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Marine Corrosion and Fatigue Of Graphite Aluminum Composites

by

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ABSTRACT

The marine corrosion and fatigue performance of two types of VSB-32/Al 6061 graphite aluminum composite materials were characterized. Corrosion tests were performed in natural flowing seawater, tidal immersion and atmospheric exposure. The residual mechanical properties of the composites were evaluated after exposure. Axial fatigue tests of the standard VSB-32/Al 6061 composite were performed in air and natural seawater. Results of environmental exposures showed that the galvanic driving force dominated the corrosion of the composite materials, and the overall performance of the composites was related to both the corrosion of the surface foil and the substrate. Residual mechanical properties did not show latent effects of the environment where corrosion was not visible, but were substantially reduced in response to visible corrosion damage. The fatigue strength of the composite increased with fiber strengthening in direct response to the increase in ultimate tensile strength. The fatigue strength of the composite displayed less sensitivity to seawater than the 6061-T6 plate.

INTRODUCTION

Metal matrix composite materials are being considered for structural applications because of the range of mechanical properties attainable. The graphite/aluminum system is particularly promising because of the very high specific strength and modulus levels attainable over other alloys and composite materials. As mechanical properties of graphite/aluminum composites have been improved, it became necessary to evaluate the environmental sensitivity of the composite system and extend the characterization data into the regime of fatigue performance.

The objective of this investigation was to characterize the marine corrosion and fatigue performance of two similar types of graphite/aluminum composite materials. The approach included the production of VSB-32/Al-6061 uniaxially reinforced composite plates which were exposed in marine environments including natural flowing seawater, tidal immersion, and atmospheric exposure. Mechanical property tests of the composite material were performed prior to and after marine environment exposure. Analysis of test results were performed to correlate type and degree of corrosion attack with the residual mechanical properties of the composite.

BACKGROUND

A recent review of results of corrosion tests of graphite/aluminum has been prepared by Pfeifer[1]. This review detailed the results of corrosion exposures of T-50/Al 6061 in 3.5% NaCl and distilled water, T-50/Al 201 and T-50/Al 202 panels exposed to the marine atmosphere, Gr/Al 202 with Al 1100 interlayer foils exposed to the marine atmosphere and alternating immersion in laboratory seawater, and T-50/Al 201 with 6061 with various combinations of alloy foils including 1100, 2024, 3003, 5056, and 6061 exposed in the marine atmosphere, alternate seawater immersion, salt spray and relative humidity cabinets. The summary of the corrosion exposures as discussed by Pfeifer[1] suggested that the mode of corrosion observed with graphite/aluminum composites was predominantly pitting and severe exfoiliation. Metal/matrix interfaces were found to limit corrosion resistance and both chemical and mechanical factors contributed to corrosion. As expected, the aluminum alloy composition affected corrosion resistance, particularly when comparing the Al 6061 matrix and Al 201 matrix alloys. Finally, it was found that corrosion behavior of graphite aluminum panels were quite sensitive to fabrication process and efficiency. To date there have been no controlled experiments to evaluate the residual mechanical properties of graphite/aluminum composites.

The results of the corrosion evaluation performed to date were employed in the design of this experimental program. Specifically, Al 6061 was chosen as both a matrix and foil cladding material in order to provide some inherent corrosion resistance. Extensive NDE was performed to eliminate (as much as possible) material produced with consolidation defects. Finally, mechanical property tests were performed before and after marine exposure to determine extent of latent environmental effects, as well as quantify the degree of degradation caused by the environment.

MATERIAL

The metal matrix composite plates used in this investigation were produced from pitch-based VSB-32 fibers and a matrix of 6061 aluminum alloy. The VSB-32 fibers were supplied by Union Carbide Corporation and displayed typical properties as follows:

Tensile Strength	1720 MPa
Young's Modulus	3.8×10^5 MPa
Fiber Diameter	7-11 Mm
Numbers Fiber/Tow	2000

The fiber tows were coated with a TiB layer which was used to promote wetting during the subsequent liquid metal infiltration process. The infiltrated fiber tows appeared as aluminum wires which typically has 45 volume percent fiber as supplied by Materials Concept Inc. DWA Composites Specialties Inc. then diffusion bonded the infiltrated wires between surface foil claddings to produce the metal matrix plates.

The graphite/aluminum plates used in this investigation were produced in two configurations. The standard plates consisted of three uniaxial layers of wires between 0.15 mm thick Al 6061 surface foils which resulted in plate thicknesses ranging from 1.8 to 1.9 mm. Figure 1 is a photomicrograph of a typical corss section of the standard material. Encapsulated plates were also produced with three uniaxial layers of wire between 0.15mm thick surface foils. However, additional foils were wrapped around the wires to reduce the fiber volume and increase the transverse strength of the composite. Figure 2 is a photomicrograph of the encapsulated composite material, which was produced in thicknesses of 2.0 to 2.1 mm. A total of 8 panels of both types of composite plates were produced with planar dimensions of 216 mm x 216 mm.

EXPERIMENTAL PROCEDURES

Marine Corrosion Exposures

The marine corrosion exposures were accomplished by removing panels from the composite plates and exposing them to three types of environments for varying lengths of time. Separate specimens were exposed in each environment for corrosion characterization and residual mechanical property measurements. The planar dimensions of the two types of specimens were as follows:

Corrosion Panels	101 x 67 mm
Residual Mechanical Property Panels	101 x 101 mm

The graphite/aluminum composites were exposed with and without edge protection. Edge protection consisted of a continuous bead of RTV compound applied to the edges of selected panels.

All panels were exposed to one of three marine environments at the LaQue Center for Corrosion Technology, Wrightsville Beach, North Carolina, USA. The environments included:

(1) Complete submergence in natural, flowing seawater (0.6-0.9 m/S);
(2) Alternate immersion in tidal zone;
(3) Marine atmospheric exposure, 25 meters from the ocean.

Separate panels of both types of composite were removed for corrosion evaluation and residual mechanical property tests after 6 and 12 week exposures. Control panels of 6 mm thick 6061-T6 Aluminum plate were also exposed to the three marine environments for 6 and 12 weeks.

Residual Mechanical Properties Testing

Longitudinal and transverse tensile strength and Young's modulus were determined for the baseline and exposed plates using a standard Instron Universal testing machine. The exposed plates were nominally 100 mm square and the tensile samples were prepared from these panels according to the geometry shown in Figure 3. The longitudinal samples were 9.5 mm wide by the full length of the plates and the transverse samples were typically 38-75 mm long by 12 mm.wide. Both types of samples were the full thickness of the composite plates. In some instances, particularly when the plate edges were left unprotected, swelling at the edges required removal of a small amount of material. This is indicated by "edge corrosion" on Figure 3. Unless an excessive amount of material had to be removed from the edges, four longitudinal and five transverse samples were prepared from each plate. The samples were usually prepared by shear cutting. However, corrosion of the standard composite after the 12 week flowing seawater exposure was too severe to allow shearing and samples from these plates were prepared by hand sawing and carefully filing the edges smooth.

One mm. thick aluminum tabs were bonded to each side of the sample end in order to minimize stress concentrations at the testing machine grips. Despite the tabs, many of the longitudinal samples fractured near or within the grips. However, no correlation could be made between the fracture location and tensile strength.

Strain measurements for the Young's modulus calculations were made with a 13 mm gauge length clip-on electrical extensometer. Residual stresses which result from the composite processing were removed by loading the sample to 50% of their anticipated maximum load, unloading to 5% of maximum, and then reloading to failure. The load-extension curve obtained during reloading was used to determine the material's modulus in the absence of residual stresses.

Fatigue Testing

The fatigue testing of the standard graphite/aluminum composite was performed on a SONNTAG SF-IU test machine, at a test frequency of 30 Hz. The fatigue specimens, shown in Figure 4, were axially loaded with a stress ratio of 0.05. Specimens were aligned using grips with a coupling of low melting temperature metal which was melted before specimen setup, then cooled after setup for the fatigue test. Specimen failure was defined as complete separation, and specimens which remained intact for more than 5×10^7 cycles were removed and designated as runouts.

The fatigue tests were performed in air and seawater. The former environment was laboratory air, approximately 24°C and 50% relative humidity. The application of seawater was accomplished by mounting a 50 ml plastic cup around the fatigue specimen test section. This reservoir was filled with natural seawater from the LaQue Center for Corrosion Technology, and the water was changed daily throughout the fatigue tests.

RESULTS AND DISCUSSION

Corrosion of Graphite/Aluminum Composites

All of the panels which were exposed to marine environments were subjected to corrosion analysis. This included the panels employed in the residual mechanical properties analysis as well as the corrosion test panels. The usual practice of describing corrosion behavior is to report weight loss, thickness reduction, and depth of pitting attack. Due to the nature of the attack observed with these composites, such descriptions were inapplicable. For example, most of the graphite/aluminum composites experienced weight gain from the oxide formed and trapped during the corrosion process. The analysis used herein will be in the form of qualitative descriptions of the corrosion and pitting behavior.

The corrosion behavior exhibited by the exposed panels is described according to five different types of attack observed in these tests. These include:

(a) Slight and incipient pitting;

(b) Pitting of surface foils;

(c) Slight blistering of surface foils;

(d) Blistering of surface foils;

(e) Edge separation of matrix, fiber and foils;

(f) Uniform edge corrosion

All types of observed corrosion attack are illustrated schematically in Figure (5), and these descriptions are included in the tabulations of corrosion test results to be presented in the following sections.

Corrosion of Graphite/Aluminum in Flowing Seawater

The results of the corrosion tests of both types VSB-32/Al 6061 composites in flowing seawater are shown in Table 1. The extent of corrosion attack experienced by the standard and encapsulated composites after six weeks exposure to flowing seawater was related to the edge protection provided each panel. When a good sealant was maintained as shown in Figure 6, no edge corrosion or blistering occurred, and the panels experienced only slight surface pitting. This pitting is typical of 6061 aluminum alloys and similar to that seen with the control exposures, Figure 7. This behavior was related to all six week exposure panels with edge protection with one exception (AC-1). In this case, a small failure of the sealant compound resulted in intrusion of seawater to the edge which caused edge attack and blistering. Panels exposed without edge protection experienced edge attack and blistering along the fiber path, Figure 6.

Both types of panels exposed for twelve weeks in flowing seawater displayed substantially different behavior than the six-week exposures. The twelve-week exposure panels displayed pitting attack as shown in Figure 8 which pierced the surface foils and allowed seawater to come in contact with the graphite/aluminum interfaces. When this situation occurred, the aluminum corrosion product blistered the composite and exposed more matrix for corrosion attack as the corrosion process progressed from the pit. Figure 9 is a photomicrograph of a typical blister. This form of corrosion attack was not related to the edges of the panels as both the protected and unprotected panels experienced similar corrosion attack.

Corrosion of Graphite/Aluminum under Alternate Tidal Immersion

Table 2 presents results of the corrosion analysis of VSB-32/Al 6061 composites exposed to the tidal zone environment. All of the standard and encapsulated specimens experienced similar corrosion except for the effects of edge protection. The surface of the panels had incipient to light pitting as shown in Figure 10 with some pits causing small blisters as seen in the flowing seawater exposures. The edges of the corrosion panels which were protected did not experience any corrosion where the protective compound remained intact. Two panels (AB-3 and AF-3) did experience some edge attack due to bond failure of the sealant. The panels without any edge protection suffered slight to moderate edge corrosion. The encapsulated panels appeared to have slightly greater resistance to edge corrosion which is likely the result of the greater volume of aluminum in the matrix. Interestingly, the tidal environment did not show a clear exposure time dependence, and proved to be the least aggressive marine environment included in this test program.

Corrosion of Graphite/Aluminum in the Marine Atmosphere

Results of the corrosion exposures of the VSB-32/Al 6061 composites in the marine atmsophere are shown in Table 3. The surfaces of the standard and encapsulated panels experienced incipient to light pitting with some slight blistering around the pits as shown in Figure 11 (for standard material). This is typical for the 6061 aluminum alloy as shown in Figure 7. The panels with edge protection were free of edge corrosion. The panels exposed to the marine atmosphere without edge protection experienced edge corrosion which was usually severe enough to cause separation.

The twelve-week exposure panels with edge protection, Figure 11, did not appear significantly different from similar six week exposures as shown in Figure 12. The twelve week exposures without edge protection displayed advanced edge attack, Figure 11. This attack appeared to accelerate with time, indicating that the process would most probably continue until all of the aluminum matrix was oxidized.

Summary of Corrosion Exposures

The results of the corrosion exposures performed in this program show that the overall performance of the composite reflects both the performance of the graphite/aluminum substrate and the performance of the surface foils. The dominant factor in the corrosion of VSB-32/Al 6061 appears to be the galvanic cell between the graphite and aluminum with a driving force of 1.0 to 1.2 volts.[2] As long as the surface foils of the composite prevent matrix invasion, the corrosion performance was equivalent to that of the surface foils. After matrix invasion occurred, the galvanic couple was activated, and accelerated corrosion took place. The corrosion attacked both the matrix material and the matrix/foil interface, and was seen to be assisted by the production of corrosion products. There was a slight difference in the behavior of the two variations of graphite/aluminum tested due to the difference in fiber loading of the composites. However, there was no difference in inherent corrosion mechanism when comparing the standard and encapsulated materials.

Three different marine environments were included in this program. Regarding performance of the surface foils, the flowing seawater was the most aggressive, while the tidal immersion and atmospheric exposures were similar in pitting performance, but less aggressive than the flowing seawater. Where matrix invasion occurred, and free edges were exposed, the marine atmsophere and the flowing seawater were the most severe environments, and the tidal exposure resulted in a substantially decreased level of corrosion.

Residual Mechanical Properties

The purpose of the residual mechanical property tests was to evaluate possible latent effects of the marine environments on the mechanical properties of the VSB-32/Al 6061 composites. Due to the variation of fiber volume, and consolidation differences inherent in the batch processing of composite wire and plate, the mechanical properties of the unexposed plates varied not only from plate to plate, but also within each plate. Therefore, small changes in residual mechanical properties could be related to inherent material scatter, as well as effects of environmental exposures. In this context, it should be noted that a total of 24 individual panels were exposed for various durations in the three marine environments and subsequently used for post-exposure mechanical property tests. Only one panel of each type of VSB-32/Al-6061 composite was employed in evaluating mechanical properties prior to exposure.

Table 4 is a summary of the mechanical property test results from both types of graphite/aluminum composites where tests were performed in the as-received, unexposed condition. These tests show that the standard composite displays superior longitudinal strength and modulus when compared to the encapsulated composite. This clearly reflects the higher fiber volume loading of the standard material. On the other hand, the transverse tensile strength of encapsulated composite is superior as expected; again because of the difference in fiber loading (Table 4).

The residual tensile strength test results for all corrosion exposures of the standard VSB-32/Al 6061 composite are plotted in Figure 13, while similar data is presented for the encapsulated composite in Figure 14. In most cases, the data points presented in Figure 13 and 14 are the average of five tensile tests with specimens removed in such a way as to exclude material with obvious corrosion attack, except for surface foil pitting.

The results of residual mechanical property tests of the standard graphite/aluminum composite shown in Figure 13 suggests that there was no significant deleterious effect of any of the marine environments provided no evidence of corrosion attack was observed. The average tensile strength data for all exposures, (except twelve week tests in flowing seawater) fell in the range of 550-670 MPa. This range compared favorably with the data from the unexposed panel, and was consistent with the scatter inherent in the mechanical properties of these materials. In general, a tensile strength degradation on the order of 10-15% occurred in all environments for which specimens without visible corrosion attack could be tested. This is a reflection of the effects of the incipient/light pitting which occurred in all test environments.

Figure 13 also includes two other data points which were the average of tests performed on tensile specimens which had visible corrosion damage such as blistering or foil delamination. These specimens experienced twelve weeks of exposure in flowing seawater. These data show that after the matrix was invaded and corrosion occurred, there was a substantial decrease in average tensile strength. The order of this decrease reflects the severity of corrosion attack in the matrix of the standard composite material.

The residual mechanical property test results for the VSB-32/Al 6061 encapsulated composite are shown in Figure 14. All data points are average values for tensile tests performed with specimens displaying no visible corrosion damage. These data agree with the trends developed with the standard composite in that there was only slight degradation of tensile properties resulting from marine environment exposures. All data points are lower than for the standard composite because of the lower fiber loading of the encapsulated plates. The three lowest points in Figure 14, which occurred in the twelve week tidal and marine atmosphere exposures, were all developed from the same plate of material. This suggests that inherently lower mechanical properties were responsible for the results rather than effects of the environmental exposures.

The results of the residual mechanical property tests with the VSB-32/Al-6061 composites indicate that there are no latent effects with any of the marine environments which result in severe degradation of tensile properties in the case where no visible corrosion attack is evident. In the case where corrosion attack has occurred as evidenced by severe pitting, blistering and foil delamination, the composites displayed substantial reduction in tensile strength. This reduction was in response to the vigorous attack of the 6061 aluminum matrix and the matrix foil interface separation.

Fatigue of Standard VSB-32/Al 6061 Composite

The results of fatigue tests performed in air with the VSB-32/Al 6061 standard composite are plotted in Figure 15. This figure also includes similar data for 5 mm diameter Al 6061-T635 bar[3] as well as B/Al 6061 unidirectional composite[4,5]. The results indicate that the graphite/-aluminum composite shows improved fatigue properties over wrought Al-6061-T635, as observed in a previous investigation of fiber reinforced metals[4]. The graphite/aluminum fatigue strength at 5 x 10^7 cycles was over twice that of Al6061-T635 bar, reflecting the fact that the fibers are the load bearing members in the composite. It can also be seen that the slopes of the fatigue curves of VSB-32/Al 6061 and Al6061-T635 bar are similar, suggesting that the matrix material controls the actual fatigue failure mechanism in the composite. This is consistent with the observations of Lynch and Kershaw in evaluating the fatigue performance of B/Al 6061 composite[4]. Figure 15 also shows that the fatigue strength of VSB-32/Al 6061 is comparable with that of B/Al 6061[4,5]. This is further illustrated in Figure 16 which shows the fatigue data for VSB-32/Al 6061 and B/Al 6061 composites and Al-6061-T635 bar normalized with respect to ultimate tensile strength. This figure shows that the fatigue strength of the graphite/aluminum composite increases with ultimate strength, suggesting that this composite is not fatigue strength limited.

The results of fatigue tests performed in air and natural seawater with VSB-32/Al 6061 standard composite are shown in Figure 17. Data from air and saltwater tests performed on 13 mm diameter Al 6061-T6 bar is included in Figure 17. The Al 6061-T6 data was from rotating cantilever tests (R=-1) and xial equivalent stresses (R=0) shown in Figure 17 were calculated using the Goodman expression. These data indicate the deleterious effect of saltwater on fatigue properties in Al 6061-T6 was also present in the seawater fatigue performance of the VSB-32/Al 6061 composite. The degradation in fatigue properties of the composite was not as severe as in the Al 6061-T6. The respective shapes of the saltwater fatigue curves indicates that the corrosion fatigue bahavior of the composite is similar to that of the wrought plate. However, the fibers attenuate the environment effects on the fatigue life of the composite.

CONCLUSIONS

The objective of this investigation was to characterize marine corrosion and fatigue performance of two similar type of graphite/aluminum composite materials. A key element in the corrosion investigation was an evaluation of the residual mechanical properties of the composite in response to environmental exposure. The following conclusions are suggested by the results of marine exposures and tests performed in this investigation:

- The overall corrosion performance of the VSB-32/Al 6061 composite reflects both the performance of the surface foils and that of the graphite/aluminum substrate;
- The dominant factor in the corrosion of the standard and encapsulated composites was the galvanic driving froce between the VSB-32 fibers and the Al 6061 matrix;
- The encapsulated composite was slightly more resistant to corrosion attack, but the corrosion mechanisms of both types of composite were similar;
- Where corrosion was not evident, there was no latent effects on residual mechanical properties due to corrosion exposure;
- Visible corrosion damage resulted in significant degradation of residual mechanical properties;
- The fatigue strength of VSB-32/Al 6061 composite increased with fiber strengthening in direct response to the increase in ultimate tensile strength;
- The reduction in fatigue strength of VSB-32/Al 6061 due to sea-water environment was less than the reduction experienced with aluminum 6061-T6 plate.

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TABLE 1

CORROSION EXPOSURE RESULTS FOR VSB-32/6061
ALUMINUM IN FLOWING SEA WATER

STANDARD

Specimen Number	Length of Exposure (weeks)	Edge Protection (yes or no)	Visual Observation surface	edge
AB-1	6	yes	SP	N
AB-2	6	no	P, B	E, corr
AC-1	6	yes	B	E
AC-2	6	no	B	E, corr
AE-3	12	yes	P, B	N
AE-4	12	no	P, B	E, corr
AF-1	12	yes	P, B	E, corr
AF-2	12	no	P, B	E, corr

ENCAPSULATED

Specimen Number	Length of Exposure (weeks)	Edge Protection (yes or no)	Visual Observation surface	edge
BA-1	6	yes	SP	N
BA-2	6	no	P, B	E, corr
BB-1	6	yes	SP	N
BB-2	6	no	B, P	E, corr
BA-3	12	yes	B, P	N
BA-4	12	no	B, P	E, corr
BF-1	12	yes	B, P	E
BF-2	12	no	B, P	E, corr

N - No visible attack

SB - Slight Blistering; B - Blistering

SP - Slight or incipient Pitting; P - Pitting

corr - general corrosion; E - edge separation

TABLE 2

CORROSION EXPOSURE RESULTS FOR VSB-32/6061 ALUMINUM IN ATMOSPHERE

STANDARD

Specimen I.D.	Length of Exposure (weeks)	Edge Protection (yes or no)	Visual Observation surface	edge
AA-3	6	yes	SP	N
AA-4	6	no	P	E, corr
AB-5	6	yes	P	N
AB-6	6	no	P	E, corr
AE-1	12	yes	SP	N
AE-2	12	no	SP	E, corr
AF-5	12	yes	P	N
AF-6	12	no	P	E, corr
ENCAPSULATED				
BB-5	6	yes	SP	N
BB-6	6	no	SP	corr
BC-3	6	yes	P, SB	N
BC-4	6	no	P, SB	corr
BE-3	12	yes	SP	N
BE-4	12	no	SP	E, corr
BF-5	12	yes	P, SB	N
BF-6	12	no	P, SB	E, corr

N - No visible attack

SB - Slight Blistering; B - Blistering

SP - Slight or incipient pitting; P - Pitting

corr - general corrosion; E - edge separation

TABLE 3

CORROSION EXPOSURE RESULTS FOR VSB-32/6061
ALUMINUM IN THE TIDAL ZONE

STANDARD

Specimen I.D.	Length of Exposure (weeks)	Edge Protection (yes or no)	Visual Observations surface	edge
AA-1	6	yes	SP	N
AA-2	6	no	SP	corr
AB-3	6	yes	P	corr
AB-4	6	no	P	corr
AC-3	12	yes	SP	N
AC-4	12	no	SP	E, corr
AF-3	12	yes	P, SB	corr
AF-4	12	no	SP	corr

ENCAPSULATED

Specimen I.D.	Length of Exposure (weeks)	Edge Protection (yes or no)	Visual Observations surface	edge
BB-3	6	yes	SP	N
BB-4	6	no	SP	corr
BC-1	6	yes	SP	N
BC-2	6	no	SP	corr
BE-1	12	yes	SP	N
BE-2	12	no	SP	N
BF-3	12	yes	P, SB	N
BF-4	12	no	P, SB	N

N - No visible attack

SB - Slight Blistering; B - Blistering

SP - Slight or incipient pitting; P - Pitting

corr - general corrosion; E - edge separation

TABLE 4

MECHANICAL PROPERTIES OF VSB-32/6061 COMPOSITES

	STANDARD	ENCAPSULATED
Longitudinal Tensile Strength	650 MPa	510 MPa
Longitudinal Modulus	177 GPa	140 GPa
Transverse Tensile Strength	25 MPa	35 MPa
Transverse Modulus	32 GPa	32 GPa
Fiber Content of Plate	40.1%	30.6%

Reported values are the average of five tests

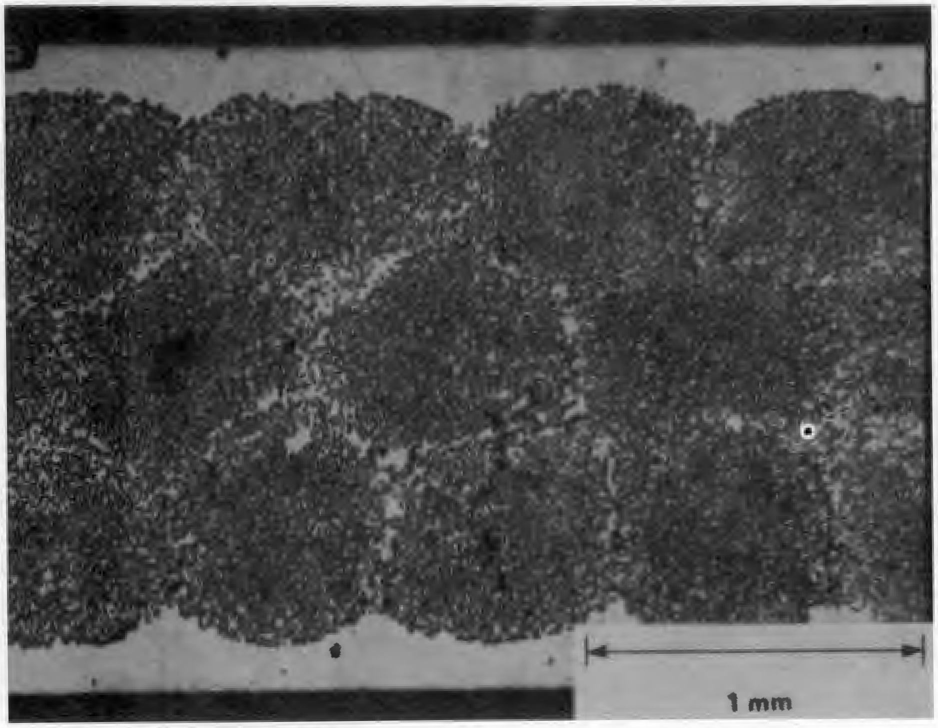


Figure 1. Photomicrograph of Cross Section of Standard VSB-32/Al 6061 Plate

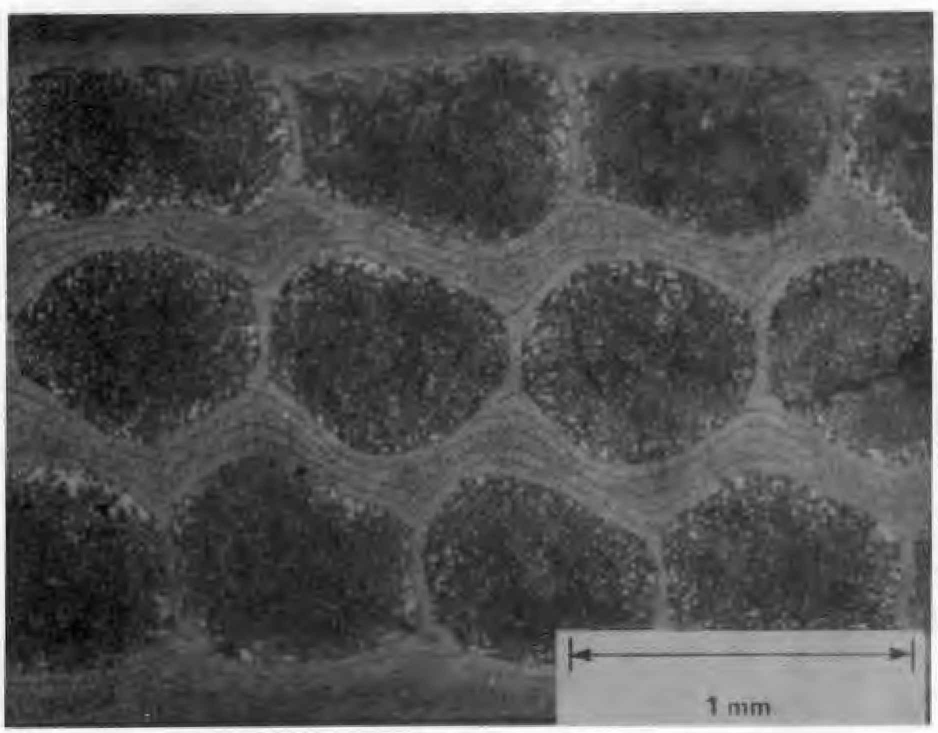


Figure 2. Photomicrograph of Cross Section of Encapsulated VSB-32/Al 6061 Plate

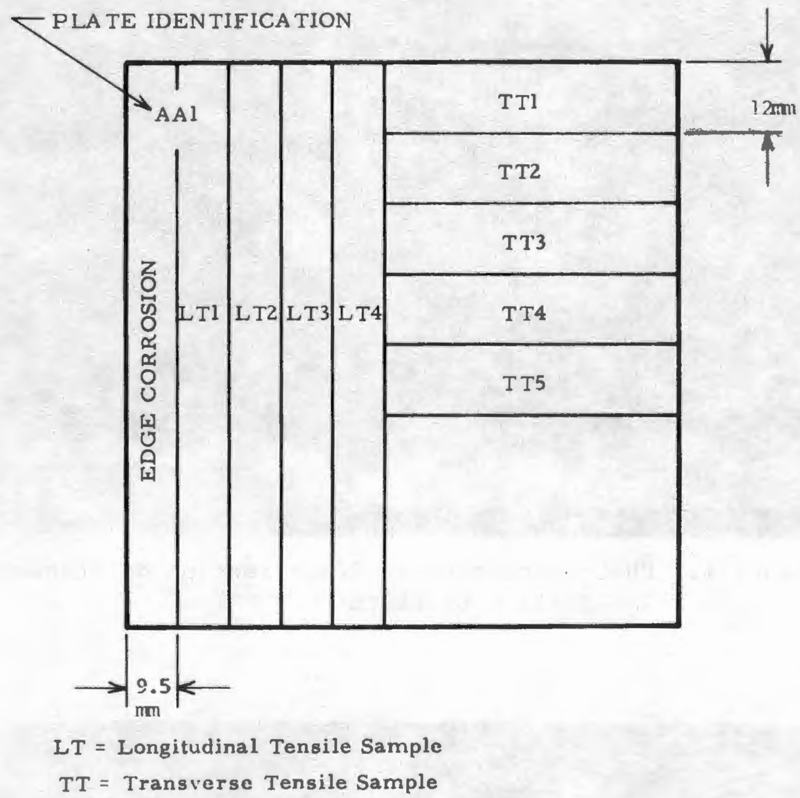


Figure 3. Typical Sample Geometry for Exposed Plates

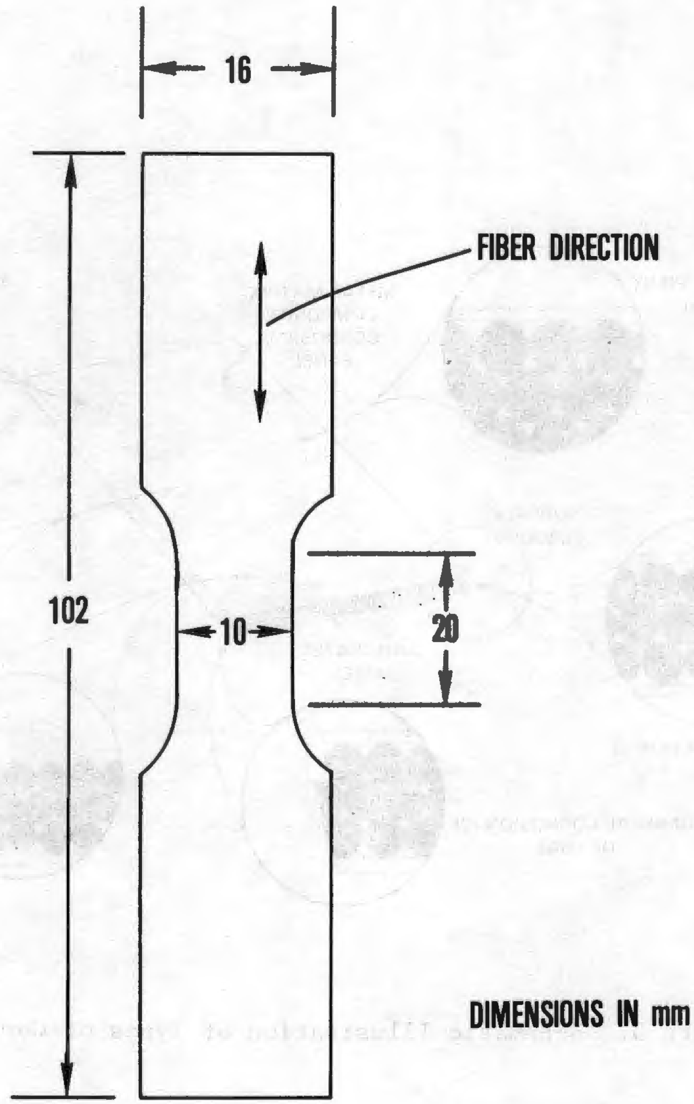


Figure 4. Drawing of Gr/Al Composite Fatigue Specimen

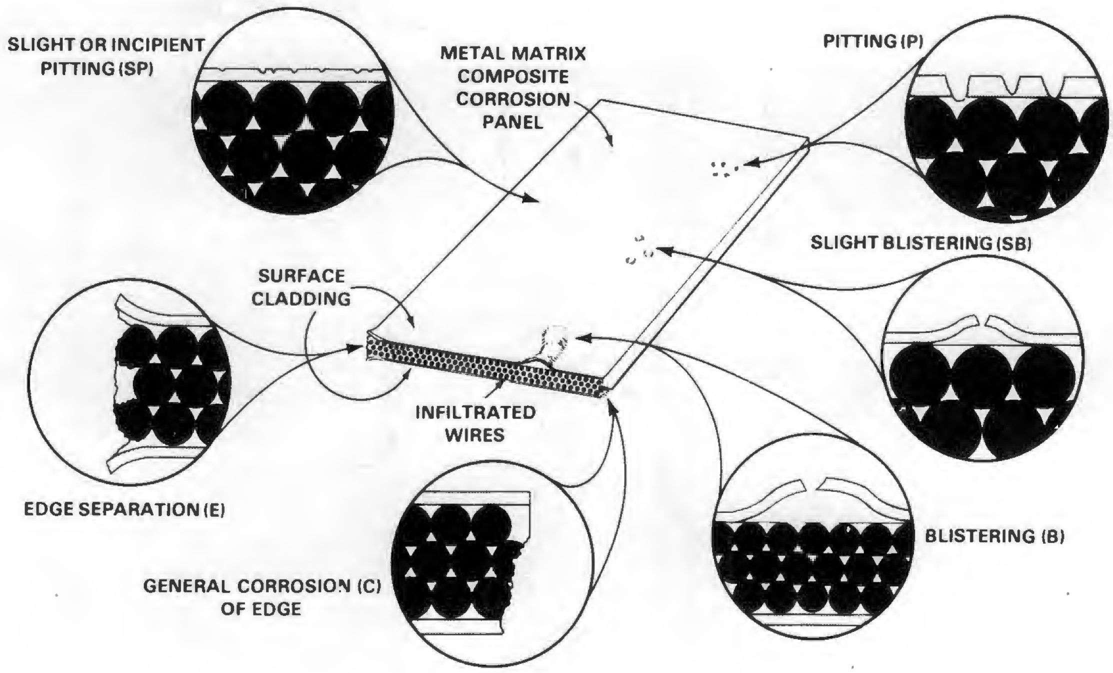


Figure 5. Schematic Illustration of Types of Corrosion Attack

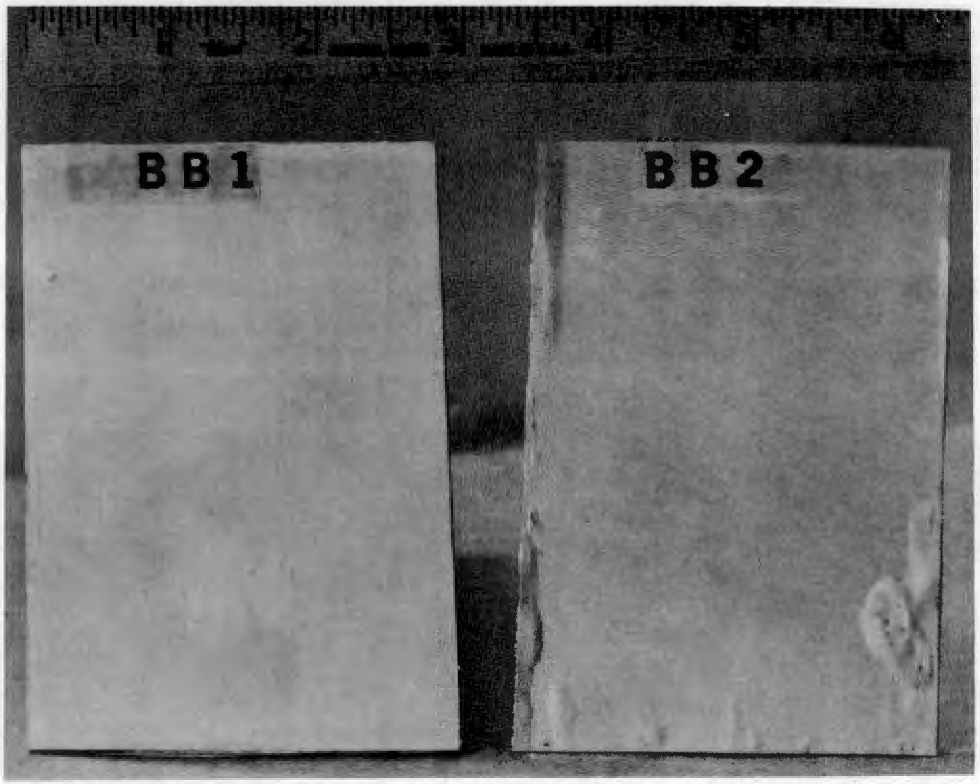
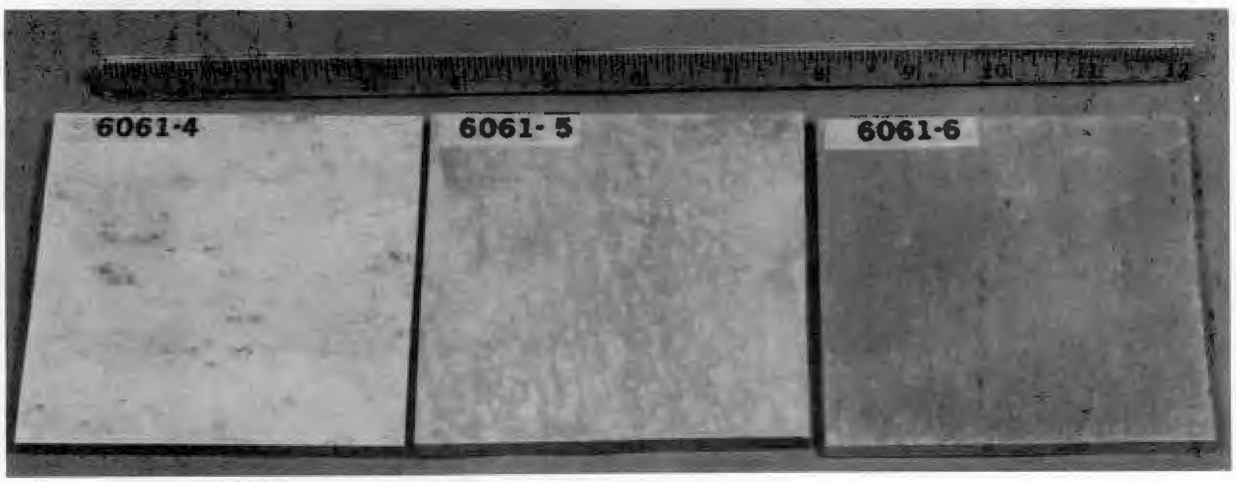


Figure 6. Corrosion Panels of VSB-32/Al 6061 (Encapsulated) After 6 Weeks Exposure to Flowing Seawater

Flowing Seawater | **Tidal Zone** | **Marine Atmosphere**

<u>**6 WEEK EXPOSURES**</u>



Flowing Seawater | **Tidal Zone** | **Marine Atmosphere**

<u>**12 WEEK EXPOSURES**</u>

Figure 7. Corrosion Panels of Aluminum 6061-T6 After 6 and 12 Weeks Exposure

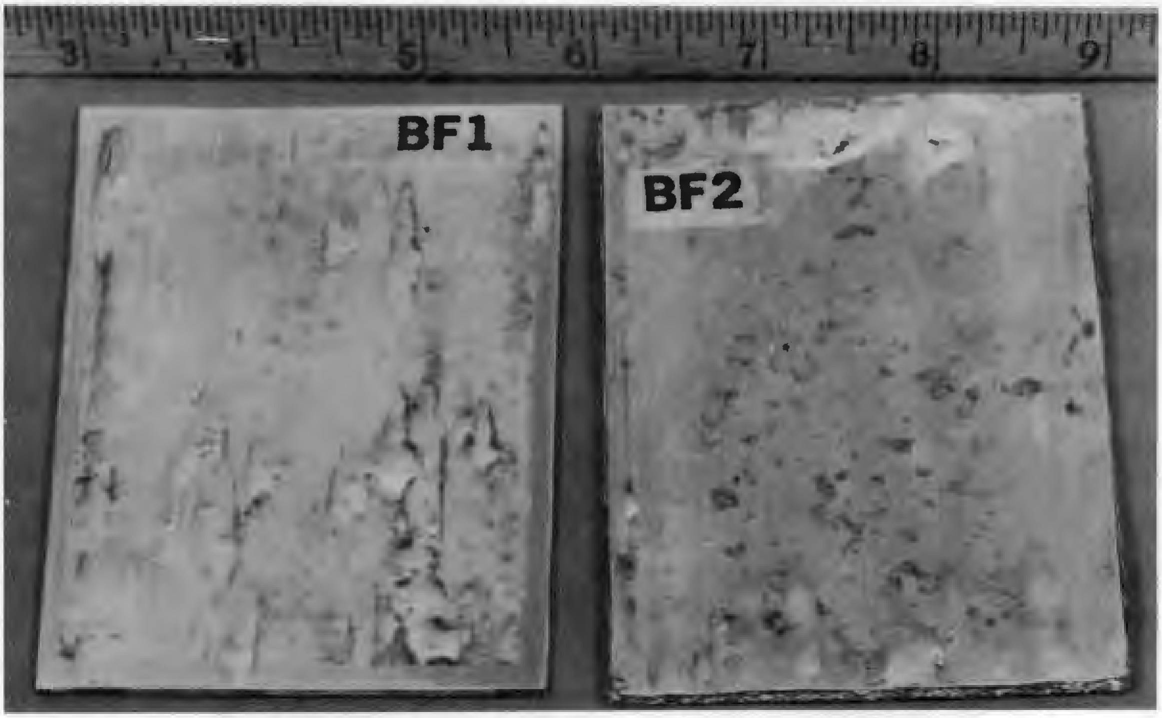


Figure 8. Corrosion Panels of VSB-32/Al 6061 (Encapsulated) After 12 Weeks Exposure to Flowing Seawater

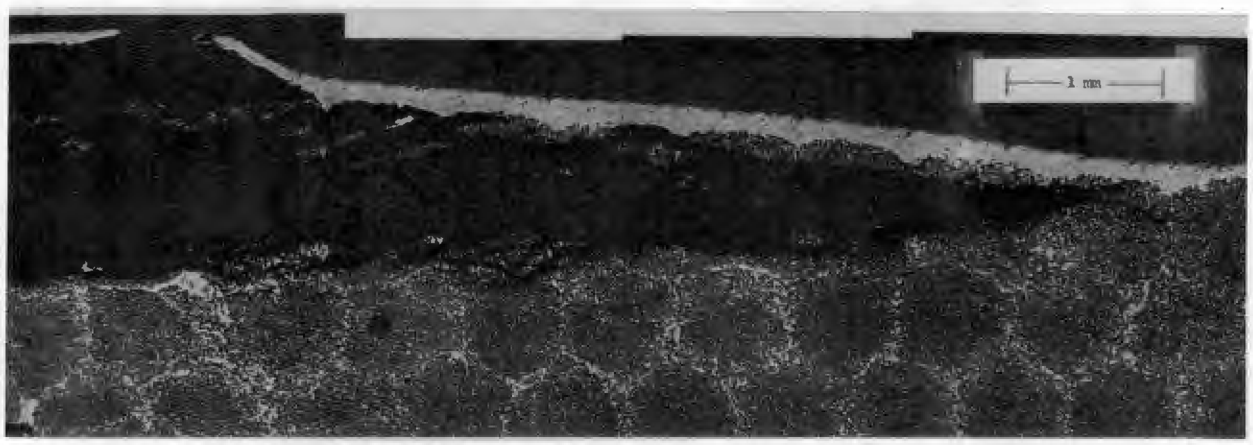


Figure 9. Photomicrograph of Blistered VSB-32/Al 6061 Composite After 12 Weeks Exposure to Flowing Seawater

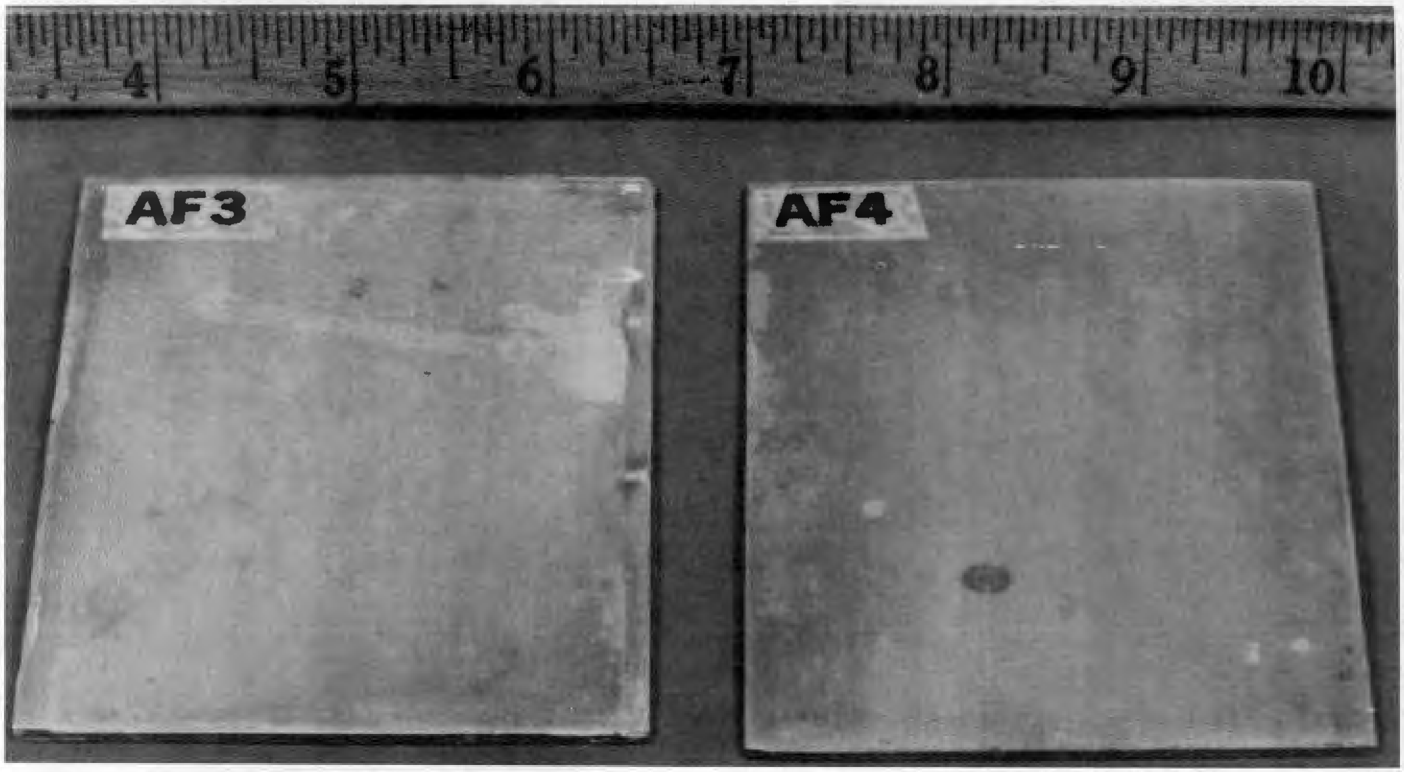


Figure 10. Corrosion Panels of VSB-32/Al 6061 After 12 Weeks Exposure to Tidal Zone Environment

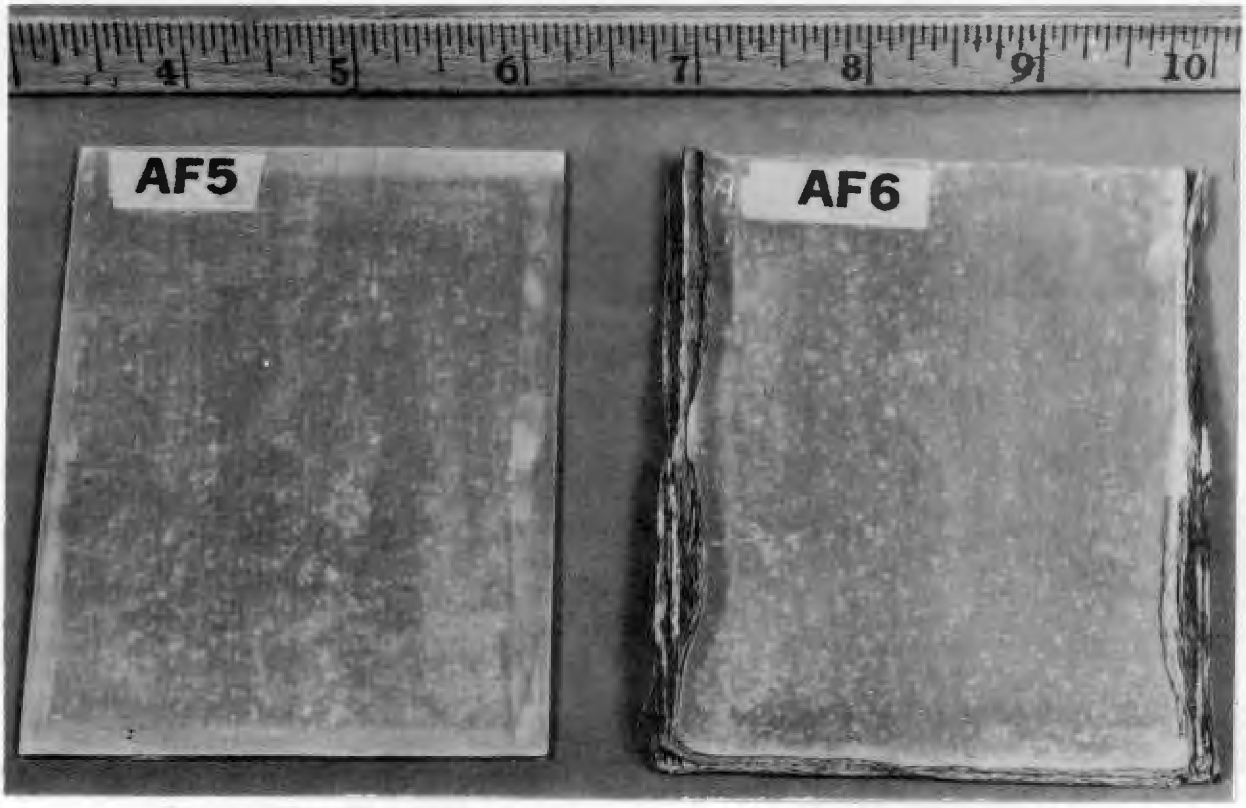


Figure 11. Corrosion Panels of VSB-32/Al 6061 After 12 Weeks Exposure to Marine Atmosphere

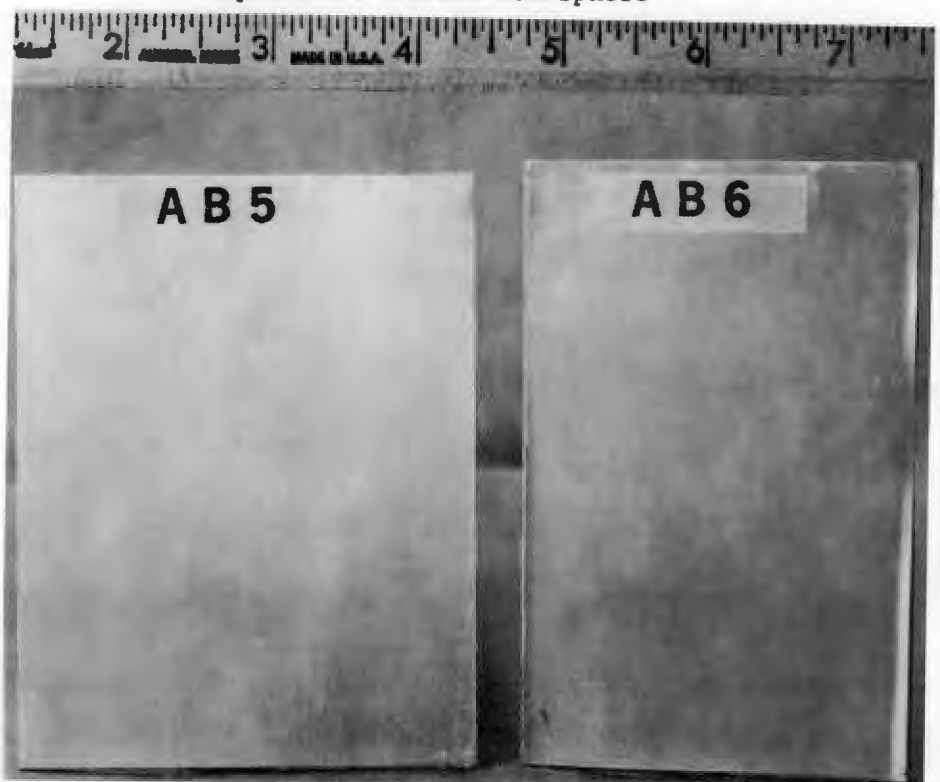


Figure 12. Corrosion Panels of VSB-32/Al 6061 After 6 Weeks Exposure to Marine Atmosphere

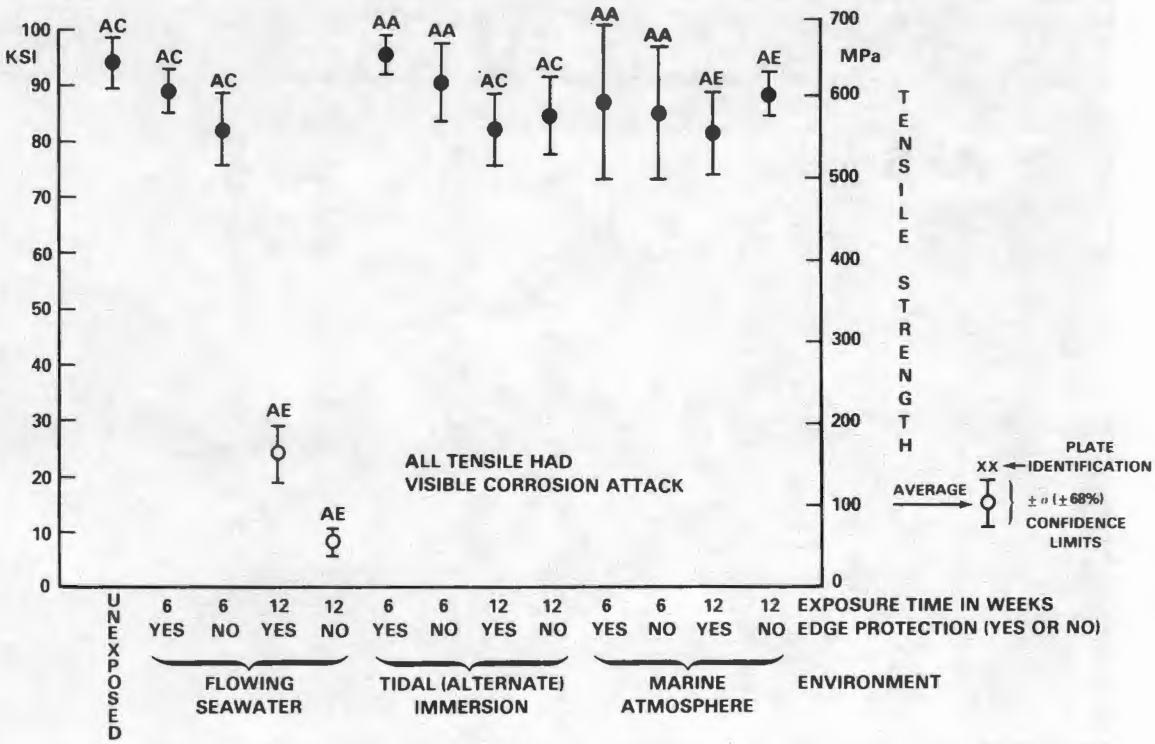


Figure 13. Residual Tensile Mechanical Properties of Standard Gr/Al Composite vs Corrosion Exposures

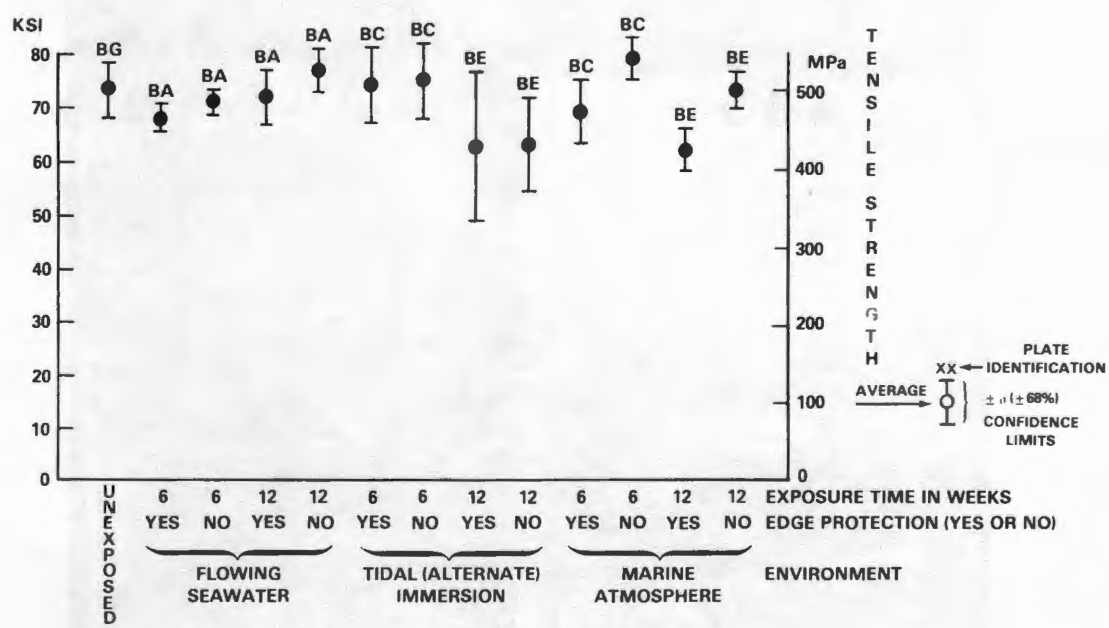


Figure 14. Residual Tensile Mechanical Properties of Encapsulated Gr/Al Composite vs Corrosion Exposures

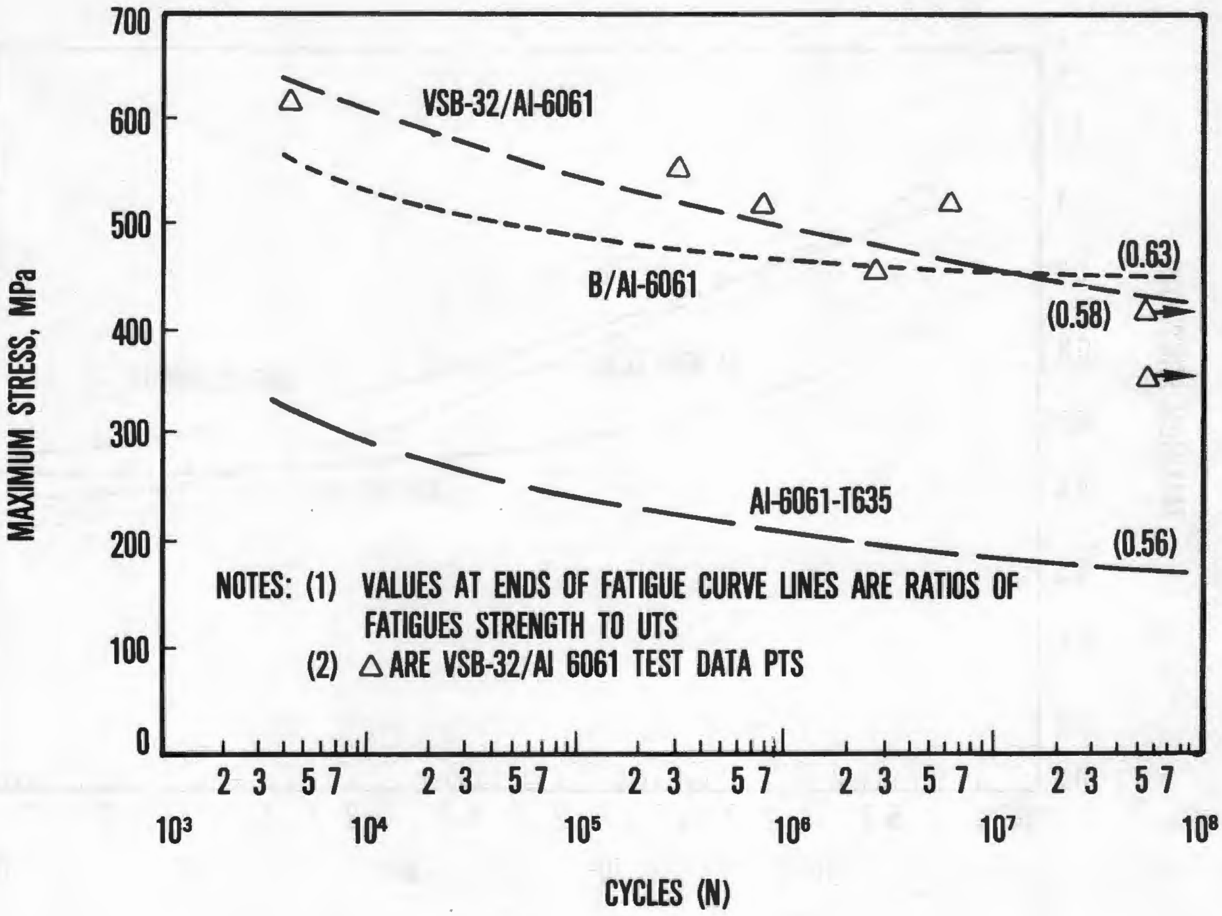


Figure 15. Axial High Cycle Fatigue Results for VSB-32/Al 6061 Composite, B/Al 6061 Composite and 5 mm Diameter Al 6061-T635 in Air

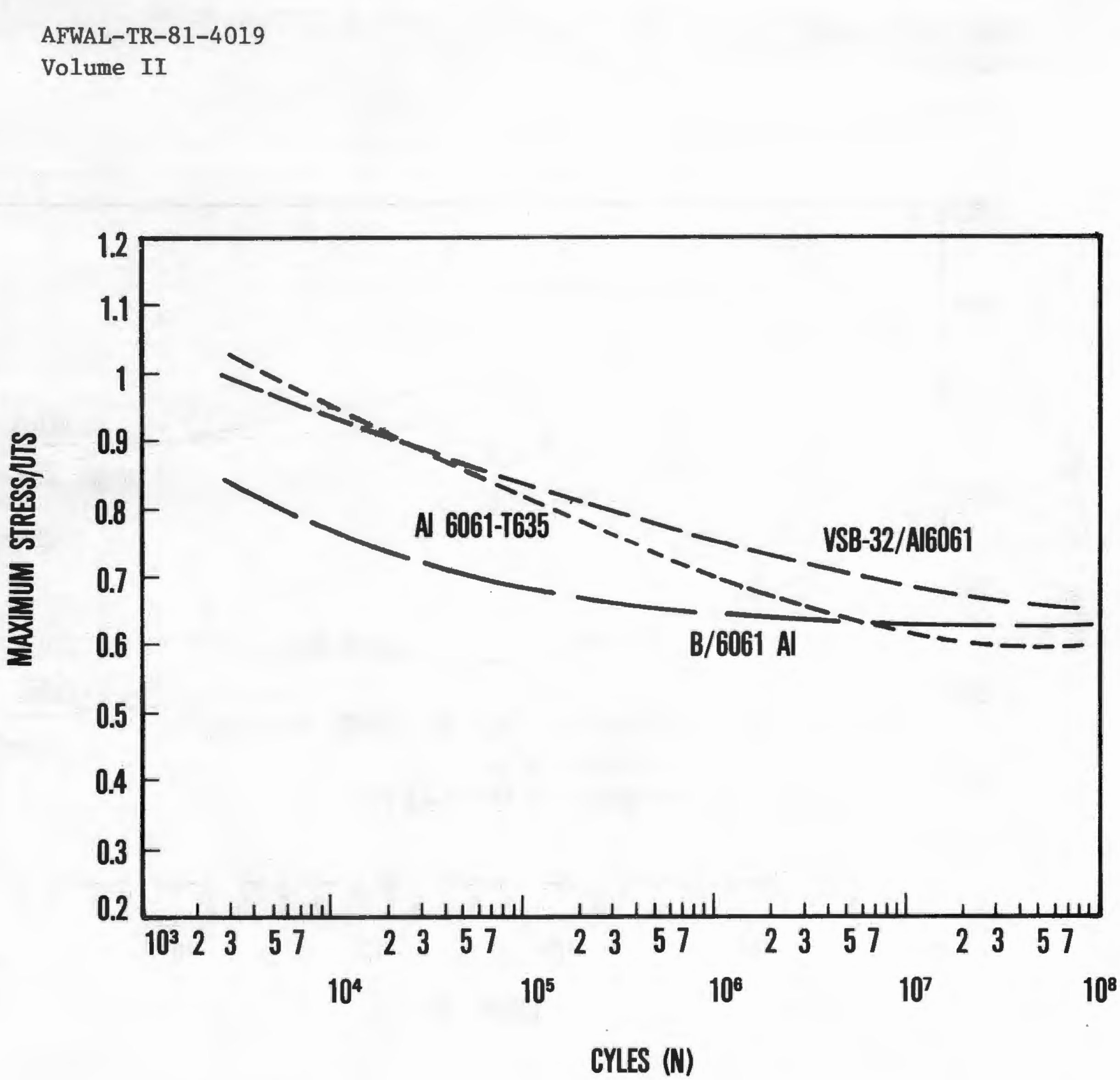


Figure 16. Normalized Axial Fatigue Data for VSB-32/Al 6061 Composite, B/Al 6061 Composite and 5 mm Diameter Al 6061-T635 in Air

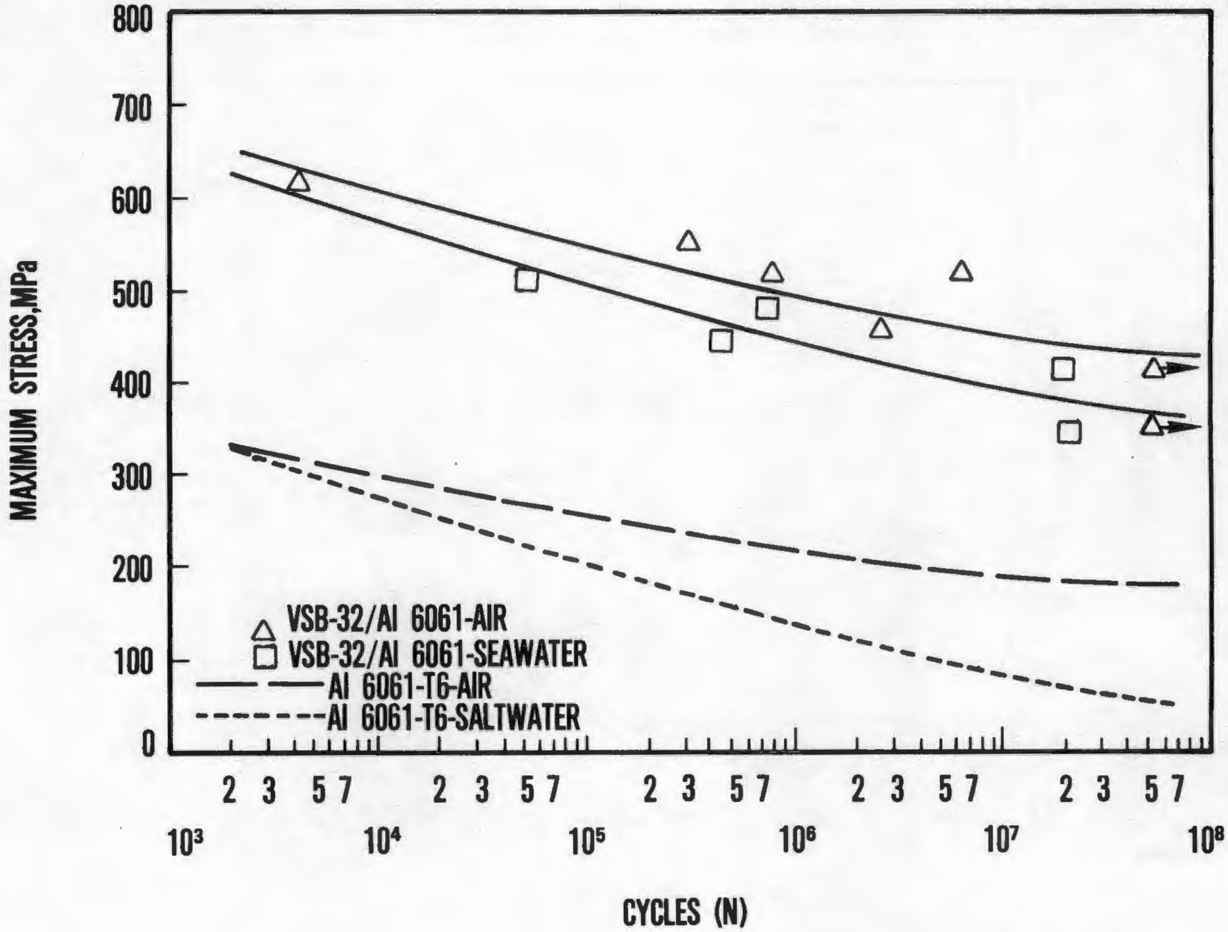


Figure 17. Axial High Cycle Fatigue Data for VSB-32/Al 6061 Composite and Al 6061-T6 Bar in Air and Salt Water