1977

Fatigue behavior of aluminum alloy weldments in a marine environment

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by

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A Thesis Submitted to the

Graduate Faculty in Partial Fulfillment of

The Requirements for the Degree of

MASTER OF SCIENCE

Department: Civil Engineering
Major: Structural Engineering

Approved:

____
In Charge of Major Work

____
For the Major Department

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For the Graduate College

Iowa State University
Ames, Iowa

1977

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INTRODUCTION

In recent years, the use of aluminum for the construction of ships and liquified natural gas tanks has increased significantly. Innovations in both welding techniques and quality control enabled fabricators to produce new ships far superior in many aspects to similar steel ocean-going vessels. Products of this "aluminum revolution" are highly visible along the west coast of the United States where fishing boats and ferry boats well in excess of 100 feet in length have been in service for several years. The United States Navy has also shown considerable interest in aluminum ships and has sponsored a surface-effect-ship program which will soon culminate in a 2,000 ton welded aluminum vessel capable of speeds in excess of 100 miles per hour.

Aluminum is an attractive material to work with for many good reasons. Ship fabricators cite light weight, ease of cutting, and good weldability as only a few. The 5000 series alloys are most common in marine applications because of their excellent corrosion resistance. Hulls made of these alloys last as long as steel with reduced maintenance requirements.

One problem incurred throughout the aluminum fabrication industry has been the lack of communication of developed welding techniques. Ship builders are often very reluctant to reveal specialized welding procedures. This problem could be relieved by the publishing of comprehensive standards for the construction of aluminum vessels. However, until such standards are developed welding procedures will be largely based on trial-and-error methods which could lead to more serious structural problems.

The aluminum industry, the United States Navy, and the Welding Research Council of the United States recognize these problems and have sought to develop a "pool" of research information on the various behavior properties of the 5000 series aluminum alloys. Naval concern is further inspired by the currently planned construction of a 2,000 ton surface-effect-ship. The hull and bulkheads of this ship require over 300,000 linear feet of high strength welds of thick aluminum plate up to 3/4 of an inch thick. Roland Decrevel, project manager of Bell Aerospace Company's 2,000 ton surface-effect-ship program, stated in a 1973 Bell Aerospace publication[2], "Welding of aluminum this thick to high design requirements has rarely been attempted in marine applications and requires welding standards considerably higher than those found in aluminum shipbuilding today."

The fatigue behavior of aluminum alloy weldments must undoubtedly be considered in any comprehensive standards. Unfortunately, although a great deal of work has been done on the fatigue of 5000 series alloys and weldments, little work has been published on the fatigue behavior of 5000 series full-thickness aluminum weldments subjected to a marine environment. The information which follows cannot totally correct this situation but can provide a basis for preliminary evaluations of this behavior and indicate areas where further investigations are needed.

Fatigue Research Background

In 1971, Iowa State University conducted a literature search[13] to determine the current state of technology with regard to the fatigue of aluminum alloy weldments. As noted earlier considerable knowledge was lacking on the fatigue behavior of weldments in thick aluminum alloys in realistic configurations and in corrosive environments. Except for a limited number of tests, research programs have utilized plates of 3/8 inch thickness, or less, tested under atmospheric conditions. Reynolds Metal Company published a report[8] in 1968 on the fatigue properties of 5083, 5086, and 5456 alloys typical of these investigations.

In 1974, Sanders and Gannon[14] presented a report on the fatigue behavior of weldments in thick aluminum (5083-0) plates. Although the effect of a corrosive environment was not studied the results of these tests revealed that fatigue lives of one inch thick welded plates of 5083-0 are significantly lower than those found for thin welded plates. Lawrence, Munse, and Burk have confirmed this observation in a report[7] published in 1975 by the Welding Research Council.

Very little research data is actually available for aluminum alloy weldments, in thick plates, subjected to saltwater corrosion. A 1974 report[10] completed by Alcoa for the United States Navy presented some limited data on the effects of saltwater corrosion on the fatigue life of weldments in one inch thick 5456 aluminum. This data indicated a reduction in the fatigue life of weldments exposed to saltwater for all stress ranges.

In foreign countries work has also been done on the corrosion fatigue of aluminum weldments. Suvorova and Shavyrin[16] of the Soviet Union showed a 30 percent reduction in the fatigue lives of spot welded D 76 AT aluminum joints immersed in a 3 percent NaCl solution for a period of one month. However, the test program utilized test specimens less than 1.5 millimeters in thickness.

Further research[15] has been performed by these same two investigators on the effect of polymer coatings on the corrosion-fatigue strength of welded joints in aluminum alloys. The limited results indicate that this procedure may provide increased fatigue life where marine environments are found. Such results could warrant further investigation.

Ito and Takeuchi of Japan presented a report[6] in 1975 on the effects of atmospheric humidity on the fatigue strength of 2021-T4, 5052-0, 5083-0, 7075-T6, and 7N01-F aluminum. This particular study concluded that the harmful corrosion occurred mainly during the first 5-10 days of exposure to the corrosive medium (in this case atmospheric humidity). The reduction in fatigue life due to such corrosion was found to be 20-25 percent. The practical application of this data is limited due to the usage of thin highly polished specimens, but the results do indicate that significant reductions may occur in the fatigue life of aluminum alloys exposed to a corrosive environment for a short period of time.

Corrosion of Aluminum Alloys

The major thrust of this investigation is to determine the effect of marine environment on the fatigue behavior of aluminum alloy weldments. Thus it is important to understand the effects of such environments on the corrosion of aluminum alloys. A brief summary is presented in this section with a more complete discussion of the predominant forms of corrosion in Appendix A.

The 5000 series aluminum alloys have shown excellent resistance to marine environments. In particular, the high magnesium content alloys such as 5083, 5086, and 5456 show exceptional performance. These alloys form an extremely durable passive oxide film which retards the process of chemical corrosion. Thus, such metals will be most resistant to corrosive attack in a high-oxygen environment such as the atmosphere or well-aerated seawater where the passive oxide film is maintained. Such a fact is in direct conflict with the corrosion behavior of common ship steels, which corrode much more rapidly when abundant oxygen is available.

The predominant form of corrosion occurring in the 5000 series alloys is pitting. Since this process is the most pronounced, further discussion of the results produced by corrosive environments will be limited to this form of attack.

Aluminum alloys are extremely resistant to corrosion in atmospheric environments. In rural environments of a nonmarine nature, average pit depth due to corrosion is approximately 1 mil with a maximum depth of

2 mils. Such pitting occurs over the first two years of exposure after which further penetration is negligible.

Marine environments contain enough salt to seriously accelerate the electrochemical process of pitting on aluminum alloys. In marine atmospheres, average pit depth is approximately 1-1/2 mils with a maximum pit depth ranging from 3 to 5 mils. Submergence in seawater causes average pit depths ranging from 5 to 15 mils, with maximum depths in excess of 20 mils. Figure 1, constructed from a composite of research data[9], shows the difference between marine and nonmarine atmospheric corrosion. A curve for corrosion due to immersion in seawater would lie significantly above the curve for corrosion in a marine atmosphere as shown in the previously mentioned figure. Although the majority of the pit penetration in marine environments occurs within the first four years of exposure, this penetration continues to proceed at a constant rate. However, this rate is relatively small.

In the study outlined in this report, specimens were subjected to a submerged saltwater environment for 30 days. Since this type of marine exposure creates the most detrimental corrosion, the resulting effects, even for this short period, should demonstrate the influence of a corrosive marine environment on fatigue behavior.

Objectives

A brief review of the discussion on marine corrosion and the previous fatigue research, indicates that short-term exposure to a marine environment creates sufficient corrosion to reduce the fatigue life of aluminum

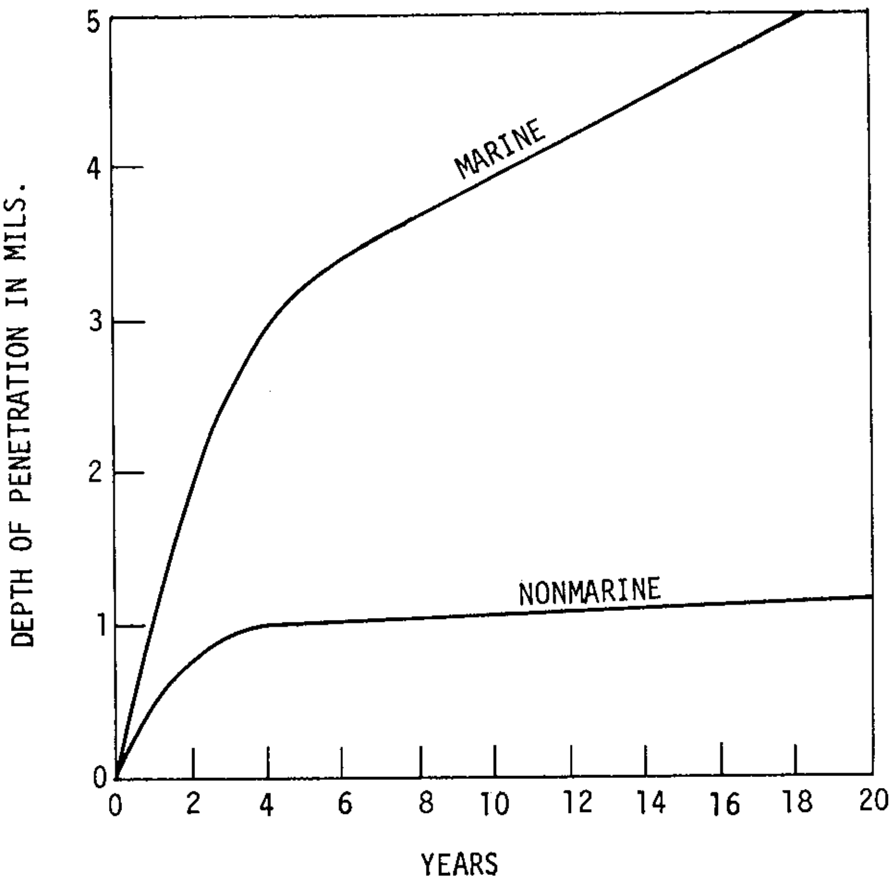


Fig. 1. Pit depth growth in marine and nonmarine atmospheres

alloy weldments. The objective of this research was to ascertain the fatigue behavior of weldments in thick 5000 series aluminum alloy plates submerged in a realistic saltwater environment for 30 days prior to testing and during the actual cyclic testing. In each case, the surface condition of the plate was not altered (except for the effects of corrosion) after receipt from the fabricator. This study also considered the effects of weld geometry, weld orientation, and residual stresses.

The program developed to determine the effects of saltwater corrosion on fatigue behavior consisted of:

1. Fatigue tests in axial tension using two different 5000 series alloys, subdivided by weld orientation and environmental exposure as shown in Table 1.

2. Static tests on standard ASTM tensile specimens to determine mechanical properties.

3. External geometry evaluation using plaster casts of weld beads on all fatigue test specimens to determine the angle at the toe of the weld at the point of fatigue crack initiation.

4. Finite element analysis of typical weld bead configurations to determine the stress concentration factor at the toe of the weld bead.

5. Surface residual stress studies using two longitudinally welded plates and two transversely welded plates. The plates were strain gaged, then sectioned.

Table 1. Test program layout

Alloy	5086-H116		5456-H116[a]		5456-H117[a]	
Thickness	1"		3/4"		3/4"	
Environment	Air	Marine	Air	Marine	Air	Marine
Plain plate	3	3	1	2	3	3
Longitudinal butt-weld	0	6	0	0	0	7
Transverse butt-weld	6	7	0	0	4	7

[a]Fatigue results for plain plate specimens of the 5456-H116 and 5456-H117 alloys were combined since their fatigue behavior does not vary significantly.

6. Weld quality assurance using radiographs of completed welds and etchings of weld cross sections to determine internal geometry and flaws.

MATERIALS, TEST SPECIMENS, WELDING, AND TEST PROCEDURES

Materials

Aluminum alloys used in the program were 3/4 inch thick 5456-H117, 1 inch thick 5086-H116, and 3/4 inch thick 5456-H116 plates. These alloys are commonly used for structural applications in marine environments, and are representative of the 5000 series high magnesium content alloys. The chemical composition of each alloy is shown in Table 2. Table 3 shows the mechanical properties of the alloys as obtained from standard plate coupon tests (ASTM Designation E8) on the alloy plates used in the program. Both the chemical compositions and mechanical properties meet the minimum acceptable standards as presented in Aluminum Standards and Data[1].

Welding Procedure and Test Specimens

There were fifteen plain plates, twenty-four transverse double-vee-groove butt-welded plates, and thirteen longitudinal double-vee-groove butt-welded plates used in the program. Most of these were used although some were reserved for the supplemental programs.

Welding procedures and parameters used in the fabrication process are shown in Table 4. All welds were made using an automatic gas metal arc welder. A typical weld cross section is shown in Fig. 2. All transverse butt-welds were made across the full length of a 60 inch wide aluminum plate which was 96 inches long for the 5086-H116 alloy and 76 inches long for the 5456-H117 alloy. No welded specimens in 5456-H116 alloy were included in this research. The welded plates

Table 2. Chemical composition of alloys in the test program[a]

	5086-H116	5456-H116	5456-H117
Silicon	0.07%	0.07%	0.05%
Copper	< 0.05	< 0.05	0.05
Magnesium	4.00	5.15	5.20
Iron	0.25	0.15	0.24
Titanium	< 0.05	< 0.05	< 0.05
Zinc	0.05	< 0.05	0.09
Manganese	0.46	0.50	0.68
Lead	< 0.05	< 0.05	< 0.05
Tin	< 0.05	< 0.05	< 0.05
Nickel	< 0.05	< 0.05	< 0.05
Chromium	0.07	0.10	0.08
Aluminum	Remainder	Remainder	Remainder

[a]All samples met the chemical limits as listed in reference 1.

Table 4. Welding procedures and parameters

Alloy	5086	5456
Amperage	320-360	300-340
Voltage	29-32	28-31
Polarity	D.C., reversed	D.C., reversed
Welding speed	12-15 ipm	12-15 ipm
Shielding gas	Argon or 83% argon 17% helium	83% argon 17% helium
Shielding gas flow	50-60 cfh	60 cfh
Filler wire	5356 aluminum	5556 aluminum
Filler wire diameter	1/16 inch	1/16 inch
Filler wire speed	450 ipm	385-430 ipm
Weld position	Horizontal	Horizontal
Number of passes	2 (one per side)	2 (one per side)
Joint type	90° double "vee" 5/8 inch land	90° double "vee" 1/4 inch land

Fig. 2. Cross section of weld in 5456 plate

were then saw cut to a 12.5 inch width. This resulted in a rectangular specimen approximately 12.5 x 60 inches with the butt-weld across the narrow dimension. The rectangular specimens were then machined to a reduced section test specimen. Longitudinal specimens were welded in roughly their final dimensions to prevent excessive relief of the residual welding stresses upon final machining.

Final machining of the test specimens to the specified dimensions was done at the Engineering Research Institute's Machine Shop. Dimensions for the fatigue test specimens are shown in Fig. 3. Each specimen was first rough cut (if necessary) then drilled, and finally the reduced test section was milled to the desired dimensions. All bolt holes were reamed then polished. Machined edges were sanded to remove machining flaws and prevent unduly sharp corners. Specimens were handled carefully at all times to prevent undue scratching of the plate surface so as not to affect the fatigue life. Care was also taken not to affect weld geometry during any machining operation.

Radiographs were provided of all welds made on the specimens. The joints were inspected to and met the requirements of ASME Boiler and Pressure Vessel Code, Section 8; NAVSHIPS Specification 0900-003-9000, Class I and NAVSHIPS Specification 0900-003-8000, Class I, with the exception of one longitudinally welded specimen which was weld repaired. This specimen only passed Class III radiographic requirements of NAVSHIPS Specification 0900-003-9000. It did not meet any of the previously mentioned requirements. Because of the weld repair this specimen was used for determining residual stresses rather than fatigue behavior.

of the load frame is shown in Fig.4. Figure 5 shows a specimen loaded in the test rig.

Basically, the test setup was very simple. The horizontal beam at the upper end of the test specimen remained fixed. The lower horizontal beam pivoted about the 3-3/4" diameter pin at the left end (Fig. 4). A specimen was then fastened between these two beams by means of steel grip plates. These plates were connected to the horizontal beams by a single large pin. Such connections allowed rotations to occur at each end of the test specimen, thus ensuring transmission of axial load only. The hydraulic actuator was so placed that the load frame arrangement provided a mechanical advantage of 2.87. Therefore, the load applied to the specimen was 2.87 times the load applied by the hydraulic ram. The entire system was calibrated prior to the initiation of the testing program.

All tests were conducted in axial tension with a nominal zero-to-tension stress cycle. Although the minimum stress on the specimen was to be zero a small minimum load was maintained on the ram for all tests in order to prevent load reversal near the zero load level. However, this minimum load (500 lb. at the ram) still resulted in a stress ratio which was effectively zero. The complete test sequence was run at machine speeds between 2 and 3.2 cycles per second.

The system was operated in the automatic mode on a continuous testing basis. Under such conditions, circuits in the control console constantly monitor the sinusoidally applied load at the ram indicating an error greater than 5 percent and shutting the system off for error in excess of 10 percent. No such errors were encountered. Since the

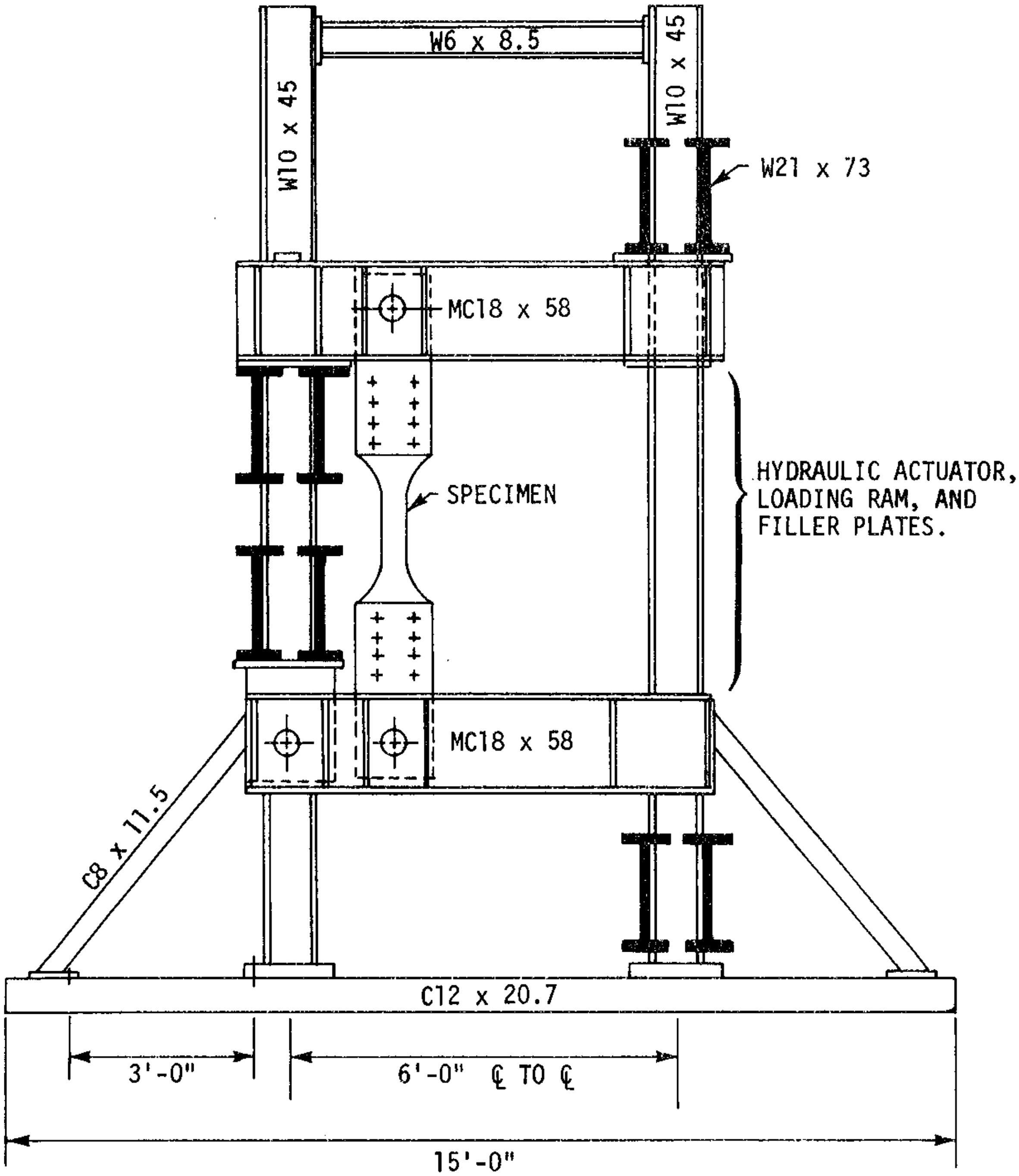


Fig. 4. Schematic of test frame

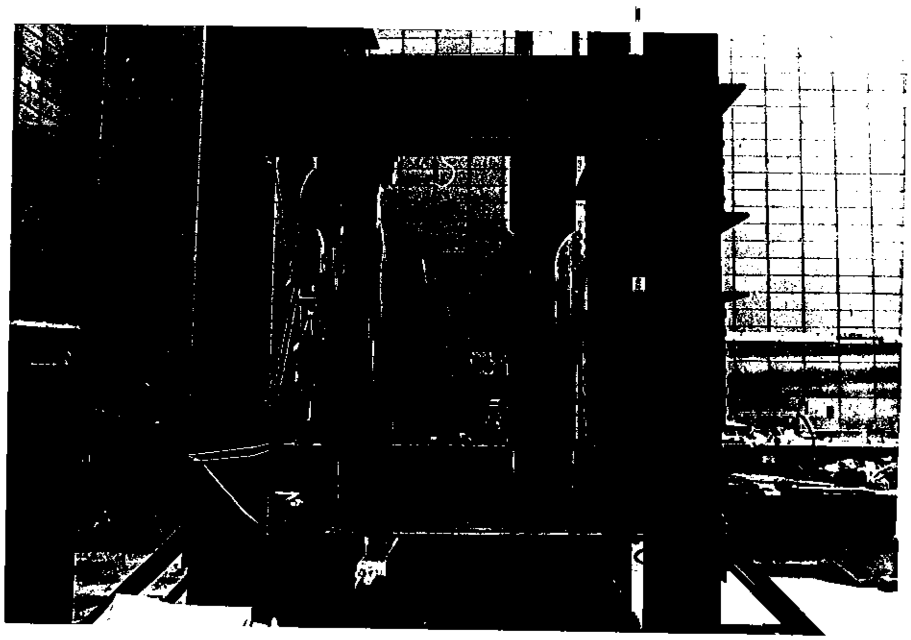


Fig. 5. Test specimen loaded in the frame

machine was of the closed-loop type, it maintained a constant load on the specimen at all times despite crack formation due to fatigue. Specimen failure resulted in automatic shutdown of the system.

All marine specimens were submerged for thirty days in a standard saltwater solution (ASTM Designation D-1141-52). Submergence was realized in a marine tank constructed from a 300 gallon, 3 x 8 ft galvanized steel tank lined with 20 mil vinyl. The salt solution was recirculated continuously across the full tank length using a teflon-filled stainless steel pump connected to a CPVC plastic piping system. Figure 6 shows the marine tank.

Solution variables were checked on a tri-weekly basis. These variables were maintained at values simulating a reasonable marine environment[3,11]. Such variables were:

temperature — 72°F

pH — 7.8

specific gravity — 1.023

dissolved oxygen — 4.2-4.5%

fluid velocity — 1 ft/min.

The tank was kept fully covered in order to prevent evaporation and promote tank stability. Conditions remained extremely constant requiring practically no solution adjustments. Brown algae formations were encountered but subsequent investigation of such growth revealed no harmful effects and indicated a healthy marine environment. In order to prevent harmful bacterial growth, the tank was cleaned and filtered every two weeks. Filtration was performed for a six to ten hour time period and consisted of gravity flow of the salt solution

Fig. 6. Marine tank

through an improvised activated carbon filter. The filtering process had no effect on the salt concentration in the tank.

In addition to a thirty day submergence in substitute seawater, the marine specimens were submerged in the same solution for the duration of the actual fatigue test. This was accomplished by means of a reusable salt tank designed to fit specimens of varying widths and thicknesses. The tank was constructed of structural steel angle with 3/4 inch plexiglass sides. All steel components were coated with three coats of industrial grade enamel suitable for marine conditions. Seals and gaskets were cut from 3/16" thick gum rubber packing and "wetted" with high quality nonmiscible petroleum gel for better sealing. Figure 7 shows a close-up of the salt tank in place.

The tank was fastened to the specimen by means of a clamping device made from two small structural angles. Slotted bolt holes in the upper angle flanges enabled the plexiglass tank to be mounted to the angles which in turn rested upon the lower steel grips. The assembled tank roughly measured 24" tall, 15" wide, and 5" deep with a total capacity of 7.5 gallons. Substitute seawater (ASTM Designation D-1141-52) was used in the tank during the testing of each marine specimen. No recirculation of the solution was made since the vibrational nature of the fatigue apparatus promoted proper water movement. Maintenance care was performed regularly in order to prevent any exposure of the steel tank frame to the salt solution. Thus, any side effects due to the corroding of the steel were eliminated.

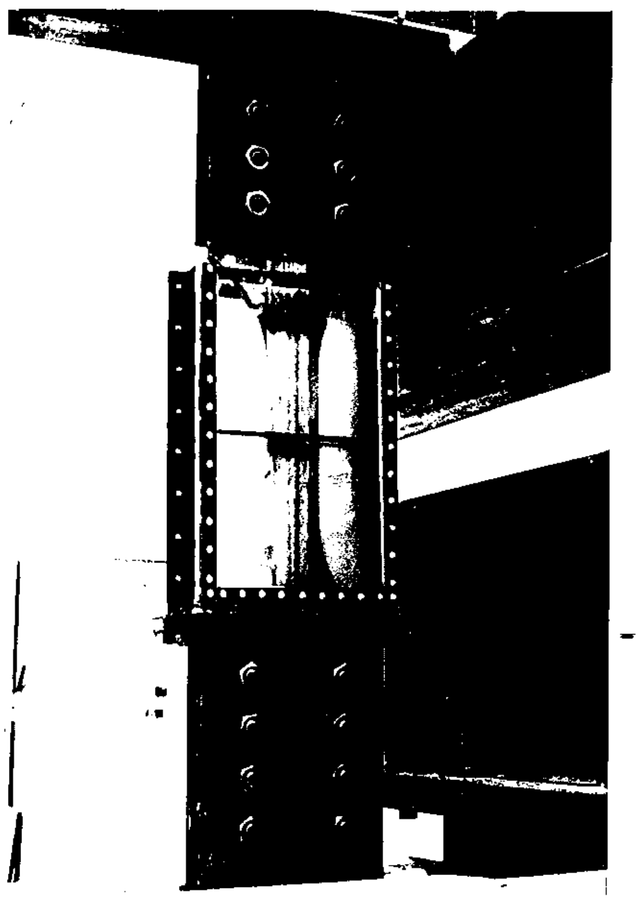


Fig. 7. Fatigue test salt tank

RESULTS OF SUPPLEMENTARY TEST PROGRAM

The main fatigue test series was supplemented by four additional investigations. These investigations focused on the following areas:

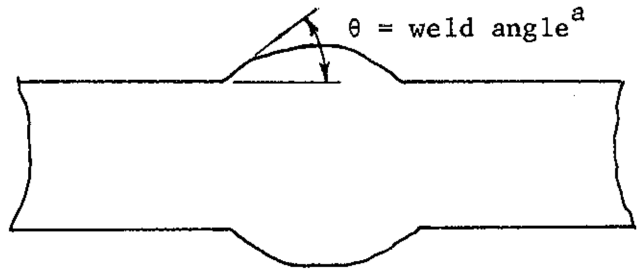
1. Determination of weld geometry
2. Computation of stress concentration factor
3. Examination of weld radiographs
4. Measurement of residual stresses.

Weld Geometry

Plaster castings were made of the weld reinforcement on all welded specimens to determine the external weld geometry. Each casting was made using adjustable wood forms filled with a special dental plaster exhibiting not only high crushing strength but also low shrinkage properties. After each welded specimen failed in fatigue, the point of crack initiation was determined and located on the corresponding plaster cast. Next, the cast was sawed near the failure location and sanded to the exact section. This polished section was then sliced from the original cast and projected on a screen by means of an overhead viewer. The magnified weld profile presented on the screen was then traced and the weld angle measured. Table 5 summarizes the weld angles for each alloy subjected to both air and marine environments.

Although the weld angles were recorded for the longitudinal weld specimens, these angles are of limited significance since the weldment is oriented in the same direction as the applied stress. The weld

Table 5. Weld angles



Alloy	Environment	Transverse weld		Longitudinal weld	
		Ave. θ	Range in θ	Ave. θ	Range in θ
5456-H117	Air	33°	19°-57°		
5456-H117	Marine	28°	15°-58°	15°	10°-18°
5086-H116	Air	33°	21°-50°		
5086-H116	Marine	21°	17°-25°	26°	22°-32°

[a]Weld angle means the most severe of the four angles in the case of longitudinal welds and the angle of the weld at the point of fracture initiation for transverse welds.

angle is significant in transverse weldments since their fatigue life has been shown to be a direct function of the weld angle[12]. A large weld angle is indicative of a greater stress concentration factor at the toe of the weld, resulting in a lower fatigue life for the specimen.

An additional factor affecting fatigue life is the roughness of the weld bead. Variations in the height of lappings on the weld bead cause great variance in the fatigue behavior of both longitudinal and transverse joints.

Stress Concentration Factor

Since the weld bead induces a stress riser at the toe of the weld, fatigue life is reduced in transverse butt weldments. Sanders and Gannon[14] determined the stress concentration factor at the toe of the welds by photoelastic models. Applying these stress concentration factors to the nominal stresses on the transverse butt-weld specimen data resulted in an excellent correlation for the fatigue lives of transverse butt-welded joints.

For this investigation, the stress concentration factor at the root of the weld was determined by finite element analysis of a typical 5456 weld cross section as previously shown in Fig. 2. The cross section was analyzed for two cases with the largest weld angle in the first case equal to 15.5° and in the second case equal to 30°. These values generally bound the average critical weld root angles as determined in the previous section.

The analysis was performed using the plane stress elements existing in the SAPIV finite element program. Figure 8 shows the mesh developed for the analysis. Tensile axial loads were applied at the end nodes to simulate a 20 ksi stress across the weld. Since weld distortion created bending about the weld area, this effect was present in the analysis. The mesh used in the analysis was not symmetrical but modeled the most common weld geometry, with one side of weld being relatively flat while the other side of the weld had higher reinforcement. Results of the analysis are presented in Table 6.

Radiographic Weld Examination

Radiographs were made of all weldments at the time of fabrication. Examination of these radiographs revealed only occasional minor porosity well within the acceptable limits. Etchings were later made of weld cross sections taken from both 5086 and 5456 plates. One such etching which is representative of these studies has already been shown in Fig. 2. Both the radiographs and etchings indicated sound welds of quality well within the acceptable limits. The details of the results of the radiographic examinations were indicated on page 16.

Residual Stresses

Residual stress distributions were determined for longitudinal and transverse welds for both alloys used in these investigations. One longitudinal weld specimen and one transverse weld specimen was used for each alloy. These specimens were chosen to be representative

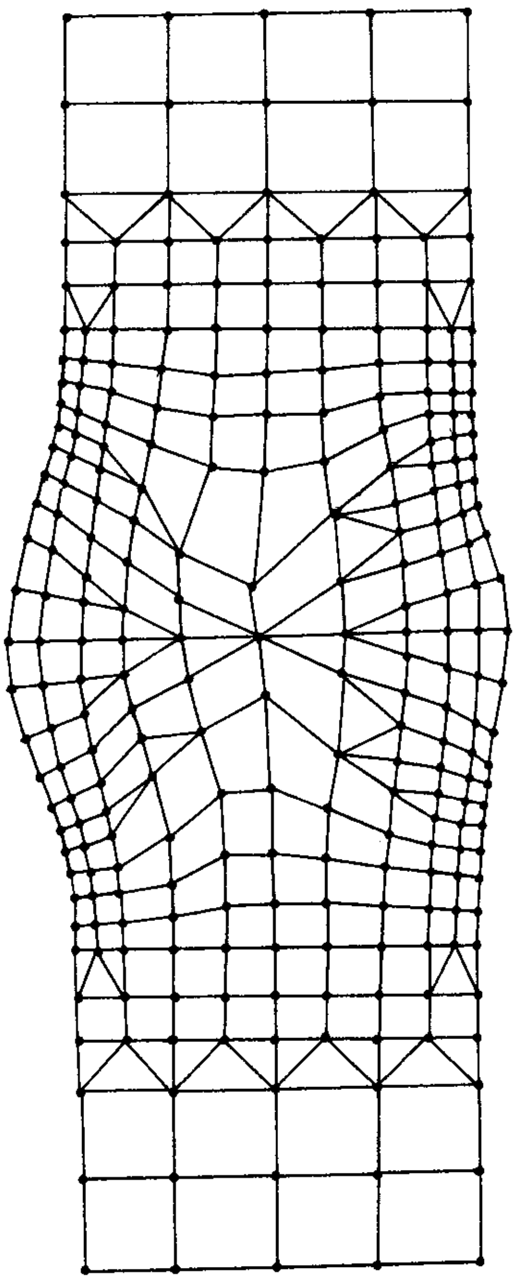
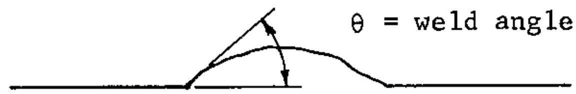


Fig. 8. Finite element mesh for a transverse butt-weld

Table 6. Stress concentration factors



Case	Weld angle θ	Stress concentration factor
1	15.5°	1.33
2	30°	1.60

of each group of specimens as a whole. However, the 5086 longitudinally welded specimen was weld-repaired at one section. Care was taken to sample the weld at a joint well away from the repaired area where radiographs indicated a sound, high quality weld.

Surface residual stresses were measured since all fatigue crack initiation were expected to occur at the surface. Strain gages were mountted adjacent to each weld and initial strain readings were taken. Next, the gages were saw cut from the specimens, and final strain readings were taken. The difference between the final and initial strains is equal to the residual strains released. These procedures are further discussed in reference 4.

Each gage consisted of a two grid rosette with the two grids at right angles. One grid was oriented parallel to the direction of stress application. Such an orientation was termed longitudinal in the studies. The remaining gage was oriented at 90° to the direction of stress application and this orientation was termed transverse. Gage locations for both longitudinally welded and transversely welded specimens are shown in Fig. 9.

Residual stresses were calculated from the measured strains using the generalized Hooke's Law equations[5] for a plane stress situation (assuming no stress through the thickness of the specimen). The equations used follow below.

$$\sigma_T = \frac{E(\epsilon_T + \gamma \epsilon_L)}{(1 - \gamma^2)}$$

$$\sigma_L = \frac{E(\epsilon_L + \gamma \epsilon_T)}{(1 - \gamma^2)}$$

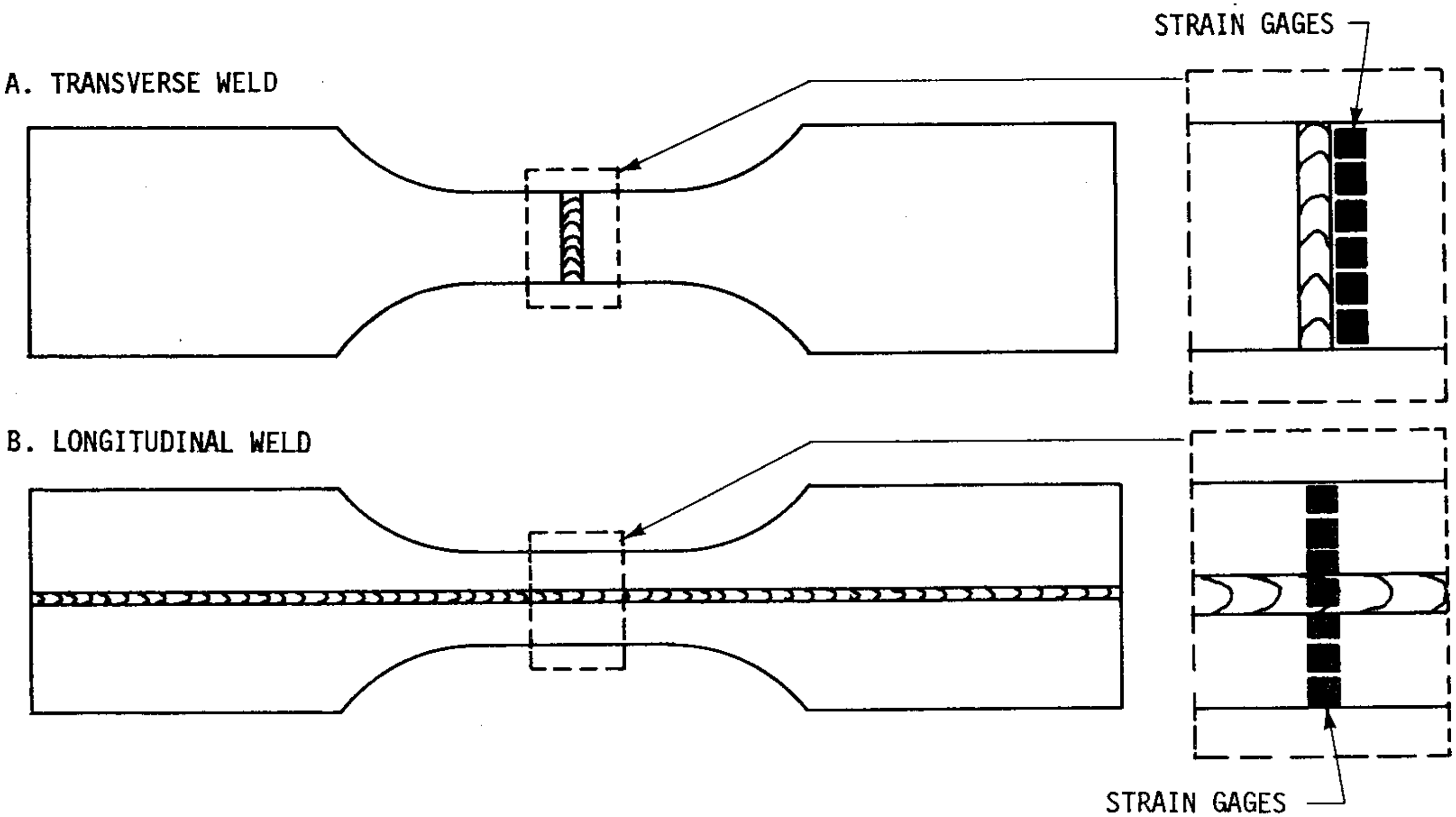


Fig. 9. Strain gage placement for residual stress studies. (Dimensions given in Figs. 10 and 11)

σ_T = stress in the transverse direction

σ_L = stress in the longitudinal direction

ϵ_T = measured strain in the transverse direction

ϵ_L = measured strain in the longitudinal direction

E = modulus of elasticity for the material

γ = Poisson's ratio for the material.

The calculated residual stresses are given in Table 7. These stresses are plotted in Fig. 10 and Fig. 11. In general, the residual stresses are highest in the 3/4" thick 5456 alloy. The transverse butt-welds exhibited a maximum residual stress of +12.7 ksi tension for 5456 alloy and maximum residual stress of +6.2 ksi tension for 5086 alloy. Longitudinal butt-welds had maximum measured residual stresses of +8.3 ksi tension for 5456 alloy and +6.1 ksi tension for 5086 alloy.

Table 7. Calculated residual stresses

		5086-H116		5456-H117	
	Location[a]	σ_L[b] (ksi)	σ_T[c] (ksi)	σ_L (ksi)	σ_T (ksi)
Transverse butt-welds	1-7/8 R	+ 0.3	+ 2.6	+ 3.8	+ 9.5
	1-1/8 R	+ 5.3	+ 6.2	+ 0.9	+ 11.6
	3/8 R	+ 0.0	+ 5.1	+ 2.1	+ 12.6
	3/8 L	- 1.1	+ 3.3	+ 1.2	+ 12.7
	1-1/8 L	- 1.8	+ 3.2	- 1.2	+ 11.5
	1-7/8 L	- 3.5	+ 1.5	+ 2.9	+ 2.3
	Location	σ_L (ksi)	σ_T (ksi)	σ_L (ksi)	σ_T (ksi)
Longitudinal butt-welds	2-3/4 R	- 4.2	- 0.4	- 1.6	+ 1.9
	1-3/4 R	- 0.9	+ 1.0	- 3.1	+ 0.5
	7/8 R	+ 3.6	+ 3.4	+ 7.6	+ 0.8
	℄	+ 6.1	+ 0.6	+ 8.3	+ 0.8
	7/8 L	+ 4.1	+ 1.1	+ 5.0	+ 0.7
	1-3/4 L	+ 1.7	+ 2.5	- 2.2	+ 0.0
	2-3/4 L	+ 0.8	+ 2.6	- 6.0	- 0.5

[a]Number indicates distance in inches from the centerline of the test section.

[b]σ_L = longitudinal stress.

[c]σ_T = transverse stress.

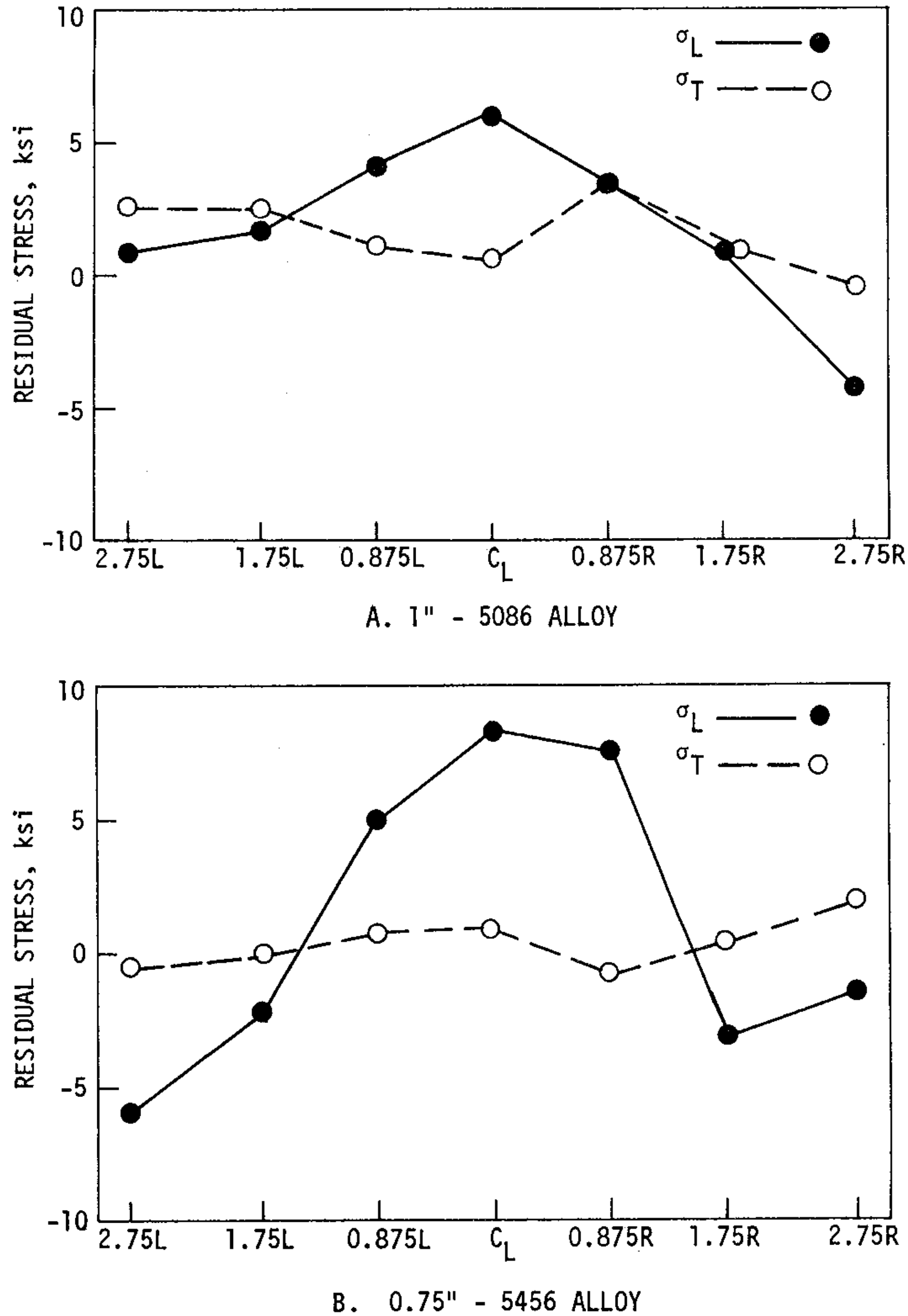


Fig. 10. Residual stress distributions for typical longitudinal welded specimens

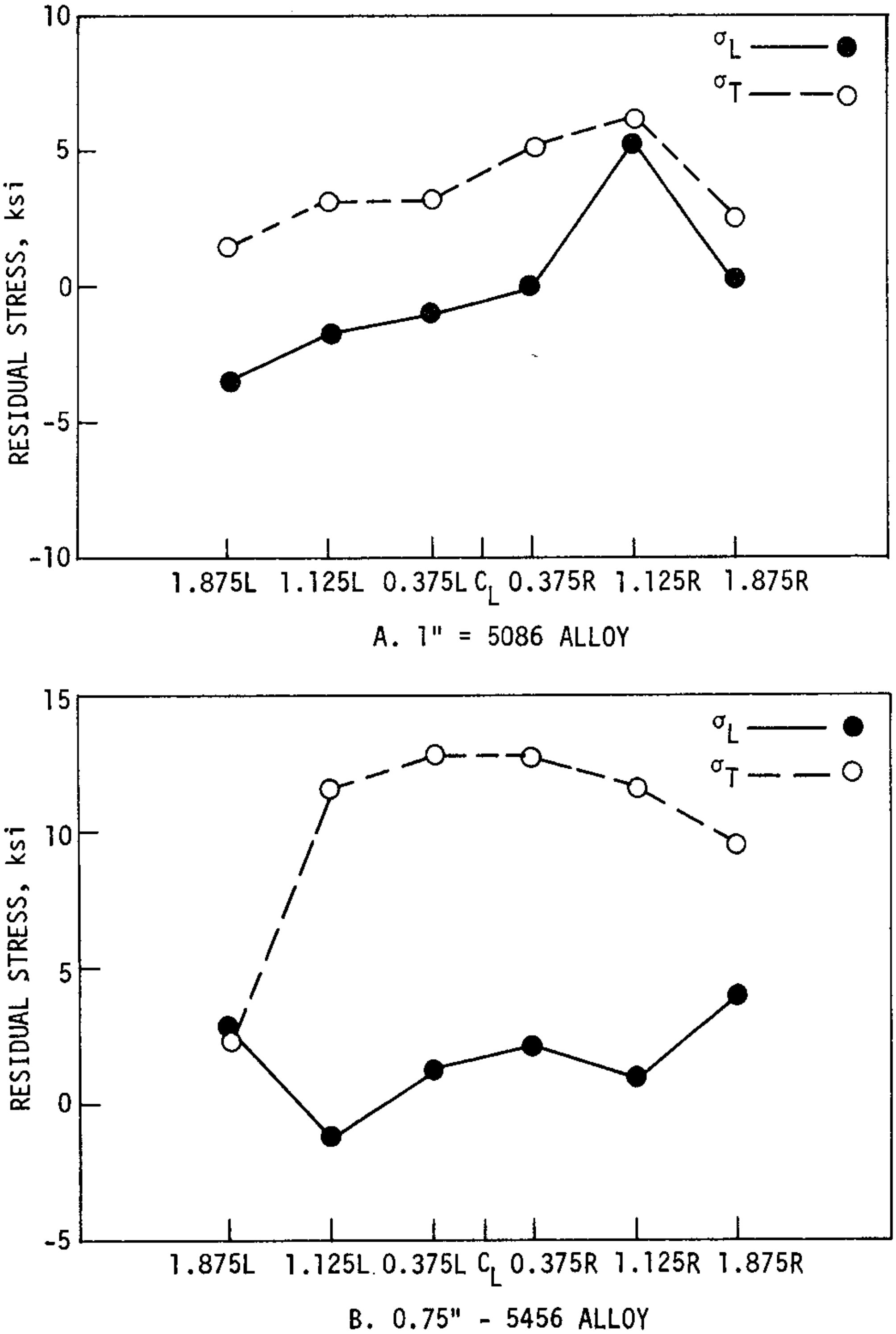


Fig. 11. Residual stress distributions for typical transverse welded specimens

RESULTS OF FATIGUE TEST PROGRAM

Fifty-two aluminum alloy specimens were axially fatigued. The results for these tests are presented in Appendix B. These results are fully annotated with regard to environmental exposure, and failure characteristics. Since the specimens used in this program were tested with as-received plate finishes, considerable variation was present in the test results. Any flaws causing premature fatigue failure non-typical of the fatigue lives for the group of specimens as a whole were noted. Such results were not plotted in the figures that follow, however, they are discussed in this section.

In addition to the surface flaws due to handling, the relative roughness of the "lappings" on the weld bead had a significant effect on the fatigue lives of the aluminum weldments. This effect is recorded in the results found in Appendix B and is discussed later in this section. Most of the welds were relatively smooth, however, several specimens exhibited extremely "rough" weld beads. Such specimens had shorter fatigue lives than the more common "smooth" weld beads. Thus, nontypical results obtained from specimens with "rough" weld were disregarded in the plotting of the following graphs.

Several other specimens failed prematurely under fatigue loading because of weld spatter or other obvious surface defects. Such results were recorded in Appendix B but are also neglected in the plotted figures.

Transverse Butt-Welds

A typical failure section representative of fatigue fractures in the transverse butt-weld specimens is shown in Fig. 12. The fatigue failure initiated at the root of the weld bead growing outward from the point of initiation in a semi-circular fashion. Failure cross sections for both marine and air specimens appeared to be identical in principle. Thus, any reduction in the fatigue life of the weldment caused by the marine environment would be due to the increased stress concentration factor at the root of the weld due to corrosion.

S-N curves (stress range versus weld life) are presented for the 5086 alloy in Fig. 13 and for the 5456 alloy in Fig. 14. The S-N curve presented in this section and in subsequent sections were obtained using a least-squares linear regression analysis[17]. Each of these graphs shows the plain plate fatigue behavior in direct comparison to the transverse butt-weld fatigue behavior for both the air and marine environments.

The results indicate a significant loss in fatigue life for both plain plate specimens and transverse weldments exposed to a saltwater environment for only 30 days. However, the plain plate exposed to a marine environment still performed better with regard to fatigue than the transverse butt-welds exposed only to air.

The data also show a divergence of the S-N curves at lower stress ranges for air and marine curves. This observation holds true for both plain plate and transverse weldments. Thus, it does not appear feasible to indicate the fatigue reduction due to saltwater corrosion as a

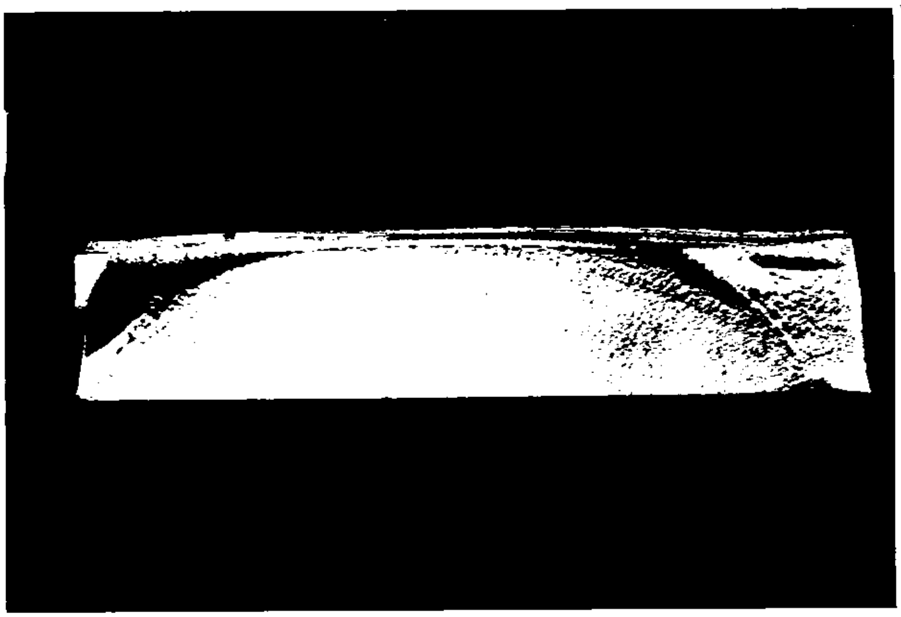


Fig. 12. Cross section of a transverse butt-weld fatigue failure

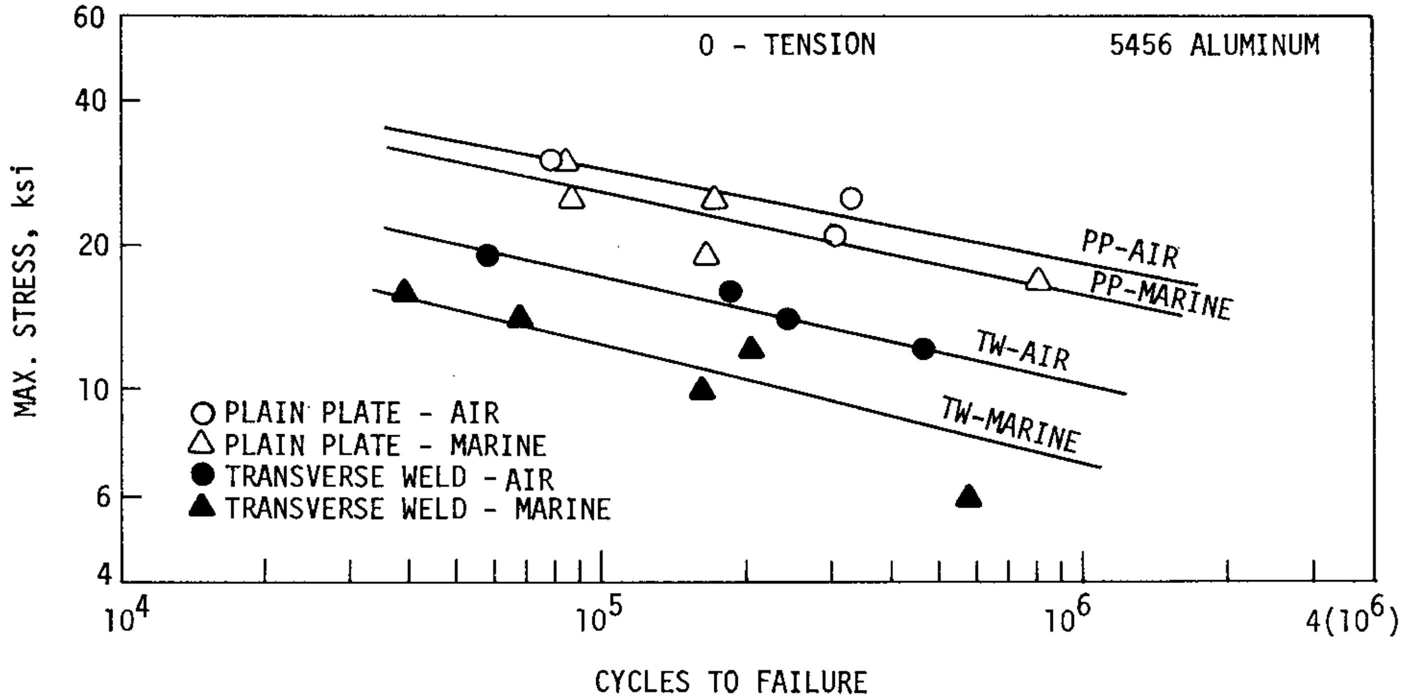


Fig. 14. S-N curves for 5456 aluminum alloy plain plate and transverse weld specimens exposed to air or saltwater

constant value. Instead, there is little fatigue life reduction for high stress range — low cycle fatigue whereas there is a very significant fatigue life reduction for low stress range — high cycle fatigue. In essence then, the effect of saltwater corrosion becomes more critical for weldments subjected to low stress ranges for a great number of cycles. This factor is especially obvious in the 5086 transverse butt weld curves in Fig. 13.

The reduction in fatigue life for 5086 transverse weldments caused by saltwater corrosion is given in Table 8 for two stress ranges.

Longitudinal Butt-Welds

Figure 15 shows a failure cross section representative of those found in the longitudinal weldments tested. Fatigue cracks initiated in the lapping irregularities of the weld bead. The failure crack grew semicircularly about the point of initiation until the final ductile failure occurred. Specimens exposed to marine environment failed similarly to those exposed to air only.

Figure 16 presents S-N curves for the 5086 alloy and Fig. 17 presents S-N curves for the 5456 alloy. The longitudinal weldments were tested with marine exposure only. Each of the previously mentioned figures shows the marine fatigue behavior of the longitudinal weldments in direct comparison to the fatigue behavior of plain plate exposed to both saltwater and air.

The results show the S-N curve for longitudinal weldments to lie only slightly below the S-N curve for plain plate exposed to saltwater.

Table 8. Reduction in fatigue life for 5086 transverse welds exposed to saltwater

Stress range	Fatigue life for air exposure	Fatigue life for marine exposure	Percentage reduction in fatigue life
16 ksi	140000 cycles	70000 cycles	50
14 ksi	600000 cycles	145000 cycles	76

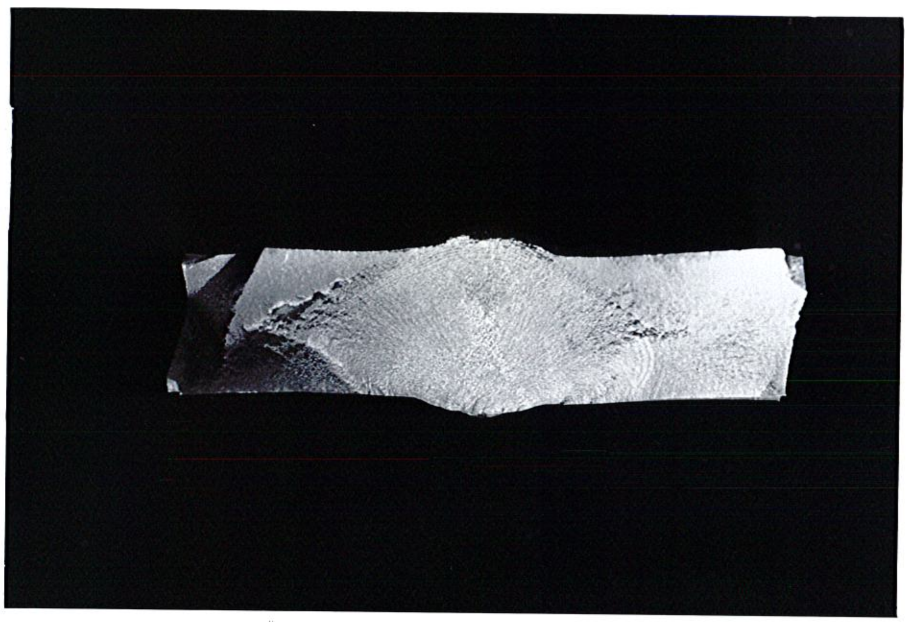


Fig. 15 Cross section of a longitudinal butt-weld fatigue failure

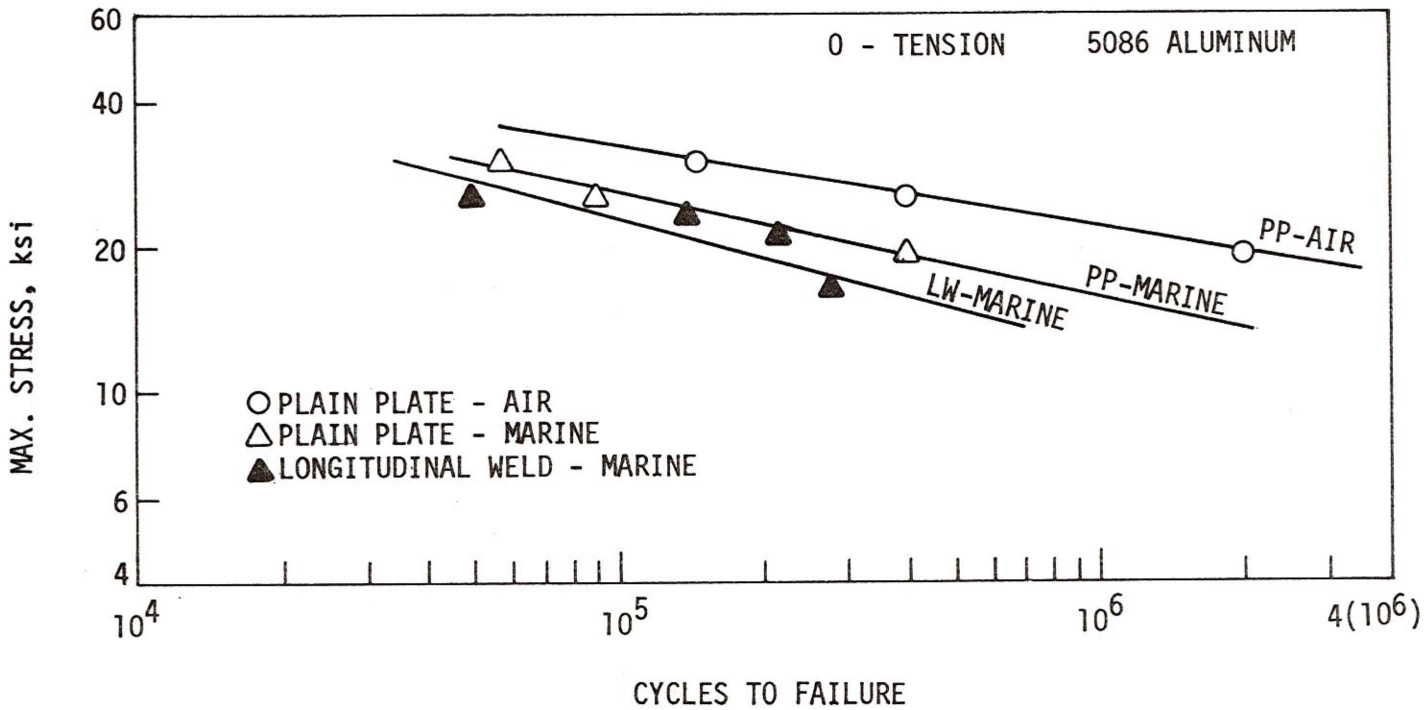


Fig. 16. S-N curves for 5086 aluminum alloy plain plate and longitudinal weld specimens exposed to air or saltwater

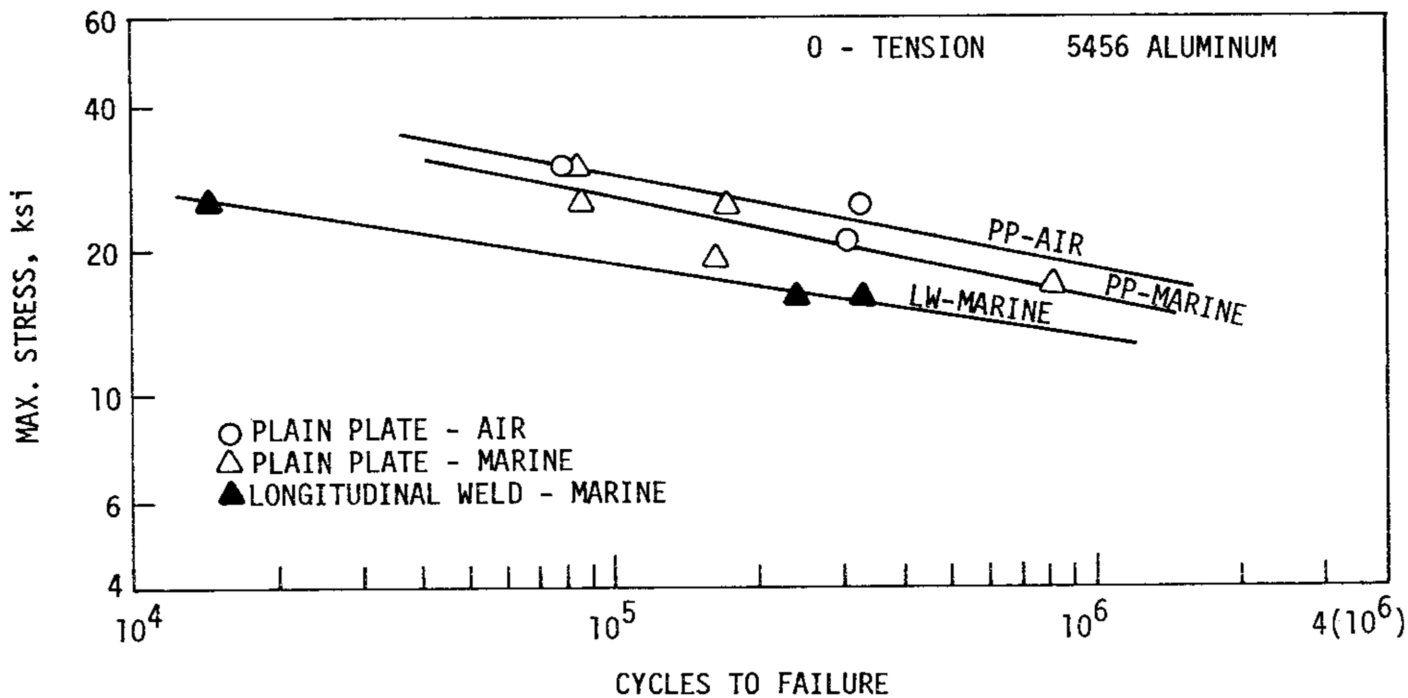


Fig. 17. S-N curves for 5456 aluminum alloy plain plate and longitudinal weld specimens exposed to air or saltwater

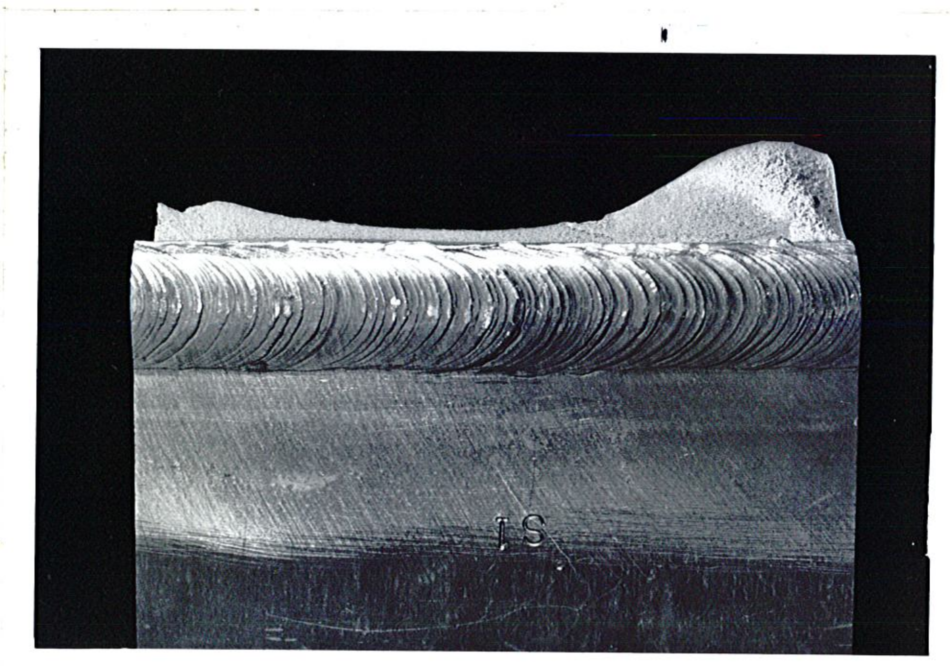
Thus, it is evident that the longitudinal weldments show saltwater fatigue performance superior to that of the transverse weldments since a significant fatigue life reduction was noted for transverse welds. Orientation of the weld in alignment with the applied stress has a beneficial effect on the fatigue performance of weldments subjected to marine corrosion. This effect has been previously noted for air exposure by Sanders and Gannon[14].

Effect of Weld Bead Roughness

Throughout the test program premature fatigue failures of both longitudinal and transverse weldments occurred. Such failures were found in specimens exposed to either air or saltwater environments. All these specimens were fully investigated. For most of these failures no apparent surface defects or weld flaws were detected to account for such fatigue behavior. Finally, the weld beads were compared on the basis of relative roughness with regard to the lappings of the weld metal.

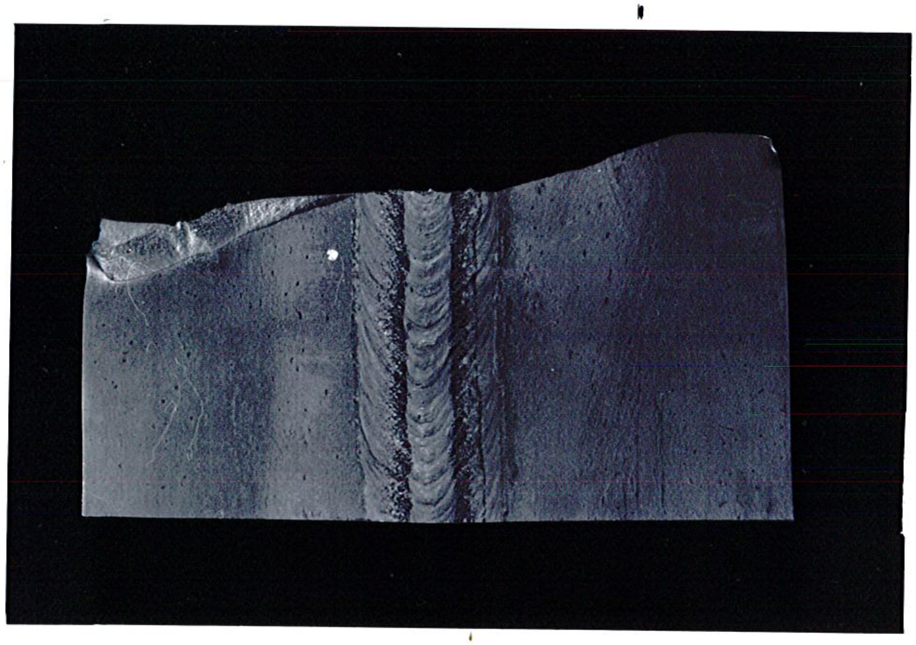
All specimens failing prematurely, without surface flaws or weld defects, had excessively rough weld beads. Figure 18 shows a smooth and rough weld bead for a transverse butt-weld. Corresponding photographs for longitudinal butt-welds are shown in Fig. 19 is visually obvious. Excessive lapping of the weld metal actually forms a saw-toothed surface along the weld bead. In transverse butt-welds, this saw-toothed surface apparently increases the stress concentration factor at the root of the weld resulting in higher effective stress ranges and shortened

A. SMOOTH WELD BEAD

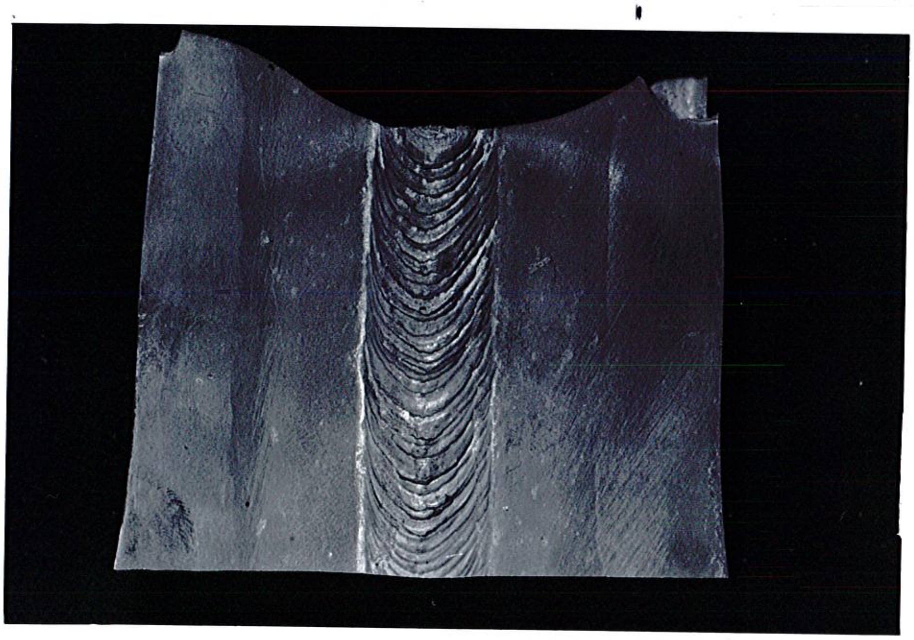


B. ROUGH WELD BEAD

Fig. 18. Weld bead lapping for transverse butt-welds



A. SMOOTH WELD BEAD



B. ROUGH WELD BEAD

Fig. 19. Weld bead lapping for longitudinal butt-welds

fatigue lives. For longitudinal welds, the fatigue crack usually initiated in the weld bead. Therefore, the general roughening of the weld bead increases the stress concentrations at the lappings, again resulting in reduced fatigue lives.

Fortunately, the majority of the specimens tested had relatively smooth weld beads. Since fatigue data for both of these surface conditions were incompatible, the smooth weld bead data was chosen as being representative of the specimens as a group, and premature failures based on rough weld beads were not used to plot S-N curves.

Effect of Weld Geometry

Several investigations[5,12] have already shown that the angle at the root of the weld bead is a prime indicator of the fatigue behavior of a transverse butt-weld with reinforcement in place. The larger the angle the greater the stress concentration factor. This fact has previously been established in Table 6. Since the average weld angle at the point of crack initiation for 5456 transverse welds was approximately 30^{o}, the appropriate stress concentration factor as determined by finite element analysis in Table 6 would be 1.60. If this factor is multiplied by the nominal stress range on the transverse weld specimen a higher effective stress range is determined.

Now the welded specimen's fatigue life under the imposed nominal stress range may be predicted as the fatigue life of a plain plate loaded at the calculated effective stress range. Utilizing a number of stress ranges and the S-N curve for 5456 plain plate air specimens, a S-N curve may be synthesized for 5456 transverse weldments in air. Such a curve is shown in Fig. 20 with the experimental fatigue results superimposed. Since the 5456 and 5086 plates are of different thicknesses the stress concentration factor calculated for a 5456 weldment should not be used for 5086 weldments. Instead an appropriate stress concentration factor should be determined for the weldments in 5086 plate.

The previously described technique could also be applied to the prediction of the fatigue lives of transverse weldments exposed to saltwater conditions. If the corrosion at the root of the weld bead was accounted for as a magnification factor to the already existing stress concentration factor, a rational method for the predicting of fatigue behavior would exist. However, further experimental studies are necessary to accumulate a body of knowledge on fatigue lives of welds on plates of different thicknesses and varying duration of exposure to saltwater. In depth study of the effect of saltwater corrosion at the root of weld beads could also be beneficial in establishing stress concentration magnification factors.

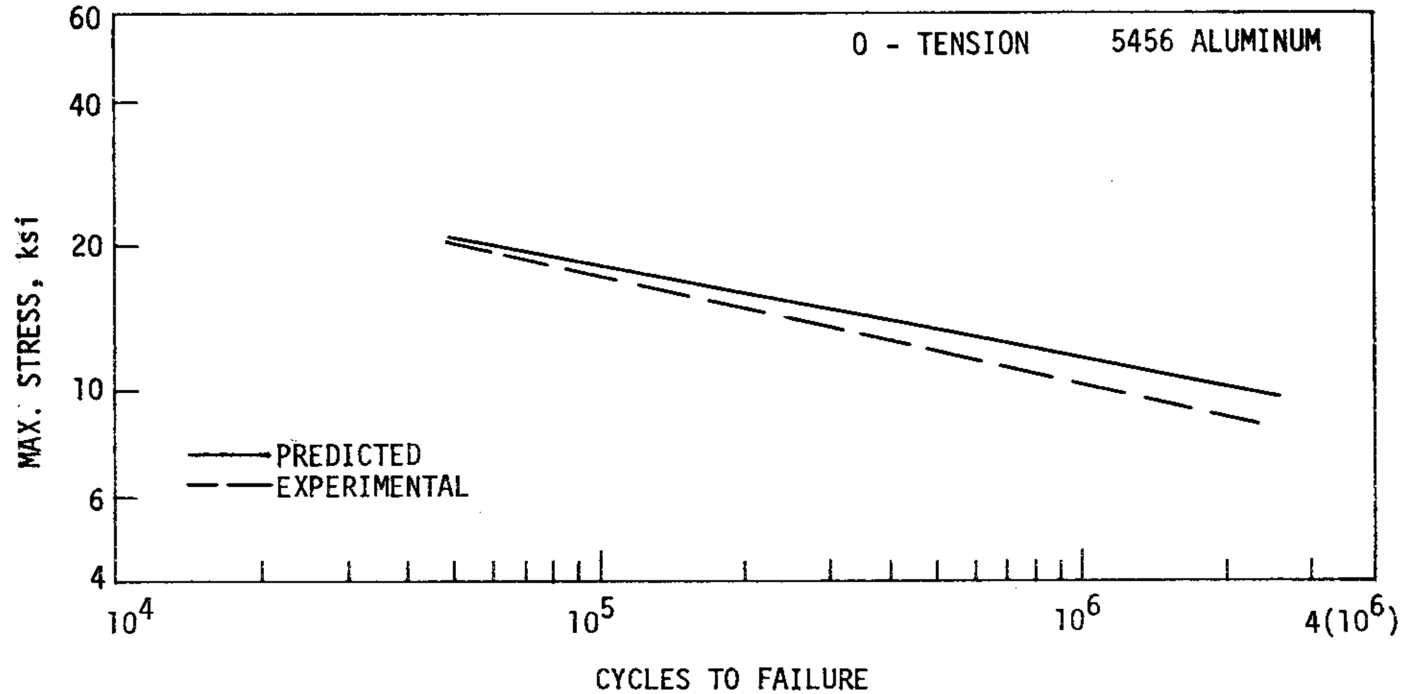


Fig. 20. Predicted and experimental S-N curves for 5456 transverse welds exposed to an air environment only

SUMMARY AND CONCLUSIONS

Summary

In recent years the use of aluminum for the construction of ships and liquified natural gas tanks has increased significantly. The fabrication of these units requires considerable welding of thick aluminum alloy plates. Since the loadings applied to these structures are frequently cyclic in nature, there exists a need for the study of the fatigue behavior of aluminum alloy weldments. Although studies have been completed on this behavior for specimens in air environment, no significant data is available for behavior in a more realistic marine environment.

The previous text presents the results of a study of the fatigue behavior of 5000 series aluminum alloy weldments subjected to a marine environment. Tests were conducted on plain plate, transverse butt-welded and longitudinal butt-welded specimens of 5086-H116 and 5456-H117 aluminum alloys. All welds were made using normal shop fabrication practices. The specimens were full thickness plates (3/4" and 1" thick) axially fatigued under a zero-to-tension stress cycle. The test section was machined to a 4 inch width for plain plates and a 5 inch width for all welded specimens. Width is narrowed in the case of plain plate since these specimens are normally run at higher stress levels. A smaller test section results in a lower total load which is more readily reproduced by the fatigue machine. Such specimens are representative of the physical conditions of aluminum plates used in field situations for the construction of ships and liquified natural gas tanks.

The tests were conducted using a servo-controlled fatigue testing system. Fifty-two full-scale tests were conducted including thirty-five tests on specimens in the marine environment with the remainder in an air environment. The marine specimens were submerged for 30 days in a holding tank containing substitute seawater (ASTM D-1141-52). These specimens were also enclosed in a tank during the testing, allowing the specimen test section to be completely submerged.

Results are presented in both tabular and graphical form. S-N diagrams show the significant reduction in fatigue life for both plain plate and weldments at all stress ranges. Results are further differentiated on the basis of alloy type and weld orientation. Failures of transverse butt-welds tested in a marine environment occurred at maximum stresses as low as 6 ksi.

The main fatigue test program was supplemented by additional investigations. Weld angles were measured at the point of fatigue crack initiation for each welded specimen. Finite element analysis was performed on a typical transverse butt-weld to determine the stress concentration factor at the root of the weld for two known weld angles. This procedure enabled the measured weld angles to be roughly related to an approximate stress concentration factor. Subsequent application of this stress concentration factor resulted in a good prediction of the fatigue behavior of transverse welds in 5456 alloy exposed to an air environment.

The remaining areas of supplemental study were weld quality and residual stress distributions. Weld quality was evaluated using radiographs provided by the fabricator. All welds were of high quality with minor porosity. Residual stresses were determined by strain gaging and sectioning a typical specimen. Results indicated that residual stresses were higher in the thinner (3/4 inch thick) plate for both transversely and longitudinally welded specimens.

Conclusions

Conclusions from the study are:

1. Saltwater corrosion significantly reduces the fatigue strength of 5456 and 5086 weldments for all stress ranges. However, the reduction in fatigue life is not constant but generally increases with decreasing applied stress range.

2. Orientation of the weld in the direction of stress application is beneficial to the fatigue strength of a joint exposed to either air or saltwater.

3. The angle at the root of the weld reinforcement is the critical factor in the determination of fatigue lives for transverse butt welds exposed to air. A larger weld angle increases the stress concentration factor at the root of the weld resulting in a higher effective stress range and lower fatigue lives.

4. The saltwater corrosion of transverse butt-welds effectively increases the stress concentration factor at the root of the weld, thus decreasing fatigue strength.

5. The true maximum stress range existing at the toe of the weld as predicted by an appropriate stress concentration factor is the best fatigue life indicator for transverse welds exposed to either air or saltwater.

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ACKNOWLEDGMENTS

This report presents the results of a research program investigating the fatigue behavior of weldments in aluminum alloys subjected to a marine environment. The program was conducted by the Engineering Research Institute of Iowa State University and was funded jointly by the Welding Research Council and the National Science Foundation with supplementary support from the Engineering Research Institute.

The aluminum material was donated by Kaiser Aluminum, Alcoa, and Bell Aerospace Company. All welding was done and donated by Rohr Industries. The joints were prepared for welding by Kaiser Aluminum. The support of the sponsors and these industries is gratefully acknowledged.

The author wishes to express his appreciation to his major professor, Dr. W. W. Sanders Jr., for his support and guidance throughout the duration of the research effort. Appreciation is also expressed to Dr. L. F. Greimann who aided in the finite element work.

Thanks is given to the Machine Shop and Electronics Shop of the Engineering Research Institute for their cooperation throughout the program.

Additional thanks is given to undergraduate student Gary Krupicka for his invaluable assistance in all phases of the project.

A special thanks is given to my wife, Alice, whose love, encouragement, and understanding bolstered me throughout the investigation.

APPENDIX A: TYPES OF CORROSION IN 5000 SERIES ALUMINUM ALLOYS

The 5000 series alloys are highly reactive metals with a great affinity for oxygen. However, the forming of a tough oxide film on the aluminum surface upon exposure to oxygen or oxidizing solutions prevents severe corrosion in most atmospheres and electrolytes. This film varies from 50 to 100 Å in thickness and remains stable in liquid environments with pH 4.5 to pH 8.5. (Oceans possess an approximate pH value of 7.8.) In general, environments providing good oxidation conditions produce a decreasing rate of corrosion with time. This generalization is not always true in moving seawater.

There are many forms of aluminum corrosion and in most circumstances these forms are combined. The following list of types of corrosion is not complete but does contain the most commonly occurring forms:

1. Pitting attack is the most commonly occurring form of corrosion in the 5000 series alloys. It is a localized form of corrosion resulting in small holes (pits) which tend to penetrate deeper into the metal with time. The deepening of the initial pits proceeds by electrochemical attack involving galvanic and/or concentration cells.

Galvanic cells often form on an aluminum surface when the protective passive layer has been breached by mechanical means. The exposed surface area is anodic, and corrodes rapidly due to the relatively small size of the exposed surface. The adhering of dirt or other matter to aluminum surfaces may also prevent the formation of a passive film. When such matter is removed an anodic area is again formed resulting in a galvanic cell.

Concentration cells occur when oxygen concentrations vary across the surface of an aluminum. Frequently, the oxygen concentration at the bottom of surface scratches is much lower than on the actual plate surface. This lack of oxygen not only creates an anodic area subject to corrosion but also inhibits the passive film retarding corrosion. Thus pit growth continues until the critical depth is reached for chemical equilibrium to occur.

Pitting attack is very mild in atmospheric environments, resulting in a roughened surface with no further deepening occurring after a given time period. Pits in aluminum placed in stationary seawater are larger than those found in atmospheric pitting, but remain shallow. Moving seawater environments usually produce greater pit depths than either atmospheric conditions or stationary seawater. Under such conditions, the corrosion does not always stop but may continue with time.

2. Intercrystalline corrosion can be found where a continuous grain boundary precipitate encourages galvanic action. In the case of the 5000 series alloys, this precipitate would usually be magnesium, the primary alloying constituent. Since magnesium is anodic to aluminum, selective corrosion attack will occur at the grain boundaries of the alloy. Although this form of corrosion rarely appears in properly heat-treated alloys, improper control of the cooling of weld areas can create significant precipitation of magnesium at the grain boundaries located in the weld's fusion zone. Obviously, such regions are subject to intercrystalline corrosion.

3. Stress-corrosion occurs when static surface tensile stresses act in combination with a corrosive environment. Failure is initiated by corrosion of anodic areas on the aluminum's surface. Once corrosion begins, the tensile surface stresses are intensified at the roots of the corroded region, and crack formation occurs. Gradually these cracks will grow and deepen until fracture may be eminent.

The 5000 series alloys used in the ship-building industry are almost free from stress-corrosion attack unless continuous magnesium precipitate is present at the grain boundaries. Such precipitation is generally produced by excessive cold-working followed by heat treatment. Again, improper control of the cooling of weld areas may also produce magnesium precipitates.

4. Galvanic corrosion is a basic mechanism found in many other forms of corrosion. When two dissimilar metals exist in an electrolyte such as seawater, electric currents flow between the metals. The anodic metal provides electrons which are then deposited on the cathodic metal. Thus, the anodic metal is selectively corroded. Such a sequence of events is termed a galvanic process.

APPENDIX B: FATIGUE DATA

Specimen Coding

Material — A — Aluminum   S — Steel

A1 — 5083-0
A2 — 5086-H116
A3 — 5456-H117
S1 — ABS Class C

Environment —

A — Air
M — Marine

Joint —

PP — Plain Plate
T — Transverse Weld
L — Longitudinal Weld

Weld Reinforcement —

R — Reinforcement Removed
W — As Welded

Plate Number —

1,2,3,...

Example

A3MTR 5

Aluminum 5456	Marine Environment	Transverse Weld	Reinforcement Removed	Plate Number 5

Note — In the case of a plain plate specimen no weld exists. Thus, the weld-reinforcement term is omitted from the specimen code. The two letters omitted are merely replaced by PP.

Failure Type Code

A — Normal fatigue failure. (In case of welds failure at weld.)

B — Premature fatigue failure at the weld due to excessive roughness of the weld bead.

C – Premature fatigue failure in the plate material due to surface flaw. (Surface defect given after code letter in the data tables.)

D – Fatigue failure in the plate material. These specimens exhibit somewhat extended fatigue life due to:

1. Extremely smooth weld beads.

2. Small weld angles unrepresentable of the welded specimens as a whole. (Failure initiated at surface defects.)

Any failures classified other than A showed fatigue behavior in variance with the majority of test results. Thus such results were deemed nonrepresentable fatigue behavior and were disregarded in the S-N plots included in the main text.

Test Data

Plain plate

Joint type	Stress range (ksi)	Air	Marine	Failure type
5456				
A3APP1	30	79600		A
A3APP3	25	332800		A
A3APP2	21	192500		C — Deep scratch
A4APP3	21	308800		A
A3MPP6	30		82900	A
A3MPP5	25		86300	A
A3MPP7	25		170200	A
A4MPP2	19		163530	A
A4MPP1	17		817000	A
5086				
A2APP2	25	400000		A
A2APP1	19	294300		C — Scratch
A2APP3	19	2000000+		No failure
	30 (retest)	146300		A
A2MPP6	30		56600	A
A2MPP4	25		89900	A
A2MPP5	19		400000	A

Transverse butt-weld

Joint type	Stress range (ksi)	Air	Marine	Failure type
5456				
A3ATW3	19	58300		A
A3ATW1	16	187800		A
A3ATW2	14	245600		A
A3ATW9	12	464400		A
A3MTW5	16		38800	A
A3MTW4	14		67700	A
A3MTW6	12		51190	B
A3MTW10	12		202280	A
A3MTW7	10		161300	A
A3MTW11	8		1000000+	No failure
A3MTW8	6		574830	A
5086				
A2ATW1	19	19600		A
A2ATW3	14	150900		B
A2ATW7	14	223800		B
A2ATW8	14	512000		A
A2ATW9	12	2000000+		No failure
	14 (retest)	750000		A
A2ATW2	10	2000000+		No failure
	16 (retest)	236600		A
A2MTW4	16		74630	A
A2MTW12	14		566220	D
A2MTW5	14		180170	A
A2MTW10	12		563510	D
A2MTW11	12		416160	A
A2MTW6	12		323480	A
A2MTW13	11		269640	A

Longitudinal butt-weld

Joint type	Stress range (ksi)	Air	Marine	Failure type
5456				
A3MLW1	25		14500	A
A3MLW2	19		189500	D
A3MLW3	17		184000	C -- Machining flaw
A3MLW4	16		156400	B
A3MLW5	16		329800	A
A3MLW7	16		241030	A
A3MLW6	14		175400	C -- Deep scratch
5086				
A2MLW1	25		59900	A
A2MLW2	23		140200	A
A2MLW3	21		215000	D
A2MLW4	19		139500	C -- Weld spatter
A2MLW5	19		202210	A
A2MLW6	16		274900	A