weld + STA	TWU-21-S-3	71.37	59.58	1.2	EWB
		TWU-21-S-4	71.61	65.15	2.3	EWB
		Average	71.49	62.37	1.8	
2024 T851 (1")	Basic unwelded	TCU-24-A	72.77	67.43	7.0	
		TCU-24-B	71.96	66.39	6.0	
		Average	72.37	66.91	6.5	
	As welded	TWU-24-W-3	47.33	38.44	0.7	EWB
		TWU-24-W-4	48.22	38.01	0.8	EWB
		Average	47.78	38.23	0.8	
	Weld + AGE	TWU-24-A-3	48.95	44.22	0.6	EWB
		TWU-24-A-4	47.65	44.11	0.5	EWB
		Average	48.30	44.17	0.6	
	Weld + STA	TWU-24-S-3	62.41	55.85	1.0	EWB
		TWU-24-S-4	62.26	56.32	0.8	EWB
		Average	62.34	56.09	0.9	

TABLE A-4 (Continued)

Long Trans Grain

	Temper	Specimen Code	Ultimate KSI	Yield KSI	Elongation Percent (2 inches)	Fracture Zone
2219 T87 (3/4")	Basic unwelded	TCU-19-A TCU-19-B Average	70.37 69.79 70.08	56.91 56.44 56.68	13.5 11.5 12.5	
	As welded	TWU-19-W-A TWU-19-W-B Average	35.12 42.46 38.79	20.69 20.57 20.63	7.4 10.9 9.2	EWB/WB WB
	Weld + AGE	TWU-19-A-3 TWU-19-A-4 Average	39.69 44.74 42.22	31.78 31.91 31.85	0.8 1.5 1.2	EWB/WB EWB/WB
	Weld + STA	TWU-19-S-3 TWU-19-S-4 Average	61.50 62.10 61.80	42.42 43.24 42.83	10.5 8.5 9.5	PM PM
7039 T64 (1")	Basic unwelded	TCU-39-A TCU-39-B Average	63.36 62.86 63.11	53.85 54.04 53.95	14.0 13.0 13.5	
	As welded	TWU-39-W-3 TWU-39-W-4 Average	49.88 49.81 49.85	32.16 31.64 31.90	10.4 10.4 10.4	PM PM
	Weld + AGE	TWU-39-A-3 TWU-39-A-4 Average	48.16 47.50 47.83	35.48 34.53 35.01	7.0 7.5 7.3	PM PM
	Weld + STA	TWU-39-S-3 TWU-39-S-4 Average	61.63 61.42 61.53	52.19 52.16 52.18	9.5 8.5 9.0	WB WB
X7002 T6 (3/4")	Basic unwelded	TCU-02-A TCU-02-B Average	64.74 65.05 64.90	55.05 55.24 55.15	12.8 13.5 13.2	
7106 T6 (1")	Basic unwelded	TCU-06-A TCU-06-B Average	62.00 62.43 62.22	53.59 54.29 53.94	14.0 14.8 14.4	

TABLE A-5

Notched Tension Test Data for Plate Alloys

Specimens With Single Edge Notch at EWB — Long Trans Grain

Alloy	Temper	Specimen Code	σ_{gross} KSI	σ_{net} KSI	Notch + Pre-Crack Depth Inch	Final Failure & % Shear Lip	Specimen Width/Thick in/in	σ_{net} / Yield Strn.
2014-T6	As welded	TWX-14-W-3	9.99	15.21	0.360	WB/0	1.0490/0.2004	0.53
		TWX-14-W-4	11.72	18.27	0.375	EWB/0	1.0456/0.2000	0.64
		Average	10.86	16.74				
	Weld + AGE	TWX-14-A-3	15.55	25.60	0.400	EWB/0	1.0180/0.2009	0.79
		TWX-14-A-4	16.04	24.01	0.350	EWB/0	1.0550/0.2003	0.74
		Average	15.80	24.81				
	Weld + STA	TWX-14-S-3	(1)					
		TWX-14-S-4	18.49	27.77	0.350	WB/75	1.0493/0.2004	0.44
		Average						
X2021-T8E31	As welded	TWX-21-W-3	17.02	25.87	0.360	WB/100	1.0218/0.2030	1.11
		TWX-21-W-4	18.61	28.84	0.390	WB/100	1.0227/0.1981	1.24
		Average	17.82	27.36				
	Weld + AGE	TWX-21-A-3	13.29	20.62	0.360	EWB/20	1.0133/0.2019	0.57
		TWX-21-A-4	12.84	19.58	0.350	EWB/WB /100	1.0165/0.2007	0.54
		Average	13.07	20.10				
	Weld + STA	TWX-21-S-3	17.18	26.96	0.370	EWB/100	1.0190/0.2023	0.43
		TWX-21-S-4	21.64	35.08	0.390	EWB/60	1.0178/0.2030	0.98
		Average	19.41	31.02				
2024-T851	As welded	TWX-24-W-3	17.90	26.60	0.360	WB/0	1.0177/0.2004	0.69
		TWX-24-W-4	16.25	23.45	0.350	EWB/0	1.0203/0.2002	0.61
		Average	17.08	25.03				
	Weld + AGE	TWX-24-A-3	14.79	22.17	0.340	WB/10	1.0212/0.2000	0.49
		TWX-24-A-4	20.99	34.48	0.400	EWB/0	1.0220/0.2000	0.78
		Average	17.89	28.33				
	Weld + STA	TWX-24-S-3	14.65	22.34	0.360	EWB/40	1.0312/0.2000	0.26
		TWX-24-S-4	24.28	34.27	0.320	EWB/100	1.0300/0.1999	0.61
		Average	19.47	28.32				
2219-T87	As welded	TWX-19-W-3	19.63	27.20	0.215	EWB/100	0.7732/0.1993	1.32
		TWX-19-W-4	18.58	33.30	0.215	EWB/100	0.7731/0.2018	1.61
		Average	19.13	30.25				
	Weld + AGE	TWX-19-A-3	25.19	35.25	0.220	HAZ/60	0.7721/0.2015	1.11
		TWX-19-A-4	21.00	38.22	0.350	HAZ/60	0.7760/0.1762	1.20
		Average	23.10	36.74				
	Weld + STA	TWX-19-S-3	36.76	51.44	0.220	EWB/100	0.7712/0.2018	1.20
		TWX-19-S-4	35.45	47.82	0.200	PM/100	0.7728/0.2000	1.12
		Average	36.11	49.63		(longitudinal shear)		
7039-T64	As welded	TWX-39-W-3	21.63	43.72	0.350	WB/100	1.0794/0.2004	1.37
		TWX-39-W-4	26.00	44.50	0.370	WB/100	1.0700/0.2006	1.39
		Average	23.82	44.11				
	Weld + AGE	TWX-39-A-3	27.32	41.45	0.360	EWB/100	1.0562/0.2000	1.18
		TWX-39-A-4	25.62	38.64	0.370	EWB/100	1.0600/0.2010	1.10
		Average	26.47	40.05				
	Weld + STA	TWX-39-S-3	34.86	50.5[illegible]	0.350	WB/100	1.0658/0.2002	0.97
		TWX-39-S-4	34.04	50.07	0.350	WB/100	1.0529/0.2003	0.96
		Average	34.45	50.29				

(1) Failed during precracking.

TABLE A-6

Stress Corrosion Test Data Step Load 2014-T6 Sheet

Alternate Immersion | Long Trans Grain

	Temper	Specimen Code	Sustained Net Section Stress, KSI/ Exposure Hrs at Step/ X-Ray Crack Length After Exposure: Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7	Residual Ultimate Strength KSI	Residual Ultimate Strength Exposed/Unexposed	Residual % Elong (2")	Initial Pre-crack Length/Depth / Final SCC (Est.) Length/Depth In/In	Fracture Zone & % Shear Lip @ Crack Tip & Near Edge
Unnotched	Basic Unwelded	SCU-14-1 (1)	22.07 NF41 NC	28.52 NF40 NC	31.94 NF41 ----	35.08 NF68 ----	38.06 NF41 ----	41.00 NF40 NC	43.91 NF304 ----	50.00	0.71	0.2	- / 0.075 deep pit	- -
	As Welded	SWU-14-W-1 (2)	16.10 NF35 NC	18.06 NF42 NC	20.32 NF65 ----	22.45 NF40 ----	26.49 NF41 ----	28.48 NF65 NC	30.67 F72 ----	-	-	-	- / 0.375/ thru	EWB -
	Weld + AGE	SWU-14-A-1	10.70 NF113 ----	13.37 NF65 NC	18.71 NF89 NC	24.06 NF65 NC	29.40 F44 ----			-	-	-	- / 1.0/ 0.060	EWB -
	Weld + STA	SWU-14-S-2	11.50 NF112 NC	17.25 NF41 NC	23.00 NF40 NC	28.75 F44 ----				-	-	-	- / 0.640/ 0.065	EWB -
Pre-Cracked @ EWB	As Welded	SWX-14-W-1-1	9.11 NF112 NC (4)	11.40 NF41 0.235	13.67 NF40 0.235	15.95 NF64 0.235	18.22 NF65 0.235	20.51 NF89 0.250	22.78 F64 ----	-	-	-	0.300/ (5) 0.035 & 0.220/ 0.010 / 0.640/ thru	EWB thru/ 100
	Weld + AGE	SWX-14-A-2	10.48 NF65 NC	13.12 NF59 NC	15.74 NF41 NC	18.35 NF42 NC	20.97 NF65 NC	23.60 NF40 NC	26.22 F44 ----	-	-	-	0.210/ 0.015 / 0.600/ thru	EWB thru/ 50
	Weld + STA	SWX-14-S-1	10.62 NF112 NC	13.28 NF41 NC	15.93 F15 ----					-	-	-	0.430/ 0.035 / 1.900/ 0.050 (3)	EWB 100/ 100

(1) Specimen exposed 224 hrs total at 4 lower stress levels prior to Step 1.

(2) Specimen exposed 317 hrs total at 4 lower stress levels prior to Step 1.

(3) Constant 0.050" depth across specimen.

(4) NC = Crack not visible by X-ray.

(5) Two cracks.

TABLE A-7

Stress Corrosion Test Data Step Load 2021-T8E31 Sheet

Alternate Immersion | Long Trans Grain

	Temper	Specimen Code	Sustained Net Section Stress, KSI/ Exposure Hrs at Step/ X-Ray Crack Length After Exposure							Residual Ultimate Strength		Residual % Elong (2")	Initial Pre-crack Length/ Depth / Final SCC (Est.) Length/ Depth In/In	Fracture Zone & % Shear Lip @ Crack Tip & Near Edge
			Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7	KSI	Exposed / Unexposed			
Unnotched	Basic Unwelded	SCU-21-1	13.25 NF88 NC	19.87 NF41 NC	26.49 NF41 NC	33.12 NF64 NC	39.74 NF65 NC	46.36 NF81 NC	49.67 NF321 ----	62.29	0.82	0.5	---- / 0/0	gage mark ----
	As Welded	SWU-21-W-1	6.69 NF89 NC	10.04 NF65 ----	13.38 NF89 NC	16.73 NF65 NC	20.08 F69 ----			----	----	---	----(1) / 1.0/0.040	HAZ ----
	Weld + AGE	SWU-21-A-1	10.06 NF89 NC	15.09 NF65 ----	20.12 NF89 NC	25.15 NF65 NC	30.18 NF89 NC	35.21 NF41 NC	37.73 NF113 ----	51.52	0.95	0.5	---- / 0/0	EWB ----
	Weld + STA	SWU-21-S-1	13.28 NF89 NC	19.93 NF65 ----	26.57 NF89 NC	33.21 NF65 NC	39.85 NF89 NC	46.49 NF41 NC	49.82 NF113 ----	66.62	0.90	1.2	---- / 0/0	PM @ gage mark
Pre-Cracked @ EWB	As Welded	SWX-21-W-1	7.82 NF66 0.385	11.71 NF65 ----	15.62 NF89 0.410	19.55 F21				----	----	-	0.393/ 0.038 / 0.500/ 0.038 @EWB(2) 0.250/thru @HAZ	EWB/100 HAZ/0
	Weld + AGE	SWX-21-A-1	7.36 NF90 0.325	11.03 NF65 ----	14.71 NF89 0.325	18.39 NF65 0.335	22.07 NF89 0.335	25.75 NF41 0.345	27.57 NF113 ----	35.48	0.90	---	0.347/ 0.044 / 0.347/ 0.044	EWB
	Weld + STA	SWX-21-S-1	10.35 NF90 0.330	15.55 NF65 ----	20.74 NF89 0.360	25.94 NF65 0.370	31.12 NF89 0.360	36.29 NF41 0.370	38.88 NF113 ----	51.59	0.97	---	0.374/ 0.049 / 0.374/ 0.049	EWB

(1) Constant 0.040" depth across specimen.

(2) SCC extended pre-crack at EWB to 0.500"; then propagated at 90° to plane of pre-crack to cold side of HAZ where it continued an additional 0.250" across the specimen prior to final failure.

TABLE A-8

Stress Corrosion Test Data Step Load 2024-T81 Sheet

Alternate Immersion — Long Trans Grain

	Temper	Specimen Code	Sustained Net Section Stress, KSI/ Exposure Hrs at Step/ X-Ray Crack Length After Exposure							Residual			Initial Pre-crack Length/ Depth / Final SCC (Est.) Length/ Depth In/In	Fracture Zone & % Shear Lip @ Crack Tip & Near Edge
										Ultimate Strength				
			Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7	KSI	Exposed / Unexposed	% Elong (2")		
Unnotched	Basic Unwelded	SCU-24-1 (2)	21.97 NF106 NC	28.48 NF40 NC	31.74 NF41 ----	34.84 NF67 ----	37.78 NF41 ----	40.71 NF40 NC	43.59 NF304 ----	51.89	0.74	0.2	- / 0/0	- -
Unnotched	As Welded	SWU-24-W-1 (5)	17.29 NF65 NC	18.89 NF35 NC	21.88 NF37 NC	26.94 NF65 ----	29.85 NF40 NC	32.22 NF40 NC	34.82 F45 ----	-	-	-	- / 0.810/ 0.035	EWB -
Unnotched	Weld + AGE	SWU-24-A-1	21.36 NF88 NC	27.46 NF64 NC	33.57 NF64 NC	36.62 NF40 NC	39.67 NF40 NC	42.72 NF65 NC	45.77 NF287 ----	57.79	0.93	0.0	- / 0/0	EWB -
Unnotched	Weld + STA	SWU-24-S-1 (4)	13.87 NF64 NC	19.41 NF88 NC	24.96 NF64 NC	30.50 NF64 NC	33.28 NF40 ----	36.05 NF41 ----	38.82 (1) F0 ----	-	-	-	- / 0/0	EWB
Pre-Cracked @ EWB	As Welded	SWX-24-W-1 (6)	11.13 NF61 0.300	13.36 NF44 0.300	15.59 NF42 0.300	17.83 NF65 0.300	20.05 NF40 0.335	22.28 NF40 0.375	24.50 F24 ----	-	-	-	0.400/ 0.050 / 0.650/ thru/ 0.500 (7)	EWB thru/ 20
Pre-Cracked @ EWB	Weld + AGE	SWX-24-A-1 (3)	11.40 NF40 0.300	12.67 NF40 0.300	13.94 NF65 0.285	15.21 NF40 0.300	16.47 NF45 ----	17.74 NF64 0.325	19.10 NF257 ----	34.12	1.34	-	0.360/ 0.050 / 0.360/ 0.050	EWB 10/5
Pre-Cracked @ EWB	Weld + STA	SWX-24-S-1	22.33 NF49 0.325	24.81 NF40 0.340	27.29 NF65 0.350	29.77 NF40 0.360	32.29 NF45 0.350	34.76 NF64 0.360	37.25 NF257 ----	50.57	0.98	-	0.415/ 0.055 / 0.415/ 0.055	EWB 100/-

(1) Failed in air after step loading. No evidence of SCC on fracture surface.

(2) Specimen exposed 232 hrs total at 4 lower stress levels prior to Step 1. Reduction in ultimate strength attributed to corrosion.

(3) Specimen exposed 276 hrs total at 4 lower stress levels prior to Step 1.

(4) Specimen also exposed 112 hrs @ 11.09 KSI.

(5) Specimen exposed 194 hrs total @ 3 lower stress levels prior to Step 1 shown.

(6) Specimen also exposed 64 hrs @ 8.91 KSI.

(7) Crack length 0.650" on origin surface and 0.500" on thru side.

TABLE A-9

Stress Corrosion Test Data Step Load 2219-T87 Sheet

Alternate Immersion — Long Trans Grain

	Temper	Specimen Code	Sustained Net Section Stress, KSI/ Exposure Hrs at Step/ X-Ray Crack Length After Exposure: Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7	Residual Ultimate Strength KSI	Residual Ultimate Strength Exposed/Unexposed	Residual % Elong (2")	Initial Pre-crack Length/Depth / Final SCC (Est.) Length/Depth In/In	Fracture Zone & % Shear Lip @ Crack Tip & Near Edge
Unnotched	Basic Unwelded	SCU-19-1 (4)	20.03 NF106 NC	25.13 NF40 NC	27.67 NF41 ----	31.31 NF67 ----	33.90 NF41 ----	36.51 NF40 NC	39.03 NF304 ----	51.50	0.91	2.6	- 0/0	- -
	As Welded	SWU-19-W-1 (3)	13.62 NF42 NC	16.51 NF64 NC	18.27 NF40 NC	20.04 NF40 NC	21.54 NF64 NC	23.2C NF184 NC	24.86 NF305 NC	45.90	0.98	2.2	- 0/0	EWB -
	Weld + AGE	SWU-19-A-1 (2)	15.22 NF88 NC	19.57 NF64 NC	23.92 NF64 NC	26.09 NF40 NC	28.27 NF40 NC	30.44 NF65 NC	32.63 NF287 ----	48.17	0.93	1.3	- 0/0	EWB -
	Weld + STA	SWU-19-S-1	10.53 NF112 ----	13.16 NF64 NC	18.34 NF88 NC	23.69 NF64 NC	29.00 F67 (8) ----			-	-	-	- 0.820/ 0.040	EWB -
Pre-Cracked @ EWB	As Welded	SWX-19-W-1	19.33 NF65 0.275	21.74 NF89 0.285	24.16 NF64 0.285	26.57 NF89 0.300	28.99 NF65 0.390	31.41 NF66 0.425	36.25 NF66 ----	(7)	-	-	0.459/ 0.052 0.470/ 0.052 (1)	EWB 100/ 100
	Weld + AGE	SWX-19-A-1	8.62 NF90 0.080	12.94 NF64 ----	17.25 NF89 0.135	21.56 NF65 0.275	25.88 NF17 0.280	30.18 NF41 0.300 (6)	32.35 NF113 ----	45.84	0.89	-	0.337/ 0.038 0.337/ 0.038	EWB 100/ 100
	Weld + STA	SWX-19-S-1	10.88 NF90 0.300	16.33 NF64 ----	21.77 NF89 0.300	27.21 NF65 0.360	32.69 F21 ----			-	-	-	0.352/ 0.062 0.600/ thru/ 0.450 (5)	EWB thru/ 100

(1) Specimen exposed 234 hrs total at 4 lower stress levels prior to Step 1. Increase in Crack length attributed to corrosion.

(2) Specimen exposed 176 hrs total at 2 lower stress levels prior to Step 1.

(3) Specimen exposed 261 hrs total at 5 lower stress levels prior to Step 1.

(4) Specimen exposed 233 hrs total at 4 lower stress levels prior to Step 1.

(5) Crack propagated through the specimen. Length or emergence side was 0.450".

(6) Increase in Crack length reading attributed to yawning of Crack with increasing load.

(7) Failed during unloading.

(8) Failed in air before loading to next Step.

TABLE A-10

Stress Corrosion Test Data Step Load 7002-T6 Sheet

Alternate Immersion — Long Trans Grain

	Temper	Specimen Code	Sustained Net Section Stress, KSI/ Exposure Hrs at Step/ X-Ray Crack Length After Exposure							Residual Ultimate Strength			Initial Pre-crack Length/ Depth / Final SCC (Est.) Length/ Depth In/In	Fracture Zone & % Shear Lip @ Crack Tip & Near Edge
			Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7	KSI	Exposed / Unexposed	% Elong (2")		
Unnotched	Basic Unwelded	SCU-02-1 (1)	21.24 NF106 NC	26.66 NF40 NC	29.57 NF41 ----	33.14 NF67 ----	35.91 NF41 ----	38.66 NF40 NC	41.48 NF304 ----	53.42	0.78	1.9	- / 0/0 (Severe Corrosion)	gage mark -
Unnotched	As Welded	SWU-02-W-1 (2)	17.43 NF41 NC	18.62 NF64 ----	21.21 NF40 NC	23.28 NF40 NC	25.17 NF64 NC	27.11 NF184 NC	29.05 F284 ----	-	-	-	- / 0/0(4)	HAZ -
Unnotched	Weld + AGE	SWU-02-A-1 (3)	17.28 NF88 NC	22.22 NF64 NC	27.15 NF64 NC	29.62 NF40 NC	32.09 NF40 NC	34.56 NF65 NC	37.03 NF287 ----	48.54	0.88	0.5	- / 0/0	EWB -
Unnotched	Weld + STA	SWU-02-S-1 (3)	18.31 NF88 NC	23.55 NF64 NC	28.78 NF64 NC	31.40 NF40 NC	34.01 NF40 NC	36.63 NF65 NC	39.25 NF287 ----	45.15	0.70	1.3	- / 0/0	EWB/ WB -
Pre-Cracked @ EWB	As Welded	SWX-02-W-1	9.32 NF89 NC	13.97 NF64 ----	18.63 NF89 NC	23.28 NF65 NC	27.94 NF89 NC	32.59 NF41 NC	34.93 NF113 ----	43.70	0.88	-	0.204/ 0.034 & 0.191/(6) 0.013 / 0.204/ 0.034 & 0.191/ 0.013	EWB 100/ 100
Pre-Cracked @ EWB	Weld + AGE	SWX-02-A-1	10.22 NF89 0.375	15.32 NF64 ----	20.43 NF89 0.375	25.54 NF65 0.395	30.64 NF89 0.395	35.75 NF41 0.400	38.30 NF113 ----	41.29	0.79	-	0.400/ 0.031 / (5)	EWB 100/ 100
Pre-Cracked @ EWB	Weld + STA	SWX-02-S-1	11.57 NF41 0.350	17.35 NF88 0.385	23.14 NF41 0.385	28.92 NF40 0.385	34.70 NF89 0.420	40.49 F17 ----		-	-	-	0.380/ 0.070 / (5)	EWB/ WB 50/50

(1) Specimen exposed 232 hrs total at 4 lower stress levels prior to Step 1.

(2) Specimen exposed 283 hrs total at 5 lower stress levels prior to Step 1.

(3) Specimen exposed 179 hrs total at 2 lower stress levels prior to Step 1.

(4) Failure attributed to severe corrosion which reduced cross section and contributed to tensile failure.

(5) See discussion in text on Crack appearance.

(6) Two fatigue Cracks.

TABLE A-11

Stress Corrosion Test Data Step Load 7039-T64 Sheet

Alternate Immersion — Long Trans Grain

	Temper	Specimen Code	Sustained Net Section Stress, KSI/ Exposure Hrs at Step/ X-Ray Crack Length After Exposure: Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7	Residual Ultimate Strength: KSI	Residual Ultimate Strength: Exposed/Unexposed	Residual: % Elong (2")	Initial Pre-crack Length/Depth / Final SCC (Est.) Length/Depth In/In	Fracture Zone & % Shear Lip @ Crack Tip & Near Edge
Unnotched	Basic Unwelded	SCU-39-1	24.62 NF64 ----	27.09 NF46 ----	29.55 NF45 ----	32.01 NF69 ----	34.48 NF45 ----	36.93 NF307 ----		53.42	0.89	4.5	- 0/0	- -
	As Welded	SWU-39-W-1 (1)	12.27 NF35 NC	13.82 NF41 NC	16.64 NF54 NC	18.15 NF40 NC	20.01 NF40 IG	21.57 NF64 IG	23.23 F72 ----	-	-	-	- 0/0 (6)	HAZ -
	Weld + AGE	SWU-39-A-1 (2)	18.50 NF88 NC	23.79 NF64 NC	29.07 NF64 NC	31.72 NF40 NC	34.36 NF40 NC	37.00 NF65 NC	39.65 F80 ----	-	-	-	1.0/ 0.020 (7) 1.0/ 0.060	EWB -
	Weld + STA	SWU-39-S-1 (2)	15.60 NF88 NC	20.55 NF64 NC	24.68 NF64 NC	26.75 NF40 NC	29.98 NF40 NC	31.21 NF65 NC	33.44 NF287 ----	56.97	1.03	5.2	- 0/0	EWB -
Pre-Cracked @ EWB	As Welded	SWX-39-W-1 (3)	18.16 NF64	20.75 NF65 NC	23.35 NF88 NC	25.94 NF64 Pit & IG	28.53 NF89 Pit & IG	31.13 NF64 Pit & IG	33.72 F68 ----	-	-	-	0.400/ 0.014 (8) (6)	HAZ -
	Weld + AGE	SWX-39-A-1 (4)	20.07 NF64 NC	22.57 NF89 0.235	25.09 NF64 0.275	27.59 NF89 0.275	30.09 NF64 0.275	32.61 NF66 ----	37.63 NF66 ----	53.00	1.02	-	0.300/ 0.027 0.300/ 0.027	EWB 100/ 100
	Weld + STA	SWX-39-S-1 (5)	19.56 NF40 0.275	22.82 NF64 0.325	26.08 NF65 0.325	29.34 NF89 0.325	32.60 NF64 0.425	35.86 NF89 0.450	39.12 F20 ----	-	-	-	0.360/ 0.060 (10)	EWB 100/ 100

(1) Specimen exposed 260 hrs total at 4 lower stress levels prior to Step 1.

(2) Specimen exposed 176 hrs total at 2 lower stress levels prior to Step 1.

(3) Specimen exposed 192 hrs total at 3 lower stress levels prior to Step 1.

(4) Specimen exposed 236 hrs total at 4 lower stress levels prior to Step 1.

(5) Specimen exposed 129 hrs total at 2 lower stress levels prior to Step 1.

(6) Failure occurred in heat affected zone and is attributed to severe corrosion which reduced cross section and caused tensile failure.

(7) Constant 0.020" depth one surface of specimen. Constant 0.060" depth other surface.

(8) Estimated from surface crack length since failure occurred out of the plane of the Crack.

(9) Inadvertently step loaded above 75% yield strength.

(10) See discussion in text on crack appearance.

TABLE A-12

Stress Corrosion Test Data Step Load 7106-T6 Sheet

Alternate Immersion | Long Trans Grain

	Temper	Specimen Code	Sustained Net Section Stress, KSI/ Exposure Hrs at Step/ X-Ray Crack Length After Exposure							Residual Ultimate Strength			Initial Pre-crack Length/ Depth / Final SCC (Est.) Length/ Depth in/In	Fracture Zone & % Shear Lip @ Crack Tip & Near Edge
			Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7	KSI	Exposed / Unexposed	% Elong (2")		
Unnotched	Basic Unwelded	SCU-06-1 (1)	19.66 NF41 NC	25.41 NF40 NC	28.43 NF65 ----	31.25 NF67 ----	33.82 NF41 ----	36.45 NF40 NC	39.07 NF304 ----	47.27	0.75	0.2	0.10"deep pit on edge of specimen	gage mark -
	As Welded	SWU-06-W-1 (2)	13.10 NF65 NC	14.11 NF35 NC	16.45 NF41 NC	19.21 NF64 NC	21.92 NF40 IG	24.78 NF40 IG	26.79 F45 ----	-	-	-	- (5)	EWB
	Weld + AGE	SWU-06-A-1	10.67 NF112 ----	13.35 NF64 NC	18.69 NF88 NC	24.03 NF64 NC	29.36 F44 ----			-	-	-	- (4)	EWB -
	Weld + STA	SWU-06-S-1	12.09 NF113 ----	15.11 NF64 NC	21.15 NF96 NC	27.19 NF64 NC	33.25 NF64 NC	36.27 NF40 ----	39.29 F41 ----	-	-	-	- (4)	EWB -
Pre-Cracked @ EWB	As Welded	SWX-06-W-1 (3)	13.56 NF40 NC	16.26 NF40 NC	18.97 NF64 NC	21.68 NF65 NC	24.39 NF88 NC	27.10 NF63 NC	29.81 F21 NC	-	-	-	0.350/ 0.015 (4)	EWB/ WB 30/50
	Weld + AGE	SWX-06-A-1	12.22 NF124 0.430	15.26 F20 ----						-	-	-	0.420/ 0.065 (4)	EWB/ WB 10/30
	Weld + STA	SWX-06-S-1	13.39 NF112 0.810	16.73 F3 ----						-	-	-	0.380/ 0.070 (4)	EWB/ WB 100/ 100

(1) Specimen exposed 201 hrs total at 4 lower stress levels prior to Step 1.

(2) Specimen exposed 173 hrs total at 3 lower stress levels prior to Step 1.

(3) Specimen exposed 112 hrs total at 1 lower stress level prior to Step 1.

(4) See discussion in text on crack appearance.

(5) Failure attributed to severe corrosion followed by tensile failure.

TABLE A-13

Stress Corrosion Test Data for 2 XXX Series Aluminum Alloys, Constant Load Unnotched Sheet Specimens

Alternate Immersion, 500 Hrs. — Long Trans. Grain

Alloy	Temper	Specimen Code	Sustained Stress % Yield	Sustained Stress KSI	Exposure Hours	Residual Ultimate Strength, KSI / % Elong. (2")	Fracture Zone	Residual Ultimate / Unexposed Ultimate
2014 T6	Basic, Unwelded	SCU-14-2	69.4	43.87	NF568	59.16/0.2	gage mark	0.84
		SCU-14-3	75.0	47.39	NF504	64.96/1.2	----	0.92
	As Welded	SWU-14-W-2	65.0	28.49	NF504	44.20/0.8	EWB	0.82(3)
		SWU-14-W-3	75.0	32.87	F127	----	EWB	----
		SWU-14-W-4	70.0	30.67	NF500	43.88/0.4	EWB	0.81
	Weld + AGE	SWU-14-A-2	55.0	29.40	NF500	57.53/1.7	EWB	0.97
		SWU-14-A-3	65.0	34.76	NF500	52.57/0.4	EWB	0.88(3)
		SWU-14-A-4	75.0	40.10	F20	----	EWB	----(4)
	Weld + STA	SWU-14-S-3	50.0	28.75	F33	----	EWB	----(4)
		SWU-14-S-4	40.0	23.00	NF500	57.12/0.5	PM	0.94
X2021 T8E31	Basic, Unwelded	SCU-21-2	75.0	49.67	NF500	75.38/6.2	----	0.99
	As Welded	SWU-21-W-2	60.0	20.08	F308	----	HAZ(2)	----
		SWU-21-W-3	55.0	18.40	F128	----	HAZ(2)	----
		SWU-21-W-4	40.0	13.38	NF500	42.16/1.8	HAZ/EWB(1)	0.90
	Weld + AGE	SWU-21-A-2	75.0	37.73	NF501	50.61/1.0	EWB	0.94
	Weld + STA	SWU-21-S-2	75.0	49.82	NF501	65.59/BOG	PM	0.88
2024 T81	Basic, Unwelded	SCU-24-2	69.4	43.57	NF568	54.43/1.0	gage mark	0.78
		SCU-24-3	75.0	47.10	NF504	69.44/3.5	----	0.99
	As Welded	SWU-24-W-2	60.0	32.15	NF504	53.72/0.2	WB	0.99
		SWU-24-W-3	70.0	37.51	NF500	51.95/0.2	WB	0.96
		SWU-24-W-4	75.0	40.19	F33	----	EWB	----
	Weld + AGE	SWU-24-A-2	75.0	45.77	NF500	59.42/0.1	EWB/WB	0.96
	Weld + STA	SWU-24-S-2	70.0	38.82	NF500	59.65/1.2	WB	0.96
		SWU-24-S-3	75.0	41.60	NF500	63.74/2.7	EWB/WB	1.02
2219 T87	Basic, Unwelded	SCU-19-2	72.1	39.03	NF568	61.76/3.2	----	0.91
		SCU-19-3	75.0	40.61	NF500	68.08/8.2	----	1.01
	As Welded	SWU-19-W-2	75.0	24.86	NF500	46.79/1.2	EWB	1.00
	Weld + AGE	SWU-19-A-2	75.0	32.63	NF500	50.74/0.5	EWB	0.98
	Weld + STA	SWU-19-S-2	55.0	29.00	NF500	64.69/5.3	PM	0.93
		SWU-19-S-3	65.0	34.22	NF500	63.56/5.3	PM	0.91
		SWU-19-S-4-4	75.0	39.49	F34(5)	----	WB	----

(1) SCC origin, 0.150" x 0.040" in HAZ, Cold Side
(2) Cold side of HAZ
(3) Microstructure examination indicated reduction in strength due to pitting at edge of weld bead
(4) Microstructure examination revealed I.G. cracking at origin and branching along main failure line
(5) Lack of penetration on bottom of weld was noted at origin of failure in microscopic examination

TABLE A-14

Stress Corrosion Test Data for 7XXX Series Aluminum Alloys, Constant Load Unnotched Sheet Specimens

Alternate Immersion, 500 Hrs. | Long Trans. Grain

Alloy	Temper	Specimen Code	Sustained Stress % Yield	Sustained Stress KSI	Exposure Hours	Residual Ultimate Strength, KSI / % Elong. (2")	Fracture Zone	Residual Ultimate / Unexposed Ultimate
X7002 T6	Basic, Unwelded	SCU-02-2	72.1	41.47	NF568	59.94/5.2	----	0.88
		SCU-02-3	75.0	43.14	NF500	67.78/9.8	----	0.99
	As Welded	SWU-02-W-2	75.0	29.05	NF500	48.92/0.8	EWB	1.00
	Weld + AGE	SWU-02-A-2	75.0	37.03	NF500	53.43/1.0	EWB	0.97
	Weld + STA	SWU-02-S-2	50.0	26.17	NF500	64.96/12.0	PM	1.00
		SWU-02-S-3	75.0	39.26	NF500	63.45/4.5	EWB	0.98
7039 T64	Basic, Unwelded	SCU-39-2	72.1	37.00	NF568	53.92/5.3	----	0.90
		SCU-39-3	75.0	38.49	NF504	59.04/8.5	----	0.98
	As Welded	SWU-39-W-2	65.0	21.58	NF504	55.41/5.5	EWB	1.10
		SWU-39-W-3	75.0	24.90	NF500	51.36/1.1	EWB/WB	1.02
	Weld + AGE	SWU-39-A-2	75.0	33.44	NF500	50.12/2.5	EWB	0.91
	Weld + STA	SWU-39-S-2	75.0	39.65	F247	----	EWB	----
		SWU-39-S-3	55.0	28.98	NF500	62.31/4.0	PM	1.00
		SWU-39-S-4	65.0	34.37	NF501	55.85/5.0	WB	0.89
7106 T6	Basic, Unwelded	SCU-06-2	69.0	39.07	NF568	55.23/5.2	gage mark	0.87
		SCU-06-3	75.0	42.20	NF500	60.82/5.0	----	0.96
	As Welded	SWU-06-W-2	50.0	21.13	NF504	57.51/3.1	EWB	0.99
		SWU-06-W-3	65.0	27.46	NF500	56.18/1.4	EWB	0.97
		SWU-06-W-4	75.0	31.69	NF500	50.06/2.2	EWB	0.87
	Weld + AGE	SWU-06-A-2	55.0	29.37	F281	----	EWB	----
		SWU-06-A-3	45.0	24.03	NF500	61.66/5.6	EWB	1.00
		SWU-06-A-4	50.0	26.70	F153	----	EWB	----
	Weld + STA	SWU-06-S-2	65.0	39.29	F299	----	EWB	----
		SWU-06-S-3	55.0	33.24	NF500	65.90/7.1	PM	0.99
		SWU-06-S-4	60.0	36.26	NF500	66.36/6.7	PM	1.00

TABLE A-15

Stress Corrosion Test Data for Constant Load, Precracked Sheet Specimens

Alternate Immersion, 500 Hrs. — Long Trans Grain

	Temper	Specimen Code	Sustained Stress (Net Section) %NTS/%Yield	Sustained Stress (Net Section) KSI	Exposure Hours	Residual Strength (Net) KSI	Residual Strength (Net) Exposed/Unexposed	Fatigue Precrack Length/Depth In/In	X-Ray Crack Length @ 0 & 250 Hrs Exposure In.	Final Crack Length/Depth In/In
2014 T6	As Welded	SWX-14-W-3-3	45.9/45.9	20.14	F58	-----	----	0.782/0.030	0.350/(1)	1.00/0.030
		SWX-14-W-4-4	40.9/42.7	18.74	NF513	37.87	0.83	0.590/0.050	0.510/0.510	0.590/0.050
	Weld + AGE	SWX-14-A-3	55.9/56.42	30.17	F58	-----	----	0.381/0.043	0.380/(1)	----
		SWX-14-A-4	46.9/47.3	25.31	F80	-----	----	0.410/0.050	0.375/(1)	0.700/0.080
		SWX-14-A-5	29.9/20.1	16.10	NF500	51.57	0.95	0.300/0.055	0.300/0.300	0.300/0.055
	Weld + STA	SWX-14-S-2	31.1/31.3	18.00	NF500	55.27	0.96	0.485/0.045	0.325/0.325	0.485/0.045
		SWX-14-S-3	36.5/36.7	21.13	F34	-----	----	0.380/0.035	(5)	0.600/0.035
		SWX-14-S-4	35.8/36.1	20.74	NF500	54.87	0.95	0.410/0.040	0.250/0.330	0.410/0.040
X2021 T8E31	As Welded	SWX-21-W-2	50.1/56.4	18.88	F80	-----	----	0.395/0.040	0.380/(1)	(2)
		SWX-21-W-3	38.6/43.5	14.55	F34	-----	----	0.410/0.050	(5)	(2)
		SWX-21-W-4	24.0/27.0	9.05 (8)	NF500	35.61	0.95	0.300/0.035	0.240/0 240	0.300/0.035
	Weld + AGE	SWX-21-A-3	74.6/58.2	29.26	NF500	39.08	1.00	0.310/0.040	0.305/0.305	0.310/0.040
	Weld + STA	SWX-21-S-2	78.2/58.9	39.13	NF513	61.68	1.23	0.200/0.035	0.200/0.210	0.200/0.035
2024 T81	As Welded	SWX-24-W-2	61.4/48.4	25.95	F58	-----	----	0.403/0.054	0.335/(1)	0.500/thru
		SWX-24-W-3	50.1/39.5	21.18	NF513	40.67	0.96	0.380/0.050	0.250/0.295	0.380/0.050
		SWX-24-W-4	59.3/46.8	25.07	F118	-----	----	0.390/0.065	0.375/(1)	0.730/thru
	Weld + AGE	SWX-24-A-2	75.8/31.7	19.33	NF500	-----	----	0.320/0.050	0.300/0.330	0.320/0.050
	Weld + STA	SWX-24-S-2	72.5/67.5	37.46	NF500	53.80	1.04	0.520/0.040 0.300/0.025	0.375/0.450	0.520/0.040 0.300/0.025

(1) Failed prior to 250 hrs exposure x-ray check.

(2) Specimen failed through cold side of heat affected zone and precrack plane.

(5) No x-ray check prior to failure.

(8) Gross section stress = 7.74 KSI.

TABLE A-15 (Continued)

Alternate Immersion, 500 Hrs. — Long Trans Grain

	Temper	Specimen Code	Sustained Stress (Net Section) %NTS/%Yield	Sustained Stress (Net Section) KSI	Exposure Hours	Residual Strength (Net) KSI	Residual Strength (Net) Exposed / Unexposed	Fatigue Precrack Length/Depth In/In	X-Ray Crack Length @ 0 & 250 Hrs Exposure In.	Final Crack Length/Depth In/In
2219 T87	As Welded	SWX-19-W-2	68.0/89.2	29.57	NF500	47.49	1.09	0.330/0.010	(6)	0.330/0.010
	Weld + AGE	SWX-19-A-2	73.2/78.0	33.92	NF500	46.07	0.99	0.280/0.050	0.225/0.225	0.280/0.050
	Weld + STA	SWX-19-S-2	55.8/62.1	32.72	F197	-----	----	0.240/0.055	0.210/(1)	1.00/0.090
		SWX-19-S-3	46.3/51.8	27.28	NF500	56.02	0.95	0.290/0.065	0.275/0.295	0.290/0.065
		SWX-19-S-4	37.0/41.3	21.77	NF500	55.58	0.93	0.305/0.075	0.300/0.300	0.305/0.075
X7002 T6	As Welded	SWX-02-W-2	77.0/98.65	38.21	NF500	48.77	0.98	0.270/0.070	0.270/0.270	0.270/0.070
	Weld + AGE	SWX-02-A-2	----	-----	F (loading)	-----	----	0.280/0.030	----	----
		SWX-02-A-3	81.5/86.0	42.44	F139	-----	----	0.325/0.065	0.330/(1)	1.00/0.065 (4)
		SWX-02-A-4	71.5/75.4	37.22	F-78	-----	----	0.280/0.070	0.275/0.295	1.00/0.070 (4)
	Weld + STA	SWX-02-S-2	55.8/67.1	35.14	NF500	60.06	1.07	0.405/0.045	0.375/0.375	0.405/0.045
		SWX-02-S-3	75.0/80.1	41.91	NF500	54.68	0.98	0.290/0.070	0.280/0.285	0.290/0.070
		SWX-02-S-4	85.5/91.3	47.78	NF500	52.72	0.94	0.295/0.065	0.260/0.260	0.295/0.065
7039 T64	As Welded	SWX-39-W-3	67.0/1.05	34.89	NF500	44.85	0.83	0.270/0.030	0.270/0.270	0.270/0.030
		SWX-39-W-4	76.0/1.23	40.99	NF500	43.59	0.81	0.300/0.055	0.280/0.295	0.300/0.055
	Weld + AGE	SWX-39-A-3	75.9/88.3	39.37	F389	-----	----	0.355/0.030	0.300/0.300	
		SWX-39-A-4	66.7/77.5	34.55	NF500	50.18	0.97	0.130/0.045	0.130/0.130	0.130/0.045
								0.140/0.045	0.100/0.105	0.140/0.045
	Weld + STA	SWX-39-S-4	61.3/74.4	39.36	NF500	61.00	0.95	0.315/0.060	0.275/0.280	0.315/0.060
		SWX-39-S-4-4	67.0/81.3	43.01	NF500	55.71	0.87	0.280/0.045	0.275/0.320	0.280/0.045
		SWX-39-S-4-5	65.0/78.9	41.71	NF500	60.20	0.94	0.365/0.017	0.360/0.360	0.365/0.017

(1) Failed prior to 250 hrs exposure x-ray check.

(4) Crack propagated out of the plane of the precrack into WB prior to final failure.

(6) Crack not viesable by x-ray.

TABLE A-15 (Continued)

Alternate Immersion, 500 Hrs. — Long Trans Grain

	Temper	Specimen Code	Sustained Stress (Net Section) %NTS/%Yield	Sustained Stress (Net Section) KSI	Exposure Hours	Residual Strength (Net) KSI	Residual Strength (Net) Exposed/Unexposed	Fatigue Precrack Length/Depth In/In	X-Ray Crack Length @ 0 & 250 Hrs Exposure In.	Final Crack Length/Depth In/In
7106 T6	As Welded	SWX-06-W-2	56.1/75.6	31.94	NF513	43.13	0.76	0.290/0.060	0.290/0.295	0.290/0.060
		SWX-06-W-3	63.8/86.0	36.34	NF500	54.26	0.95	0.280/0.050	0.280/0.280	0.280/0.050
		SWX-06-W-4	67.9/91.6	38.69	NF500	50.41	0.88	0.280/0.050	0.275/0.310	0.280/0.050
	Weld + AGE	SWX-06-A-2	28.3/28.6	15.28	F106	-----	----	0.395/0.052	0.335/(1)	(7)
		SWX-06-A-3	18.7/18.9	10.12	NF513	54.79	1.01	0.330/0.040	0.240/0.265	0.330/0.040
		SWX-06-A-4	25.6/25.9	13.85	F83	-----	----	0.400/0.055	0.325/(1)	(7)
	Weld + STA	SWX-06-S-2	24.4/27.1	16.38	F106	-----	----	0.306/0.058	0.300/(1)	(7)
		SWX-06-S-3	15.0/16.7	10.07	NF513	66.57	0.99	0.380/0.055	0.190/0.205	0.380/0.055
		SWX-06-S-4	20.3/22.5	13.58	NF500	63.43	0.95	0.310/0.060	0.250/0.305	0.310/0.060

(1) Failed prior to 250 hrs exposure x-ray check.

(7) See discussion of alloy.

TABLE A-16

Data Work Sheet for Calculating Stress Intensity Factor
Welded Sheet, Step Load, Alternate Immersion

Specimen Code	Fatigue Crack			Specimen			Sustained Load					Q Factor	K_I (1) KSI $\sqrt{In}$	SCC Test Results
	Depth a inches	Length 2C inches	a/2C	Width inches	Thick inches	Area inches^2	Load lbs	σ_{gross} psi	σ_{yield} psi	$\frac{\sigma_{gross}}{\sigma_{yield}}$	σ_{gross}^2 psi x 10^6			
SWX-14-A-2	0.015	0.210	0.714	1.0008	0.0778	0.0779	1975	25,353	53,470	0.474	642.7	0.99	6.08	F, last step
SWX-14-S-1	0.035	0.430	0.0814	0.9982	0.0778	0.0776	1048	13,505	57,500	0.235	182.4	1.07	4.76	F, last step
SWX-21-W-1	0.038	0.393	0.0967	0.9989	0.0657	0.0656	842	12,835	33,460	0.384	164.7	1.04	4.78	Start Prop
SWX-21-A-1	0.044	0.347	0.1268	1.0003	0.0647	0.0647	1453	22,457	50,300	0.446	504.3	1.08	8.84	NF, last step
SWX-21-S-1	0.049	0.374	0.1310	0.9994	0.0648	0.0647	1952	30,170	66,420	0.454	910.2	1.09	12.47	NF, last step
SWX-24-W-1	0.050	0.400	0.1250	1.0022	0.0789	0.0790	1432	18,126	53,590	0.338	328.5	1.09	7.57	Start Prop
SWX-24-A-1	0.050	0.360	0.1388	1.0017	0.0794	0.0795	1257	15,811	61,030	0.259	249.9	1.13	6.48	NF, last step
SWX-24-S-1	0.055	0.415	0.1325	1.0023	0.0794	0.0796	2297	28,856	55,460	0.520	832.6	1.09	12.64	NF, last step
SWX-19-W-1	0.052	0.459	0.1133	1.0032	0.1279	0.1283	3439	26,804	33,140	0.808	718.4	0.95	12.22	NF, last step
SWX-19-A-1	0.038	0.237	0.1127	1.0039	0.1284	0.1289	3846	29,837	43,500	0.685	890.2	1.00	11.34	NF, last step
SWX-19-S-1	0.062	0.352	0.1761	0.9995	0.1270	0.1269	2988	23,546	52,650	0.447	554.4	1.18	10.52	Start Prop
SWX-02-S-1	0.070	0.380	0.1842	1.0017	0.1252	0.1254	3626	28,915	52,340	0.552	836.0	1.16	13.84	Start Prop
SWX-39-A-1	0.027	0.300	0.0900	1.0019	0.1220	0.1222	4357	35,654	44,590	0.799	1271.2	0.92	11.91	NF, last step
SWX-39-S-1	0.060	0.360	0.1666	1.0010	0.1218	0.1219	3420	28,[illegible]55	52,870	0.530	787.0	1.16	12.44	Start Prop

(1) $K_I = \left[1.21 \pi \sigma^2 \frac{a}{Q}\right]^{1/2}$

TABLE A-17

Data Work Sheet for Calculating Stress Intensity Factor
Welded Sheet - Constant Load - Alternate Immersion

Specimen Code	Fatigue Crack: Depth a inches	Fatigue Crack: Length 2C inches	Fatigue Crack: a/2C	Specimen: Width inches	Specimen: Thick inches	Specimen: Area inches^2	Sustained Load: Load lbs	Sustained Load: σ_{gross} psi	Sustained Load: σ_{yield} psi	Sustained Load: $\frac{\sigma_{gross}}{\sigma_{yield}}$	Sustained Load: σ_{gross}^2 psi x 10^6	Q Factor	K_I (1) KSI $\sqrt{In}$	SCC Test Results
SWX-14-W-3-3	0.030	0.782	0.03836	0.9432	0.0773	0.0729	1431	19,630	43,880	0.447	385.3	1.00	6.62	F58
SWX-14-W-4-4	0.050	0.590	0.08475	0.9439	0.0772	0.0729	933	12,798	43,880	0.291	163.7	1.05	5.44	NF513
SWX-14-A-3	0.043	0.381	0.11286	1.0021	0.0777	0.0779	1961	25,173	53,470	0.471	633.7	1.07	9.84	F58
SWX-14-A-4	0.050	0.410	0.1219	1.0014	0.0778	0.0779	1564	20,077	53,470	0.375	403.1	1.10	8.34	F80
SWX-14-A-4-5	0.055	0.300	0.1833	0.9440	0.0778	0.0734	975	13,283	53,470	0.248	176.4	1.23	5.47	NF500
SWX-14-S-2	0.045	0.485	0.09278	1.0002	0.0778	0.0778	1092	14,035	57,500	0.244	196.9	1.06	5.63	NF500
SWX-14-S-3	0.035	0.300	0.09210	0.9968	0.0778	0.0776	1497	19,291	57,500	0.335	372.1	1.04	6.89	F34
SWX-14-S-4	0.040	0.410	0.09756	0.9971	0.0778	0.0776	1342	17,293	57,500	0.300	299.0	1.05	6.58	NF500
SWX-21-W-2	0.040	0.395	0.1013	0.9983	0.0657	0.0656	1062	16,189	33,460	0.484	262.1	1.04	6.19	F80
SWX-21-W-3	0.050	0.410	0.1219	0.9986	0.0659	0.0658	723	10,987	33,460	0.328	120.7	1.09	4.58	F34
SWX-21-W-4	0.035	0.300	0.1167	0.9983	0.0657	0.0656	508	7,743	33,460	0.231	59.9	1.10	2.69	NF500
SWX-21-A-3	0.040	0.310	0.1219	0.9944	0.0655	0.0651	1621	24,900	50,300	0.495	620.0	1.08	9.34	NF500
SWX-21-S-2	0.035	0.200	0.1750	0.9960	0.0653	0.0650	2328	35,815	66,420	0.539	1283.0	1.18	12.00	NF513
SWX-24-W-2	0.054	0.403	0.1339	1.0045	0.0792	0.0796	1621	20,364	53,590	0.379	414.7	1.11	8.76	F58
SWX-24-W-3	0.050	0.380	0.1316	1.0018	0.0791	0.0792	1362	17,196	53,590	0.320	295.7	1.10	7.15	NF513
SWX-24-W-4	0.065	0.390	0.1666	1.0022	0.0791	0.0793	1489	18,776	53,590	0.350	352.2	1.18	8.59	F118
SWX-24-A-2	0.050	0.320	0.1562	0.9995	0.0794	0.0794	1291	16,259	61,030	0.266	264.4	1.17	6.55	NF500
SWX-19-W-2	0.010	0.330	0.0303	1.0028	0.1279	0.1283	3705	28,877	33,140	0.871	833.9	0.85	6.11	NF500
SWX-19-A-2	0.050	0.280	0.1785	1.0031	0.1278	0.1282	3975	31,006	43,500	0.713	961.4	1.14	12.66	NF500
SWX-19-S-2	0.055	0.240	0.2291	1.0000	0.1280	0.1280	3848	30,062	52,650	0.571	903.7	1.32	11.96	F197
SWX-19-S-3	0.065	0.290	0.2241	0.9967	0.1282	0.1278	3080	24,100	52,650	0.458	580.1	1.33	10.38	NF500
SWX-19-S-4	0.075	0.305	0.2459	0.9962	0.1269	0.1264	2361	18,678	52,650	0.355	348.9	1.40	8.42	NF500
SWX-02-W-2	0.070	0.770	0.2592	0.9990	0.1246	0.1245	4192	33,670	38,730	0.869	1133.6	1.30	15.23	NF500
SWX-02-A-3	0.065	0.325	0.2000	1.0030	0.1230	0.1234	4534	36,742	49,370	0.744	1349.9	1.19	16.74	F139
SWX-02-A-4	0.070	0.280	0.2500	1.0029	0.1231	0.1235	4020	32,550	49,370	0.659	1059.5	1.36	14.40	F278
SWX-02-S-2	0.045	0.405	0.1111	1.0012	0.1245	0.1246	3876	31,107	52,340	0.594	967.6	1.04	12.61	NF500
SWX-02-S-3	0.070	0.290	0.2414	0.9998	0.1238	0.1238	4522	36,526	52,340	0.698	1334.1	1.33	16.33	NF500
SWX-02-S-4	0.065	0.295	0.2203	0.9986	0.1239	0.1237	5189	41,948	52,340	0.801	1759.6	1.25	18.64	NF500
SWX-39-W-3	0.030	0.270	0.1111	0.9976	0.1273	0.1210	3999	33,044	33,200	0.995	1092.2	0.91	11.69	NF500
SWX-39-W-4	0.055	0.300	0.1833	1.0014	0.1211	0.1213	4444	36,636	33,200	1.103	1342.1	1.04	16.42	NF500
SWX-39-A-3	0.030	0.355	0.0845	1.0024	0.1210	0.1213	4446	36,652	44,590	0.821	1343.4	0.89	13.12	F389
SWX-39-S-4	0.060	0.315	0.1904	1.0013	0.1217	0.1219	4215	34,577	52,870	0.654	1195.5	1.18	15.20	NF500
SWX-39-S-4-4	0.045	0.280	0.1607	1.0006	0.1212	0.1213	4787	39,464	52,870	0.746	1557.4	1.08	15.70	NF500
SWX-39-S-4-5	0.017	0.265	0.0465	1.0003	0.1220	0.1220	4884	40,032	52,870	0.757	1602.6	0.90	10.72	NF500
SWX-06-W-2	0.060	0.290	0.2069	1.0009	0.0878	0.0879	2371	26,973	42,250	0.638	727.5	1.23	11.61	NF513
SWX-06-W-3	0.050	0.280	0.1786	0.9984	0.0883	0.0882	2562	29,047	42,250	0.687	843.7	1.14	11.86	NF500
SWX-06-W-4	0.050	0.280	0.1785	0.9971	0.0876	0.0873	2955	33,848	42,250	0.801	1145.6	1.09	14.13	NF500
SWX-06-A-2	0.052	0.395	0.1316	1.0019	0.0876	0.0878	1118	12,733	53,390	0.238	162.1	1.12	5.34	F106
SWX-06-A-3	0.040	0.330	0.1212	1.0026	0.0875	0.0877	783	8,928	53,390	0.167	79.7	1.14	3.26	NF513
SWX-06-A-4	0.055	0.400	0.1375	1.0025	0.0880	0.0882	982	11,133	53,390	0.208	123.9	1.14	4.76	F83
SWX-06-S-2	0.058	0.306	0.1895	1.0035	0.0880	0.0883	1218	13,793	60,440	0.228	190.2	1.25	5.79	F106
SWX-06-S-3	0.055	0.380	0.1447	1.0050	0.0878	0.0882	723	8,197	60,440	0.136	67.2	1.18	3.45	NF513
SWX-06-S-4	0.060	0.310	0.1935	1.0032	0.0881	0.0884	1001	11,323	60,440	0.187	128.2	1.28	4.77	NF500

(1) $K_I = \left[\frac{1.21 \pi \sigma^2 a}{Q} \right]^{1/2}$

TABLE A-18

Stress Corrosion Test Data Step Load 2014-T6 Plate

Alternate Immersion

Long Trans Grain

	Temper	Specimen Code	Sustained Net Section Stress KSI/ Exposure Hrs at Step/ X-Ray Crack Length After Exposure(3)							Residual			Initial Precrack Depth / Final SCC (Est.) Depth Inch	Fracture Zone & % Shear Lip
										Ultimate Strength				
			Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7	KSI	Exposed / Unexposed	% Elong (1 3/4")		
Unnotched	Basic Unwelded	SCU-14-5(1)	29.30 NF41	32.56 NF64	35.81 NF40	39.07 NF41	42.32 NF67	45.58 NF4[illegible]	48.88 NF294	62.99	0.88	4.1	---- 0	---- ----
	As Welded	SWU-14-W-5	5.70 NF88 ----	8.56 NF64 ----	11.41 NF90 NC	14.26 NF62 NC	17.11 NF88 ----	19.96 NF64 NC	21.39 NF92 ----	44.15	0.99	3.9	---- 0	*WB ----
	Weld + AGE	SWU-14-A-5	6.46 NF88 ----	9.69 NF64 ----	12.92 NF90 NC	16.16 NF62 NC	19.39 NF88 ----	22.62 NF64 NC	24.23 NF92 ----	43.39	0.96	2.6	---- 0	WB ----
	Weld + STA	SWU-14-S-5	12.64 NF88 ----	18.96 NF64 ----	25.28 NF90 NC	31.60 NF62 NC	37.92 NF88 ----	44.24 NF64 0.050(2)	47.40 FO(5) ----	----	----	----	---- 0.050(2)	EWB ----
Pre-Cracked @ EWB	As Welded	SWX-14-W-5	3.09 NF90 0.350	4.63 NF41 0.350	6.17 NF113 0.350	7.71 NF37 ----	9.[illegible] NF113 0.350	10.80 NF42 0.350	11.57 NF64 ----	(8)	----	----	0.350 0.350	EWB 0
	Weld + AGE	SWX-14-A-5	4.80 NF90 0.340	7.20 NF41 0.340	9.60 NF113 0.340	12.00 NF37 0.340	14.41 NF113 0.360	16.81 NF42 ----	18.01 NF64 ----	(9)	----	----	0.340 0.380(6)	WB 0
	Weld + STA	SWX-14-S-5	5.93 NF90 0.393	8.90 NF41 0.503	11.87 NF113 0.503	14.84 NF37 ----	17.81 NF113 0.518	20.77 NF24(4) ----		---- ----	---- ----	---- ----	0.395 0.518(7)	EWB 100

(1) Specimen exposed 296 hrs total at 5 lower stress levels prior to Step 1 shown.

(2) Crack at EWB, 0.050" deep plus 0.050" lateral leg towards WB.

(3) Includes notch depth.

(4) Failed during handling for X-ray after alternate immersion at Step 6.

(5) Failed during loading to Step 7.

(6) Crack extension attributed to pitting corrosion.

(7) Crack extension attributed to SCC.

(8) Mechanically damaged during unloading.

(9) Failed during unloading.

TABLE A-19

Stress Corrosion Test Data Step Load X2021-T8E31 Plate

Alternate Immersion | Long Trans Grain

	Temper	Specimen Code	Sustained Net Section Stress KSI/ Exposure Hrs at Each Step/ X-Ray Crack Length After Exposure: Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7	Residual Ultimate Strength KSI	Residual Ultimate Strength Exposed/Unexposed	Residual % Elong (1 3/4")	Initial Precrack Depth / Final SCC (Est.) Depth Inch	Fracture Zone & % Shear Lip
Unnotched	Basic Unwelded	SCU-21-5	12.85 NF88 ----	19.27 NF64 ----	25.69 NF90 NC	32.12 NF62 NC	38.54 NF88 ----	44.96 NF64 NC	48.17 NF92 ----	67.67	0.92	2.7	---- 0	---- ----
Unnotched	As Welded	SWU-21-W-5	4.65 NF88 ----	6.98 NF64 ----	9.31 NF90 NC	11.64 NF62 NC	13.96 NF88 ----	16.29 NF64 NC	17.45 NF92 ----	40.53	1.13	6.3	---- 0	EWB/ WB ----
Unnotched	Weld + AGE	SWU-21-A-5	7.19 NF90 ----	10.78 NF41 ----	14.37 NF113 NC	17.96 NF37 ----	21.56 NF113 NC	25.15 NF42 NC	26.95 NF64 ----	45.32	1.09	2.7	---- 0	EWB ----
Unnotched	Weld + STA	SWU-21-S-5	12.47 NF90 ----	18.71 NF41 ----	24.95 NF113 NC	31.18 NF37 ----	37.42 NF113 NC	43.66 NF42 NC	46.78 NF64 ----	69.33	0.97	2.1	---- 0	EWB ----
Pre-Cracked @ EWB	As Welded	SWX-21-W-5	5.60 NF41 0.360	8.40 NF88 0.360	11.20 NF41 0.360	14.00 NF41 0.375	16.80 NF89 0.400	19.60 NF41 ----	21.00 NF88 ----	23.06	0.84	----	0.360 0.440(2)	EWB 30
Pre-Cracked @ EWB	Weld + AGE	SWX-21-A-5	5.03 NF41 0.350	7.55 NF88 0.350	10.07 NF41 0.350	12.58 NF41 0.360	15.09 NF89 0.365	17.61 NF41 ----	18.87 NF88 ----	23.57	1.17	----	0.350 0.395(2)	EWB 0
Pre-Cracked @ EWB	Weld + STA	SWX-21-S-5	5.49 NF41 0.343	8.25 NF88 0.348	10.99 NF41 0.373	13.74 NF41 0.558	16.49 FO(1)			----	----	----	0.343 0.558	EWB 50

(1) Failed on loading to Step 5.

(2) Crack extension attributed to corrosion.

TABLE A-20

Stress Corrosion Test Data Step Load 2024-T851 Plate

Alternate Immersion

Long Trans Grain

	Temper	Specimen Code	Sustained Net Section Stress KSI/ Exposure Hrs at Step/ X-Ray Crack Length After Exposure							Residual Ultimate Strength		Residual	Initial Precrack Depth	Fracture Zone & % Shear Lip
			Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7	KSI	Exposed / Unexposed	% Elong (1 3/4")	Final SCC (Est.) Depth Inch	
Unnotched	Basic Unwelded	SCU-24-5(1)	30.08 NF41	33.42 NF64	36.76 NF40	40.10 NF41	43.34 NF67	46.68 NF41	50.17 NF294	67.81	0.94	2.1	---- 0	---- ----
Unnotched	As Welded	SWU-24-W-5	7.65 NF88 ----	11.47 NF64 ----	15.29 NF90 NC	19.12 NF62 NC	22.94 NF88 ----	26.76 NF64 NC	28.67 NF92 ----	38.43	0.80	2.0	---- 0	WB ----
Unnotched	Weld + AGE	SWU-24-A-5	8.83 NF88 ----	13.25 NF64 ----	17.67 NF90 NC	22.08 NF62 NC	26.50 NF88 ----	30.92 NF64 NC	33.13 NF92 ----	(4)	----	----	----	WB ----
Unnotched	Weld + STA	SWU-24-S-5	11.22 NF88 ----	16.83 NF64 ----	22.44 NF90 NC	28.04 NF62 NC	33.65 NF88 ----	39.26 NF64 NC	42.07 NF92 ----	57.98	0.93	1.6	---- (2)	EWB ----
Pre-Cracked @ EWB	As Welded	SWX-24-W-5	5.33 NF41 0.375	7.99 NF88 0.375	10.66 NF41 0.375	13.33 NF41 0.375	15.99 NF89 0.375	18.66 NF41 ----	19.99 NF88 ----	27.17	1.08	----	0.375 0.375	EWB 0
Pre-Cracked @ EWB	Weld + AGE	SWX-24-A-5	5.30 NF90 0.340	7.91 NF41 0.340	10.55 NF113 0.340	13.19 NF37 0.400	15.82 NF113 0.410	18.46 NF42 ----	19.78 NF64 ----	35.72	1.26	----	0.340 0.420(3)	EWB 50
Pre-Cracked @ EWB	Weld + STA	SWX-24-S-5	5.83 NF41 0.365	8.76 NF88 0.365	11.67 NF41 0.365	14.59 NF41 0.365	17.51 NF89 0.385	20.42 NF41 ----	21.89 NF88 ----	30.54	1.08	----	0.365 0.385(3)	EWB 30

(1) Specimen exposed 296 hrs. total at 5 lower stress levels prior to Step 1.

(2) Small area of corrosion at EWB.

(3) Crack extension attributed to corrosion

(4) Mechanically damaged on unloading.

TABLE A-21

Stress Corrosion Test Data Step Load 2219-T87 Plate

Alternate Immersion — Long Trans Grain

	Temper	Specimen Code	Sustained Net Section Stress, KSI/ Exposure Hrs at Step/ X-Ray Crack Length After Exposure: Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7	Residual Ultimate Strength: KSI	Residual Ultimate Strength: Exposed / Unexposed	Residual % Elong (1-3/4")	Initial Precrack Depth / Final SCC (Est.) Depth Inch	Fracture Zone & % Shear Lip @ Crack Tip & Near Edge
Unnotched	Basic Unwelded	SCU-19-5 (1)	25.50 NF41	28.33 NF64	31.17 NF40	34.00 NF41	36.88 NF67	39.70 NF41	4..50 NF294	64.04	0.91	3.6	- 0	- -
Unnotched	As Welded	SWU-19-W-5	4.13 NF88 ----	6.19 NF64 ----	8.25 NF90 NC	10.37 NF62 NC	12.38 NF88 ----	14.44 NF64 NC	15.47 NF90 ----	42.25	1.09	6.0	- 0	WB -
Unnotched	Weld + AGE	SWU-19-A-5	6.37 NF88 ----	9.56 NF64 ----	12.74 NF90 NC	15.93 NF62 NC	19.11 NF88 ----	22.29 NF64 NC	23.99 NF90 ----	46.69	1.11	5.3	- 0	EWB -
Unnotched	Weld + STA	SWU-19-S-5	8.57 NF90 ----	12.85 NF41 ----	17.13 NF113 ----	21.42 NF37 NC	25.70 NF113 NC	29.98 NF42 NC	32.12 NF64 ----	61.55	0.99	7.9	- 0	PM -
Pre-Cracked @ EWB	As Welded	SWX-19-W-5 (2)	12.10 NF88 0.210 +	13.61 NF64 0.210 +	15.12 NF89 0.210 +	16.64 NF65 0.210 +	18.15 NF89 0.210 +	19.66 NF68 0.210 +	22.69 NF65 ----	32.31	1.07	-	0.210 0.210 + 0.070	HAZ 100
Pre-Cracked @ EWB	Weld + AGE	SWX-19-A-5 (3)	14.70 NF88 0.210	16.53 NF64 0.210	18.3. NF89 ----	20.21 NF65 0.210	22.04 NF89 0.210	23.88 NF68 ----	27.56 NF65 ----	35.95	0.98	-	0.210 0.210	HAZ 100
Pre-Cracked @ EWB	Weld + STA	SWX-19-S-5	9.93 NF90 0.225	14.89 NF41 0.225	19.85 NF113 0.225	24.82 NF37 0.225	29.78 NF113 0.225	34.74 NF42 ----	37.22 NF64 ----	(4)	-	-	0.225 0.225	HAZ 100

(1) Specimen exposed 296 hrs total at 5 lower stress levels prior to Step 1.

(2) Specimen exposed 304 hrs total at 4 lower stress levels prior to Step 1.
Crack Tip began branching at step preceding Step #1, 10.59 KSI. Final length of short transverse grain crack was 0.070".

(3) Specimen exposed 304 hrs total at 4 lower stress levels prior to Step 1.

(4) Mechanically damaged during unloading.

TABLE A-22

Stress Corrosion Test Data Step Load 7039-T64 Plate

Alternate Immersion

Long Trans Grain

	Temper	Specimen Code	Sustained Net Section Stress, KSI/ Exposure Hrs at Step/ X-Ray Crack Length After Exposure							Residual				
										Ultimate Strength			Initial Precrack Depth / Final SCC (Est.) Depth Inch	Fracture Zone & % Shear Lip @ Crack Tip & Near Edge
											Exposed			
			Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7	KSI	Unexposed	% Elong (1-3/4")		
Unnotched	Basic Unwelded	SCU-39-5[1]	24.24 NF41	27.03 NF64	29.72 NF40	32.41 NF41	35.10 NF67	37.79 NF41	40.45 NF294	61.67	0.98	11.3	- 0	- -
	As Welded	SWU-39-W-5	6.38 NF88 ----	9.57 NF64 ----	12.76 NF90 NC	15.95 NF62 NC	19.14 NF88 ----	22.33 NF64 NC	23.93 NF92 ----	50.82	1.02	10.0	- 0	PM (gage mark) -
	Weld + AGE	SWU-39-A-5	7.00 NF41 NC	10.50 NF88 NC	14.00 NF41 NC	17.51 NF41 NC	21.01 NF89 NC	24.51 NF41 ----	26.26 NF88 ----	49.13	1.03	8.2	- 0	PM -
	Weld + STA	SWU-39-S-5[2]	10.44 NF90 ----	15.65 NF41 ----	20.87 NF113 NC	26.09 NF37 ----	31.31 NF113 0.075/ 0.075	36.53 NF42 0.150/ 0.100/ 0.075	39.14 F64 ----	-	-	-	- 0.280 (6)	EWB/WB (5)
Pre-Cracked @ EWB	As Welded	SWX-39-W-5	9.07 NF41 0.370	13.61 NF88 0.370	18.14 NF41 0.370	22.68 NF41 0.370	27.22 NF89 0.370	31.75 NF41 -	34.02 NF88 -	39.72	0.70	-	0.370 0.370	EWB 100
	Weld + AGE	SWX-39-A-5	9.28 NF41 0.400	13.93 NF88 0.400	18.57 NF41 0.400	2[illegible].21 NF[illegible] 0.400	27.86 NF89 0.400	32.50 NF41 -	34.89 NF88 -	51.28	1.28	-	0.400 0.400	EWB 100
	Weld + STA	SWX-39-S-5	10.06 NF41 0.340	15.09 NF88 0.340	20.12 NF41 0.375	25.15 NF41 0.415	30.17 (3) F89 ----			-	-	-	0.340 0.600 (4)	EWB/WB (5) 20

(1) Specimen exposed 296 hrs total at 5 lower stress levels prior to Step 1.

(2) Separate cracks developed at EWB.

(3) Failed in air after exposure at Step 5.

(4) Crack curved following EWB. Crack length includes curvature.

(5) Origin @ EWB. Final failure WB.

(6) Linear length measured on fracture face.

TABLE A-23

Stress Corrosion Test Data Step Load 7106-T6 & X7002-T6 Plate

Alternate Immersion — Long Trans Grain

Temper	Specimen Code	Sustained Net Section Stress, KSI/ Exposure Hrs at Step/ X-Ray Crack Length After Exposure							Residual Ultimate Strength			Initial Precrack Depth / Final SCC (Est.) Length Inch	Fracture Zone & % Shear Lip @ Crack Tip & Near Edge
		Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7	KSI	Exposed / Unexposed	% Elong (1-3/4")		
Basic[(1)] Unwelded 7106-T6	SCU-06-5	24.27 NF41 NC	27.06 NF64 NC	29.76 NF40 NC	32.45 NF41 NC	35.15 NF67 NC	37.84 NF41 NC	40.46 NF294 NC	61.66	0.95	13.4	- 0	- -
Basic[(1)] Unwelded X7002-T6	SCU-02-5	24.77 NF41 NC	27.52 NF64 NC	30.27 NF40 NC	33.02 NF41 NC	35.77 NF67 NC	38.52 NF41 NC	41.33 NF294 NC	63.50	1.02	11.9	- 0	- -

(1) Specimen exposed 296 hrs total at 5 lower stress levels prior to Step 1.

TABLE A-24

Stress Corrosion Test Data for Constant Load, Unnotched Plate Specimens

Alternate Immersion, 500 Hrs. Long Trans. Grain

Alloy	Temper	Specimen Code	Sustained Stress % Yield	Sustained Stress KSI	Exposure Hours	Residual Ultimate Strength, KSI / % Elong (1 3/4")	Fracture Zone	Residual Ultimate / Unexposed Ultimate
2014 T6	Basic, Unwelded	SCU-14-6	75.4	49.10	NF568	63.02/5.5	gage mark	0.88
	As Welded	SWU-14-W-6	75.0	21.39	NF501	45.71/3.6	WB	1.02
	Weld + Age	SWU-14-A-6	75.0	24.23	NF501	44.06/3.7	WB	0.90
	Weld + Sta	SWU-14-S-6	75.0	47.40	NF501	64.87/2.4	HAZ	0.96
X2021 T8E31	Basic, Unwelded	SCU-21-6	75.0	48.17	NF501	72.43/6.2	----	0.98
	As Welded	SWU-21-W-6	75.0	17.45	NF501	39.65/5.4	EWB/WB	1.10
	Weld + Age	SWU-21-A-6	75.0	26.95	NF500	45.51/1.7	EWB	1.10
	Weld + Sta	SWU-21-S-6	75.0	46.78	NF500	70.05/1.5	EWB	0.98
2024 T851	Basic, Unwelded	SCU-24-6	75.3	50.40	NF568	68.27/2.0	----	0.94
	As Welded	SWU-24-W-6	75.0	28.67	NF501	43.99/2.[illegible]	EWB/WB	0.92
	Weld + Age	SWU-24-A-6	75.0	33.13	NF501	45.37/1.4	EWB/WB	0.94
	Weld + Sta	SWU-24-S-6	75.0	42.07	NF501	61.05/2.7	EWB	0.98
2219 T87	Basic, Unwelded	SCU-19-6	75.3	42.70	NF568	68.42/5.9	----	0.98
	As Welded	SWU-19-W-6	75.0	15.47	NF501	43.59/6.4	WB	1.12
	Weld + Age	SWU-19-A-6	75.0	23.89	NF501	46.40/4.6	EWB/WB	1.10
	Weld + Sta	SWU-19-S-6	75.0	32.12	NF500	61.32/8.3	PM	0.99
X7002 T6	Basic, Unwelded	SCU-02-6	75.3	41.52	NF568	64.61/12.6	----	0.99
7039 T64	Basic, Unwelded	SCU-39-6	75.3	40.64	NF568	63.05/11.5	----	1.00
	As Welded	SWU-39-W-6	75.0	23.93	NF501	50.21/8.9	WB	1.01
	Weld + Age	SWU-39-A-6	75.0	26.26	NF501	49.25/6.9	PM	1.03
	Weld + Sta	SWU-39-S-6	75.0	39.14	F249	----	EWB/WB	----
	Weld + Sta	SWU-39-S-7	65.0	33.92	F416	----	EWB(1)/WB	----
	Weld + Sta	SWU-39-S-8	55.0	28.70	NF515	59.12/7.0	WB	0.96
7106 T6	Basic, Unwelded	SCU-06-6	75.3	40.64	NF568	62.04/13.1	----	----

(1) Origin at EWB progressing into WB and final failure. SCC length - 0.350"

TABLE A-25

Stress Corrosion Test Data for Constant Load, Pre-cracked Plate specimens

Alternate Immersion, 500 Hrs. — Long Trans Grain

	Temper	Specimen Code	Sustained Stress (Net Section) %NTS/%Yield	Sustained Stress (Net Section) KSI	Exposure Hours	Residual Strength (Net) KSI	Residual Strength (Net) Exposed / Unexposed	Fatigue Pre-Crack Depth Inch	X-Ray Crack Length @ 0 & 250 Hrs. Exposure In.	Final Crack Depth Inch.	Fracture Zone & % Shear Lip
2014 T6	As Welded	SWX-14-W-6	66.0/38.7	11.1	NF500	24.34	1.45	0.370	0.370/0.370	0.370	EWB/0
	Weld + AGE	SWX-14-A-6	83.0/63.8	20.6	F (loading)	-----	----	0.435	----	-----	EWB/0
		SWX-14-A-7	67.7/72.0	16.8	NF500	24.05	0.97	0.340	(1) 0.340/0.340	0.340	WB/50
	Weld + STA	SWX-14-S-6	79.0/34.7	21.9	F (loading)	-----	----	0.385	----	-----	EWB/40
		SWX-14-S-7	70.0/30.7	19.4	F217	-----	----	0.340	0.545/(2)	0.600	EWB/WB/75
		SWX-14-S-8	61.5/27.0	17.1	NF505	28.93	1.04	0.367	0.367/0.367	0.367	EWB/50
X2021 T8E31	As Welded	SWX-21-W-6	76.2/89.6	20.34	NF498	25.98	0.95	0.350	0.350/0.350	0.350	EWB/WB/100
	Weld + AGE	SWX-21-A-6	92.6/51.8	18.61	F (loading)	-----	----	0.370	----	-----	WB/100
		SWX-21-A-7	86.7/48.5	17.44	NF505	24.63	1.22	0.410	0.410/0.410	0.410	EWB/80
	Weld + STA	SWX-21-S-6	43.5/21.6	13.99	NF498	16.67	0.54	0.365	0.365/0.400	0.430	EWB/WB/100
		SWX-21-S-7	52.1/25.9	16.17	F226	-----	----	0.400	0.405/0.550	0.550	EWB/65
		SWX-21-S-8	60.8/30.3	18.87	F122	-----	----	0.350	0.410/- (9)	0.430	EWB/WB/75
2024 T851	As Welded	SWX-24-W-6	76.1/28.5	19.05	NF498	22.14	0.89	0.350	0.350/0.475	0.475 (8)	WB/0
	Weld + AGE	SWX-24-A-6	59.2/37.9	16.76	F (loading)	-----	----	0.360	----	-----	WB/0
		SWX-24-A-7	50.1/32.2	14.20	NF498	17.20	0.61	0.400	0.400/0.400	0.430	WB/0
		SWX-24-A-8	55.6/35.6	15.74	NF505	26.76	0.94	0.350	0.350/0.350	0.350	EWB/0
	Weld + STA	SWX-24-S-6	75.0/37.8	21.23	NF498	26.82	0.95	0.350	0.350/0.350	0.350	EWB/30
2219 T87	As Welded	SWX-19-W-6	77.0/114.0	23.53	NF530	23.60	0.78	0.220	0.220/(3)	0.220 + 0.140 (3)	WB/100
	Weld + AGE	SWX-19-A-6	76.8/88.6	28.21	NF530	34.45	0.94	0.190	0.190/0.190	0.190	WB/EWB/100
	Weld + STA	SWX-19-S-6	71.2/82.5	35.34	NF500	39.03	0.79	0.200	0.200/0.200	0.200	HAZ/PM/100
7039 T64	As Welded	SWX-39-W-6	79.5/110.0	35.07	NF498	42.32	0.96	0.390	0.390/0.390 (4)	0.390	EWB/WB/100
	Weld + AGE	SWX-39-A-6	83.6/95.6	33.48	NF498	49.59	*1.24	0.340	0.340/0.340 (4)	0.340	EWB/WB/100
	Weld + STA	SWX-39-S-6	48.6/46.8	24.43	F272	-----	----	0.340	0.340/(4)	(7)	WB/(7)
		SWX-39-S-7	40.8/39.3	20.52	F285	-----	----	0.330	0.330/(5)	(7)	WB/(7)
		SWX-39-S-8	30.2/29.1	15.19	NF505	39.84	0.79	0.315	0.315/(6)	0.315 + 0.150 (10)	EWB/WB/100

(1) Crack tip extend at 90° to plane of pre-crack, 0.070" into WB at 250 hrs exposure.

(2) Failed prior to second x-ray check. Specimen underwent 64 hrs alternate immersion prior to first x-ray for crack length apparently increasing crack length from 0.340" to 0.545".

(3) Crack tip forked into 0.030" and 0.100" long legs from tip of fatigue crack. Final fork length on fracture was 0.140" long.

(4) Small cracks evident at 90° to plane of pre-crack after 250 hrs exposure, extending into weld bead.

(5) Crack tip forked into 0.200" and 0.205" long legs from tip of fatigue crack.

(6) Crack tip forked into 0.075" and 0.040" long legs.

(7) Difficult to determine final crack length. Refer to fracture appearance in text.

(8) Crack extended non-uniformly toward one side of specimen, 0.475" deep on one side and 0.400" on other. Attributed to corrosion.

(9) Specimen exposed 18 hours prior to first x-ray check.

(10) Fork length.

TABLE A-26

Data Work Sheet for Calculating Stress Intensity Factor

Welded Plate - Step Load - Alternate Immersion

Specimen Code	σ_{ys} psi	Specimen			Sustained Stress		Crack Depth	Stress (1) Intensity	SCC Test Results	Sustained σ_{net}
		Width inches	Thick inches	Area inches^2	P lbs	σ_{gross} psi	a_o inch.	K_I KSI $\sqrt{In.}$		
SWX-14-W-5	28,520	1.0524	0.2012	0.2117	436	2,059	0.350	4.1	1st step	3.09
SWX-14-W-5	28,520	1.0524	0.2012	0.2117	1635	7,723	0.350	17.1	NF last step	11.57
SWX-14-A-5	32,310	1.0305	0.2002	0.2063	664	3,219	0.340	6.3	1st step	4.80
SWX-14-A-5	32,310	1.0305	0.2002	0.2063	1991	9,651	0.340	19.9	Corrosion	14.41
SWX-14-A-5	32,310	1.0305	0.2002	0.2063	2489	12,065	0.380	31.5	NF last step	18.01
SWX-14-S-5	63,200	1.0483	0.2002	0.2099	776	3,697	0.373	7.9	1st step	5.93
SWX-14-S-5	63,200	1.0483	0.2002	0.2099	1165	5,550	0.393	12.9	SCC start	8.90
SWX-14-S-5	63,200	1.0483	0.2002	0.2099	2717	12,944	0.518	48.1	Failed	20.77
SWX-21-W-5	23,270	1.0191	0.2014	0.2052	743	3,621	0.360	7.7	1st step	5.60
SWX-21-W-5	23,270	1.0191	0.2014	0.2052	1858	9,055	0.360	22.1	Corrosion	14.00
SWX-21-W-5	23,270	1.0191	0.2014	0.2052	2229	10,863	0.375	33.3	NF 5th step	16.80
SWX-21-A-5	35,930	1.0144	0.1974	0.2002	659	3,292	0.350	6.7	1st step	5.03
SWX-21-A-5	35,930	1.0144	0.1974	0.2002	1645	8,017	0.350	16.9	Corrosion	12.58
SWX-21-A-5	35,930	1.0144	0.1974	0.2002	2474	12,358	0.395	34.1	NF last step	18.87
SWX-21-S-5	62,370	1.0110	0.2000	0.2022	734	3,630	0.343	7.2	1st step	5.49
SWX-21-S-5	62,370	1.0110	0.2000	0.2022	1469	7,265	0.348	14.8	SCC start	10.99
SWX-21-S-5	62,370	1.0110	0.2000	0.2022	1846	9,130	0.558	38.3	Failed	13.24
SWX-24-W-5	38,230	1.0210	0.2000	0.2042	699	3,423	0.375	7.6	1st step	5.33
SWX-24-W-5	38,230	1.0210	0.2000	0.2042	2593	12,398	0.375	30.5	NF last step	19.99
SWX-24-A-5	44,170	1.0165	0.1999	0.2032	713	3,509	0.340	6.9	1st step	5.30
SWX-24-A-5	44,170	1.0165	0.1999	0.2032	1783	8,775	0.340	17.6	Corrosion	13.19
SWX-24-A-5	44,170	1.0165	0.1999	0.2032	2674	13,159	0.420	38.5	Last step	19.78
SWX-24-S-5	56,090	1.0139	0.2008	0.2036	760	3,733	0.365	8.0	1st step	5.83
SWX-24-S-5	56,090	1.0139	0.2008	0.2036	2281	11,203	0.365	24.8	Corrosion	17.51
SWX-24-S-5	56,090	1.0139	0.2008	0.2036	2852	14,008	0.385	34.4	Last step	21.89
SWX-19-W-5	20,630	0.7693	0.2050	0.1577	687	4,356	0.210	5.9	1st step	6.05
SWX-19-W-5	20,630	0.7693	0.2050	0.1577	1203	7,628	0.210	10.9	Corrosion	10.59
SWX-19-W-5	20,630	0.7693	0.2050	0.1577	2062	13,075	0.210	24.1	NF 9th step	18.15
SWX-19-A-5	31,850	0.7730	0.2043	0.1579	852	5,396	0.210	7.3	1st step	7.35
SWX-19-A-5	31,850	0.7730	0.2043	0.1579	3196	20,241	0.210	37.0	NF last step	27.56
SWX-19-S-5	42,830	0.7738	0.1997	0.1545	1098	7,107	0.225	10.4	1st step	9.93
SWX-19-S-5	42,830	0.7738	0.1997	0.1545	4127	26,712	0.225	59.1	NF last step	37.22
SWX-39-W-5	31,900	1.0741	0.2003	0.2151	1279	5,946	0.370	12.7	1st step	9.07
SWX-39-W-5	31,900	1.0741	0.2003	0.2151	3198	14,867	0.370	39.5	NF 4th step	22.68
SWX-39-A-5	35,010	1.0607	0.2007	0.2129	1231	5,782	0.400	13.8	1st step	9.28
SWX-39-A-5	35,010	1.0607	0.2007	0.2129	3078	14,457	0.400	42.3	NF 4th step	23.21
SWX-39-S-5	52,180	1.0633	0.2000	0.2127	1455	6,841	0.340	13.0	1st step	10.06
SWX-39-S-5	52,180	1.0633	0.2000	0.2127	2911	13,686	0.340	27.0	SCC start	20.12
SWX-39-S-5	52,180	1.0633	0.2000	0.2127	4366	20,527	0.415	62.6	Failed	30.17

(1) Calculated from equction shown for following table.

TABLE A-27

Data Work Sheet for Calculating Stress Intensity Factor Welded Plate, Constant Load, Alternate Immersion

	Specimen				Sustained Stress		Crack Depth		Stress Intensity (1) K_I KSI$\sqrt{In}$			
σ_{ys} psi	Code (SWX)	Width inches	Thick inches	Area inches^2	P lbs	σ_{gross} psi	Initial a_{o_i} inches	Final a_{o_f} inches	a_{c_i}	a_{o_f}	SCC Test Results	Sustained $\frac{\sigma_{net}}{\sigma_{ys}}$
28,520	14-W-6	1.0348	0.2008	0.2078	1475	7,098	0.370	---	16.1	----	NF500	0.38
32,310	14-A-7	1.0343	0.2009	0.2078	2344	11,280	0.340	---	23.8	----	NF500	0.52
63,200	14-S-7	1.0436	0.2004	0.2091	2740	13,104	0.340	0.600	25.8	64.0	F217	0.31
63,200	14-S-8	1.0390	0.2006	0.2084	2303	11,051	0.367	---	25.0	----	NF505	0.27
23,270	21-W-6	1.0187	0.2021	0.2059	2815	13,672	0.350	---	No solution	----	NF498	0.89
35,930	21-A-7	1.0165	0.2008	0.2041	2124	10,407	0.410	---	29.0	----	NF505	0.48
62,370	21-S-6	1.0179	0.2018	0.2054	1844	8,978	0.365	0.430	19.5	24.7	NF498	0.22
62,370	21-S-7	1.0178	0.2014	0.2050	2012	9,815	0.400	0.550	24.4	40.3	F226	0.26
62,370	21-S-8	1.0211	0.1984	0.2026	2512	12,399	0.350	0.430	25.8	34.9	F122	0.30
38,230	24-W-6	1.0167	0.2005	0.2038	2547	12,498	0.350	---	27.7	----	NF498	0.28
44,170	24-A-7	1.0260	0.2000	0.2052	1772	8,635	0.400	0.430	21.6	24.1	NF498	0.32
44,170	24-A-8	1.0243	0.2000	0.2049	2123	10,361	0.350	---	21.7	----	NF505	0.36
56,090	24-S-6	1.0241	0.2003	0.2051	2675	13,042	0.350	---	27.4	----	NF498	0.38
20,630	19-W-6	0.7724	0.1972	0.1523	2562	16,822	0.220	---	No solution	----	NF530	1.11
31,850	19-A-6	0.7757	0.1990	0.1544	3238	20,971	0.190	---	32.0	----	NF530	0.88
42,830	19-S-6	0.7726	0.2013	0.1555	4075	26,206	0.200	---	41.5	----	NF500	0.82
31,900	39-W-6	1.0620	0.2005	0.2129	4409	20,709	0.390	---	No solution	----	NF498	1.10
35,010	39-A-6	1.0648	0.2003	0.2133	4537	21,271	0.340	---	No solution	----	NF498	0.95
52,180	39-S-6	1.0598	0.2002	0.2122	3520	16,588	0.340	---	33.7	----	F272	0.47
52,180	39-S-7	1.0640	0.2000	0.2128	3013	14,159	0.330	---	26.9	----	F285	0.39
52,180	39-S-8	1.0553	0.2000	0.2111	2249	10,654	0.315	---	18.9	----	NF505	0.29

(1) $K_I^2 = \dfrac{\sigma_{gross}^2 W \left[7.59 \frac{a}{W} - 32\left(\frac{a}{W}\right)^2 + 117\left(\frac{a}{W}\right)^3 \right]}{(1-\nu^2)}$ $\quad a = a_{o(i,f)} + \dfrac{K_I^2 (1-\nu^2)}{6\pi \sigma_{ys}^2}$ $\quad \nu = 0.33$

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13. ABSTRACT Adequate knowledge of the stress corrosion thresholds of welded aluminum ~~alloys is required by designers to utilize mechanical properties fully.~~ ~~This~~ The program determined threshold stress levels for 2014-T6, X2021-T8E31, 2024-T81, 2219-T87, X7002-T6, 7039-T64, and 7106-T6. Variables were sheet and plate, long transverse grain direction, welded and post-weld heat treated, notched and unnotched. Tests were conducted using step load and constant load 500 hours alternate immersion in synthetic sea water at sustained stress levels up to 75-percent yield strength. All basic, unwelded alloys, sheet and plate, had thresholds above 75-percent yield strength. Thresholds for unnotched sheet alloys were below 75-percent yield strength for 2014-T6, as welded (W), weld + age (A) and weld + solution heat treat + age (S), X2021-T8E31 (W), 2024-T81 (W), 2219-T87 (S), 7039-T64 (S) and 7106-T6 (A) (S). The most susceptible to stress corrosion cracking was X2021-T8E31 (W). A fatigue crack at the edge of the weld bead caused increased susceptibility to stress corrosion for several of the sheet alloy-weld-tempers. For unnotched plate product, stress corrosion cracking was incurred for only 2014-T6 (S) and 7039-T64 (S) below 75-percent yield strength; this was at higher stress levels than the (W) and (A) tempers tested. A fatigue crack at the edge of the weld bead caused severe susceptibility to stress corrosion cracking for plate alloys, X-2021-T8E31 (S), 7039-T64 (S) and 2014-T6 (S). An Engineering Data Materials Matrix is presented. Stress corrosion cracking typically initiated at the edge of the weld bead and progressed along the fusion line branching into the weld bead and heat affected zone. Progression was characterized by a series of jumps exhibiting both corrosion and stress corrosion stages. () Additional work is recommended in spectrum loading and natural environment stress corrosion testing, electron beam welding and basic studies of microstructural effects.

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