High Cycle Fatigue Behavior of 5086-H116 Aluminum Alloy Electron Beam Welds

Excellent mechanical properties of electron beam welds in an aluminum alloy are attributed to the lack of visible porosity

BY ROBERT R. HARDY, JR.

ABSTRACT. Static and dynamic mechanical property tests were conducted on 1 in. (25.4 mm) thick 5086-H116 alloy aluminum electron beam welds. The results indicate that the properties of the welds compare favorably with those of 5086-H116 plate. The mechanical properties of the 5086-H116 electron beam welds are significantly superior to those of 5086-H116 gas metal arc welds. The fatigue performance of the electron beam welds is from 85% to 100% better than that of gas metal arc welds at 10^8 cycles. The excellent properties of the electron beam welds are attributed to the absence of porosity and other common arc weld defects.

Introduction

Background

Since low structural weight is essential for marine craft, high-strength, corrosion-resistant weldable aluminum alloys have been selected as the primary hull material. An investigation was conducted on the high-cycle fatigue behavior of 5086-H116 and 5456-H117 aluminum alloys and welds in air and in seawater (Ref. 1).

The results of this investigation showed that the fatigue performance of the two alloys is essentially identical for any condition tested. Also, if fatigue is the limiting factor in marine hulls, the higher static mechanical properties of the 5456 alloy offer no advantage over the 5086 alloy.

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The investigation also showed that the fatigue strength of 5456-H117 and 5086-H116 welds is considerably lower than that of base metal in both air and seawater. It was concluded that minute porosity, within allowable radiographic standards, significantly reduces the fatigue strength of aluminum alloy welds.

To eliminate porosity in aluminum alloy welds, the electron beam welding (EBW) process is being considered for fabrication of marine aluminum structures, since it produces excellent weld quality and is being used to fabricate critical structures in industry. The Grumman Aerospace Corporation of Bethpage, New York, is fabricating the wing box for the Navy's F-14 jet fighter using the EBW process. The wing box is a critical structure in this jet airplane. General Electric Company of Philadelphia, Pennsylvania, is also fabricating new aluminum pressure hulls for the Link submersible by the EBW process.

Scope

This paper presents the results of a study of the high-cycle fatigue behavior of 5086-H116 aluminum alloy electron beam welds in air. The objectives of the study were to ascertain differences in fatigue behavior between welds produced by GMAW and EBW processes.

Table 1—Mechanical Properties and Specification Properties

	Alloy	
	5086-H116	Specified minimum
Ultimate tensile strength, ksi	45.0	40.0
Yield strength (0.2% offset), ksi	32.0	28.0
Elongation in 2 in. gage, %	25.5	10.0
Reduction in area, %	40.0	–

Procedure

Material

The aluminum alloy selected for the investigation was 5086-H116, conforming to interim Federal specification QQ-A-00250/20. Typical mechanical properties determined for the alloy, together with corresponding specification requirements, are indicated in Table 1.

Welding Preparation

Butt welds of 5086-H116 aluminum alloy, measuring 12 × 30 × 1 in. (305 × 762 × 25.4 mm) thick, were prepared by the EBW process. Welding conditions details are given in Table 2.

Weld Evaluation

The completed welds were evalu-

Table 2—Welding Conditions Employed in Fabricating 5086-H116 Aluminum Alloy Electron Beam Butt Welds

Process	Electron beam
Equipment	Sciaky electron beam machine
Weld joint	Square butt; edge finish—63 rms
Beam voltage	35 kv
Beam current	222 mA
Travel speed	30 ipm (726 mm/min.)
Gun-to-work distance	8 in. (203.2 mm)
Focus point	Plate surface
Chamber size	39 ft (11.9 m) in diameter by 80 (24.4 m) ft high

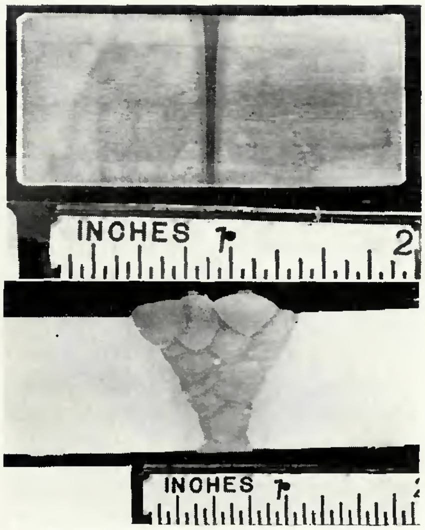


Fig. 1—Photomacrographs of aluminum alloy 5086-H116 welds: A (top)—electron beam; B (bottom)—gas metal arc

ated by radiographic and macrographic examination, tensile tests, rotating cantilever-beam fatigue tests, transverse side bend tests, dynamic tear tests, and microhardness surveys. Tensile properties were determined by using standard 0.505 in. (12.8 mm) diameter transverse weld tensile specimens. Transverse weld side bend specimens, 3/8 in. (9.5 mm) thick, were taken through the cross section. Toughness properties were determined with standard 5/8 in. (15.9 mm) thick dynamic tear specimens. Hardness surveys were made across the weld, heat-affected zone, and base metal.

The fatigue properties were developed from the rotating cantilever-beam fatigue test. A constant, dead-weight load was applied at the bearing end, and the maximum reversed stress, $S_r = \pm Mc/I$, was calculated from the applied load. All specimens were cut transverse to the weld. The test sections of the specimens were circumferentially and longitudinally polished to ensure complete removal of machining marks and to provide a uniform, fine metallographic quality surface finish (Ref. 1).

Table 3—Mechanical Properties of the Welds

	Yield strength, (0.2% offset), ksi	Tensile strength, ksi	Elongation in 2 in., %	Reduction in area, %	Dynamic tear energy at +30 F, ft-lb
Base metal	32.4	45.3	25.5	40.0	245[a]
Electron beam weld	27.0	44.5	18.0	41.0	240[a]
Gas metal arc weld	20.5	37.5	12.5	32.5	—
Gas metal arc[b] weld, minimum	19.0	35.0	—	—	—

[a] Notch pressed to provide a fracture path in the direction of rolling in the base plate and along the length of the weld in the electron beam weld.

[b] See Ref. 2.

Results of Weld Evaluation

Visual and Radiographic Examination

Visual examination of the welds indicated an undercut of a few thousandths of an inch on the top side of the weld. This often occurs in one-pass electron beam welds and is normally corrected by a "cosmetic pass" which adds a crown to the weld bead. The undercut had no effect on any test in this investigation, since the surfaces were removed in the preparation of the specimens.

Radiographic examination of the welds indicated two small defective areas, each approximately 1/8 in. (3.2 mm) long. In other respects, the welds met the requirements of NAVSHIPS 0900-003-9000, class 3. No test specimens were taken from the defective areas. After radiographic examination, macrosections were removed from the welds. A photograph of a cross section appears in Fig. 1. A typical cross section of a GMA weld is shown for comparison.

Mechanical Properties

The mechanical properties of the 5086-H116 aluminum alloy electron beam welds and gas metal arc welds are listed in Table 3.

Mechanical properties of the gas metal arc welds were obtained during other concurrent in-house investigations. Radiographic examination of these gas metal arc welds indicated that their quality met the requirements of NAVSHIPS 0900-003-9000, class 3.

Figures 2 and 3 show the fracture surfaces of transverse weld tensile specimens fabricated by both the GMAW and EBW processes. Figure 4 shows the fracture surfaces of the dynamic tear test specimens.

Fatigue Test

The fatigue test results of the electron beam welds appear in Table 4. Fatigue test results of 5086-H116 base metal and GMA welds have previously been reported (Ref. 1). Figure 5 shows a plot of the scatter bands for the data on base metal and GMA welds. The fatigue test results of the electron beam welds are plotted in Fig. 6 for comparison to the base metal and GMA weld fatigue results.

Side Bend Test

Figure 7 shows the electron beam

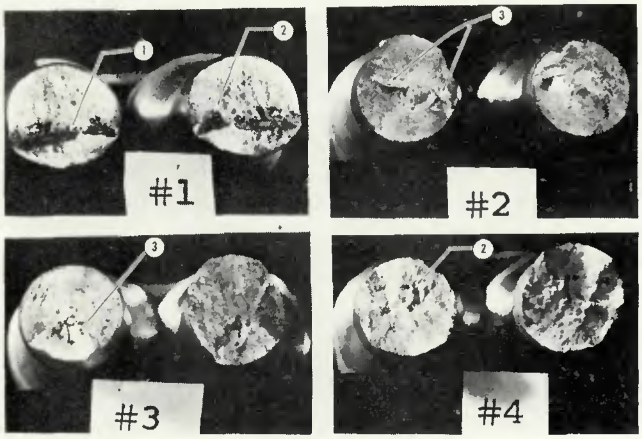


Fig. 2—Fracture surfaces of tensile test specimens showing characteristic weld defects in aluminum gas metal arc weld with encircled numbers indicating following: 1—inadequate joint penetration; 2—porosity; 3—incomplete fusion

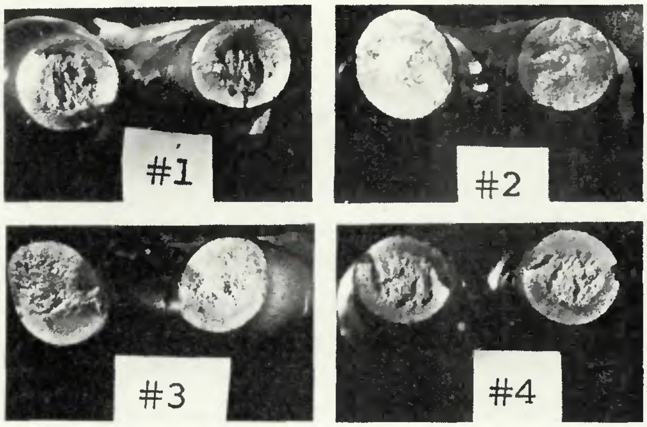


Fig. 3—Fracture surfaces of tensile test specimens from an aluminum electron beam weld

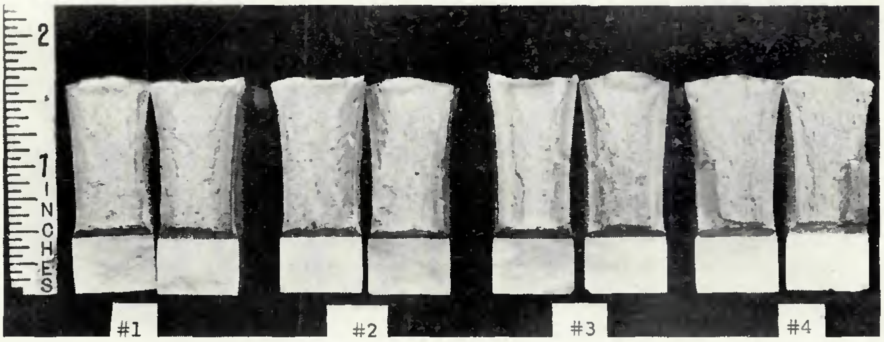


Fig. 4—Fracture surfaces of dynamic test tear specimens from an aluminum electron beam weld

Table 4—Fatigue Test Results for 5086-H116 Electron Beam Welds in Air

Stress level, ksi	Cycles	Remarks
22,500	888,000	Failed in weld area.
20,000	601,000	Failed in weld area.
20,000	885,000	Failed in weld area.
19,000	1,933,000	Failed in weld area.
18,500	616,000	Failed in weld area.
18,000	50,042,000	Failed in weld area.
18,000	2,258,000	Failed in base metal.
17,500	24,349,000	Failed in weld area.
17,500	105,458,000	Did not fail; specimen removed.
15,000	112,174,000	Did not fail; specimen removed.
12,500	105,792,000	Did not fail; specimen removed.
12,500	105,792,000	Did not fail; specimen removed.

weld side bend specimen tested at a 4T bend radius.

Hardness

Microhardness (Knoop) surveys were conducted on macrosections obtained from the electron beam and gas metal arc welds. Figure 8 shows the areas where the surveys were performed and the Knoop hardness numbers obtained.

Discussion

Table 3 and Figs. 6 and 8 show the superior properties of the electron beam welds compared to gas metal arc welds in the 5086-H116 aluminum alloy. The mechanical properties of the electron beam welds compare favorably with base metal properties, while those of GMA welds are considerably lower than base metal properties.

Figure 2 shows characteristic weld defects of aluminum GMA welds. Specimen 1 shows inadequate joint penetration and porosity associated with this defect. Specimen 2 shows incomplete fusion and a crescent-shaped defect which is caused by entrapment of impurities. Specimen 3 shows incomplete fusion caused by entrapment of impurities. Specimen 4 shows a good weld with one area of porosity.

These defects—porosity, inadequate joint penetration, and incomplete fusion—are responsible for the lower mechanical property values of aluminum GMA welds for two reasons:

1. The defects reduce cross-sectional area.
2. They introduce stress concentrations.

Also, the deleterious effect on mechanical properties due to the presence of weld defects is increased under conditions of impact and repeated loading (Ref. 3).

Porosity has been shown (Refs. 3-11) to be the major cause of the lower mechanical properties of aluminum GMA welds. Lawrence and Munse have reported (Ref. 9) that the lower tensile strength of aluminum GMA welds is in direct proportion to the lessening of cross-sectional area with increasing porosity, while the yield strength of aluminum welds gradually decreases with increasing porosity. Also, Lawrence and Munse established that porosity is a sum of macro- and microporosity and that there are different relationships between them; these relationships are as follows:

1. The amount of microporosity (0.001 to 0.01 in., i.e., 0.025 to 0.25 mm, diameter pores) exceeds the amount of macroporosity (pores larger than 0.01 in. or 0.25 mm diameter) in most aluminum welds.
2. In aluminum welds with levels of macroporosity higher than 5% of the cross-sectional area, most welds can also contain microporosity up to eight times that of the macroporosity.
3. As much as 5% microporosity can exist in a weld without the presence of any macroporosity.

Because of these relationships, any evaluation of mechanical property tests results that excludes microporosity levels would be misleading. The reason is microporosity could be present in large amounts and have a greater effect than macroporosity on the mechanical properties of aluminum welds.

The excellent mechanical properties

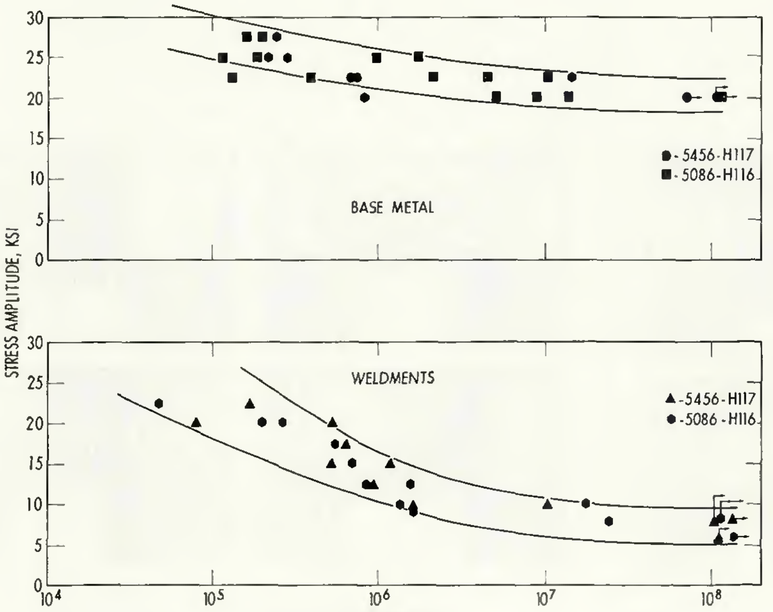


Fig. 5—Fatigue test results of marine aluminum alloy base metal and scatter bands for welds

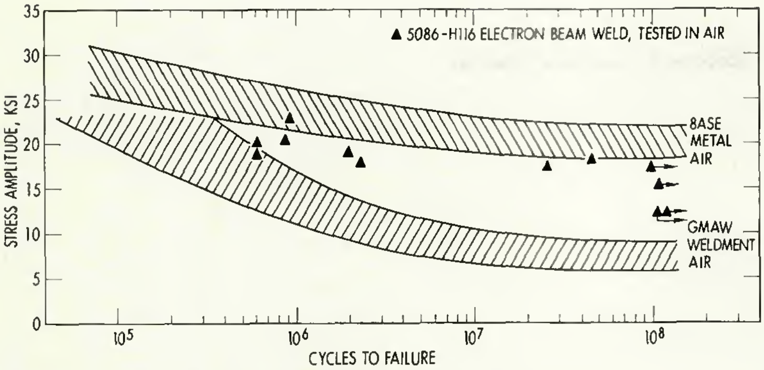


Fig. 6—Fatigue test results of 5086-H116 aluminum alloy welds

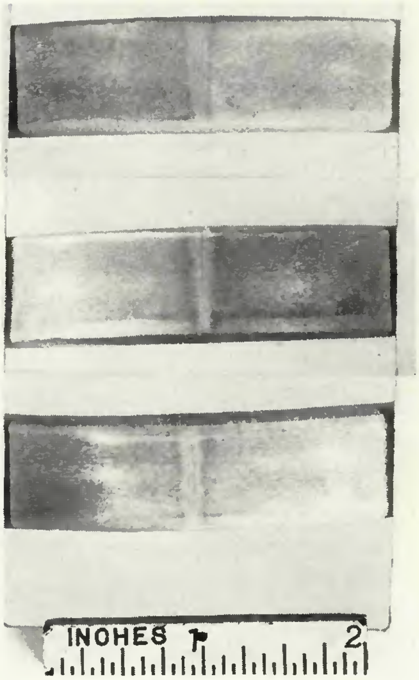


Fig. 7—Side bends, aluminum alloy 5086-H116 electron beam weld

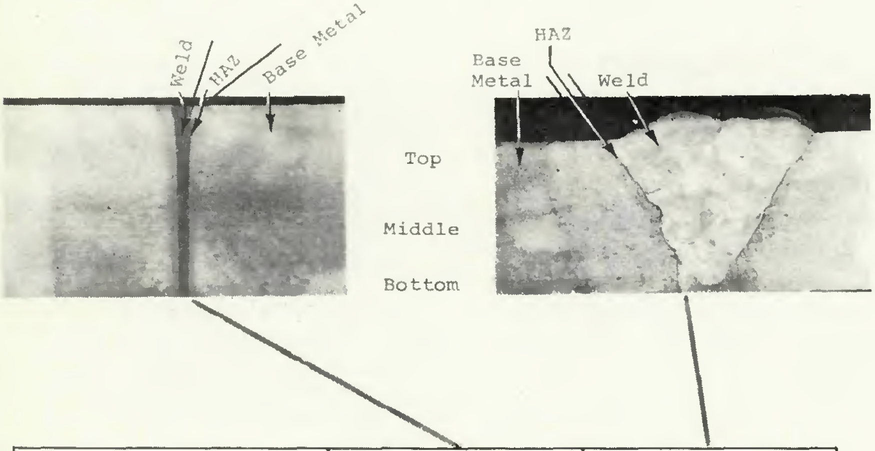
of the aluminum electron beam welds are attributed to the lack of visible porosity. This was confirmed by examining the fracture surface of the tensile specimens. Also, the EBW process produces an autogenous weld (no filler metal added); therefore, the weld zone has almost base metal properties.

While it had been shown that porosity and other weld defects result in lower static mechanical properties of the aluminum arc welds as compared to base metal properties, it has also been reported (Refs. 10-13) that these defects have a severe detrimental effect on fatigue properties. It has been shown that porosity and other weld defects also act as fatigue crack initiators.

The results of the fatigue testing in this investigation substantiate the aforementioned statements. The transcendent fatigue properties of the electron beam welds, which approached those of the base metal, were due to the unique soundness of the weld which had no detectable porosity or other weld defects.

All other tests and examinations conducted on the aluminum 5086-H116 electron beam welds produced results superior to aluminum GMA welds. The dynamic tear test results indicate a toughness equivalent to base metal, as shown in Table 3. The hardness survey across the weld was more uniform for an electron beam weld than for a GMA weld. This fact may prove to be advantageous, since a current Navy investigation has shown that GMA welds have a "soft zone" in the crown of the weld which may have an unfavorable effect on the fatigue properties. Also, the side bend tests on the electron beam welds produced no failures, while bend specimens from aluminum GMA welds are prone to fracture due to weld defects such as inadequate joint penetration or gross porosity.

The absence of weld defects is a major factor in the excellent mechanical, fatigue, and other material properties of the aluminum welds fabricated by the EBW process. This is significant, since the improvement in fatigue performance of the electron beam weld compared to GMA welds ranges from 85% to 100% increase in the stress level attained at 10^8 cycles.



Area	Electron Beam		Gas Metal-Arc	
	Average	Range	Average	Range
Bottom (root)				
Base metal	93.9	89-102	92.5	87-96
HAZ	87.5	86.6-88.5	88.9	87-92
Weld	87.0	86.6-87.5	77.3	72-83
Middle				
Base metal	92.7	88-98	91.5	88-96
HAZ	82.6	81-86	85.0	82-88
Weld	82.6	79-86	77.7	71-84
Top (crown)				
Base metal	94.4	90-102	89.9	86-96
HAZ	86.4	83-89	82.9	79-84
Weld	80.4	78-82	76.2	68-85
Average				
Base metal	93.6	88-102	91.3	86-96
HAZ	85.5	81-89	85.6	79-92
Weld	83.3	78-87.5	77.0	68-85

Fig. 8—Knoop hardness survey of aluminum alloy 5086-H116 electron beam and gas metal arc welds

Conclusions

The following conclusions are drawn from a comparison of aluminum alloy electron beam and gas metal arc welds:

1. The fatigue performance of the

5086-H116 electron beam welds in air is superior to 5086-H116 GMA welds in air. The fatigue performance of the electron beam welds compares favorably to base metal performance. This can be attributed to the absence of porosity and other weld defects.

2. The fatigue performance of the electron beam welds compared to GMA welds shows from 85% to 100% increase in the stress level attained at 10^6 cycles.

3. The strength and toughness properties of the 5086-H116 electron beam welds are significantly higher than 5086-H116 GMA welds. The electron beam weld properties compare favorably to base metal properties. The excellent properties of the electron beam welds can be again attributed to the absence of porosity and other weld defects.

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I "Development of Design Rules For Dished Pressure Vessel Heads"

by E. P. Esztergar

The present study is the continuation of an extensive investigation aimed at the development of rational design rules for formed pressure vessel heads. This problem was one of the first research projects the Design Division of PVRC selected for study and by maintaining its interest stimulated an increasing amount of work on the diverse behavior of seemingly similar head shapes. In the course of this work, not only new analysis techniques were developed but also a number of new failure modes unique to these deceivingly simple looking geometrical shapes were uncovered.

II "The Effect of Geometrical Variations on the Limit Pressures For 2:1 Ellipsoidal Head Vessels Under Internal Pressure"

by J. C. Gerdeen

This theoretical study has been conducted for the Subcommittee on Shells of the PVRC Design Division of the Welding Research Council. The impetus for this general study grew out of another specific study of the analysis of limit pressures of actual formed heads. Since it was found that actual formed heads are not uniform in thickness and that the thickness variations do affect the limit pressure, the thickness variation was studied in detail using a computer analysis that included bending theory.

Publication of these papers was sponsored by the Pressure Vessel Research Committee of the Welding Research Council.

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