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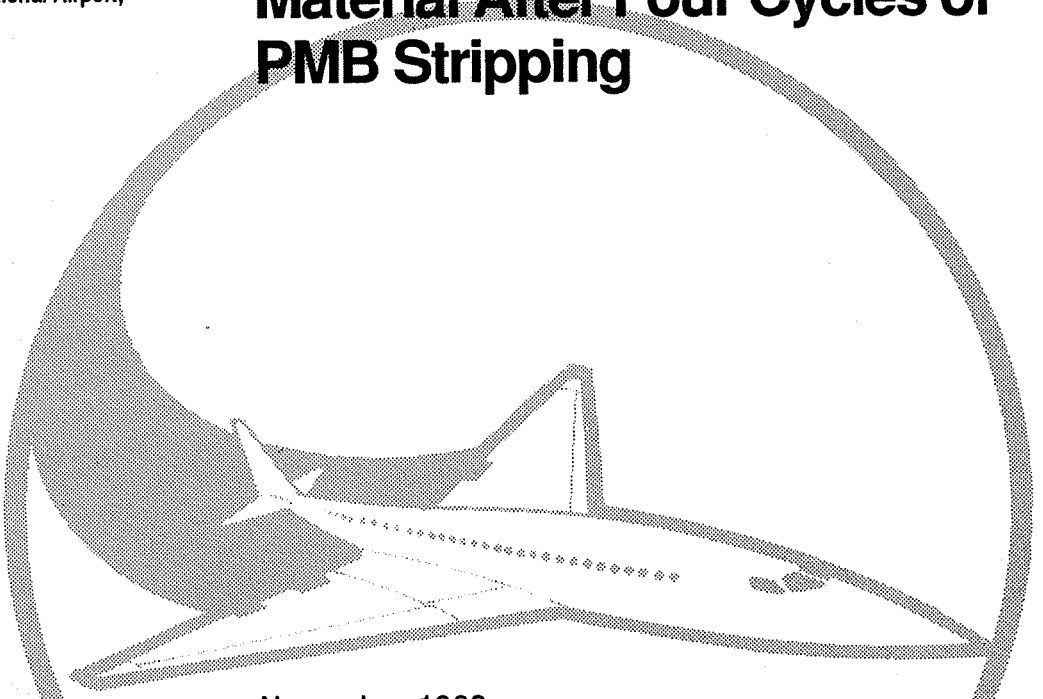
FAA Technical Center
Atlantic City International Airport,
N.J. 08405

Fatigue Testing of 2024-T3 Material After Four Cycles of PMB Stripping



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Final Report

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U.S. Department of Transportation
Federal Aviation Administration

FOREWORD

This report was prepared by Galaxy Scientific Corporation (GSC) under Contract No. DTFA03-89-C-00043 with the Federal Aviation Administration (FAA) Technical Center. Mr. John Reinhardt of the FAA Technical Center acted as Technical Monitor during this project. Ron Galliher of AeroTech Coatings Removal, Inc. conducted the painting, blasting, and Almen strip tests. Jonathan Gadola of GSC conducted the tensile and fatigue tests. Gordon Hayhoe of GSC provided technical guidance in performing the statistical analysis.

TABLE OF CONTENTS

	Page
EXECUTIVE SUMMARY	xiii
1. INTRODUCTION	1
2. BACKGROUND	2
3. TECHNICAL APPROACH	4
3.1 PMB Treatment of Materials	5
3.2 Tensile Tests	5
3.3 Fatigue Test Program	5
4. RESULTS AND DISCUSSION	7
4.1 PMB Treatment of Materials	7
4.2 Tensile Tests	9
4.3 Stress/Cycle Tests	9
4.4 Fatigue Tests	11
5. CONCLUSIONS	15
6. REFERENCES	16

APPENDIXES -

A - Plastic Media Treatment of Material
B - Tensile Tests
C - Fatigue Tests
D - Statistical Methods

LIST OF ILLUSTRATIONS

Figure		Page
1	Almen Strip Measurements	xi
3-1	Overall Description of Anodizedand Alclad Aluminum Test Program	4
4.3-1	S-N Diagram for 2024-T3 Anodized Aluminum	10
4.3-2	S-N Diagram for 2024-T3 Alclad Aluminum	10
4.4-1	Fatigue Life Distributions for Three Thicknesses of "As Received" and PMB Treated 2024-T3 Anodized Aluminum	11
4.4-2	Fatigue Life Distributions for Three Thicknesses of "As Received" and PMB Treated 2024-T3 Alclad Aluminum	12
A-1	Almen Strip Specified Dimensions	A-2
A-2	Almen Strip Test Fixture and Almen Arch Height Gauge	A-3
B-2	Plot of Stress vs. Strain for 2024-T3 Anodized Aluminum Specimen 1	B-2
B-3	Plot of Stress vs. Strain for 2024-T3 Anodized Aluminum Specimen 2	B-2
B-4	Plot of Stress vs. Strain for 2024-T3 Anodized Aluminum Specimen 3	B-3
B-5	Plot of Stress vs. Strain for 2024-T3 Alclad Aluminum Specimen 1	B-3
B-6	Plot of Stress vs. Strain for 2024-T3 Alclad Aluminum Specimen 2	B-4
B-7	Plot of Stress vs. Strain for 2024-T3 Alclad Aluminum Specimen 3	B-4
C-1	Fatigue Test Specimen Dimensions	C-2
C-2	Mounted Fatigue Specimen in Test Machine Grips	C-3
C-3	Material Testing Machine	C-4

LIST OF TABLES

Table		Page
1	Definition of Mesh Size by Particle Diameter	xi
3.1-1	Blast Parameter Specifications	5
4.1-1	Comparison of Average Arc Heights in MILS Obtained for 2024-T3 Anodized Aluminum	8
4.1-2	Comparison of Average Arc Heights in MILS Obtained for 2024-T3 Alclad Aluminum	8
4.2-1	Results of Tensile Tests on "As Received" 2024-T3 Anodized and Alclad Aluminum	9
4.4-1	Summary of Fatigue Data for 2024-T3 Anodized Aluminum	12
4.4-2	Summary of Fatigue Data for 2024-T3 Alclad Aluminum	13
4.4-3	Statistical T-Test and Confidence Intervals Showing Effects of PMB Treatment on 2024-T3 Anodized Aluminum	13
4.4-4	Statistical T-Test and Confidence Intervals Showing Effects of PMB Treatment on 2024-T3 Alclad Aluminum	14
A-1	Media Type	A-1
A-2	Blast Parameters	A-2
A-3	Paint Stripping Rate and Dwell Time for 2024-T3 Anodized Aluminum	A-4
A-4	Virgin Media Particle Size Distribution for 2024-T3 Anodized Aluminum	A-4
A-5	Particle Size Distribution after Four PMB Cycles on 2024-T3 Anodized Aluminum	A-5
A-6	Media Breakdown Rate Calculation after Treatment of 2024-T3 Anodized Aluminum	A-5
A-7	Paint Stripping Rate and Dwell Time for 2024-T3 Alclad Aluminum	A-6
A-8	Virgin Media Particle Size Distribution for 2024-T3 Alclad Aluminum	A-6
A-9	Particle Size Distribution after Four PMB Cycles on 2024-T3 Alclad Aluminum	A-7

LIST OF TABLES (Continued)

Table		Page
A-10	Media Breakdown Rate Calculation after Treatment of 2024-T3 Alclad Aluminum	A-7
A-11	Almen Strip Arc Heights in MILS for 2024-T3 Anodized Aluminum 0.032-inch Thickness	A-8
A-12	Almen Strip Arc Heights in MILS for 2024-T3 Anodized Aluminum 0.040-inch Thickness	A-8
A-13	Almen Strip Arc Heights in MILS for 2024-T3 Anodized Aluminum 0.050-inch Thickness	A-9
A-14	Almen Strip Arc Heights in MILS for 2024-T3 Alclad Aluminum 0.032-inch Thickness	A-9
A-15	Almen Strip Arc Heights in MILS for 2024-T3 Alclad Aluminum 0.040-inch Thickness	A-10
A-16	Almen Strip Arc Heights in MILS for 2024-T3 Alclad Aluminum 0.050-inch Thickness	A-11
B-1	Tensile Test Parameters	B-1
C-1	Fatigue Test Parameters	C-1
C-1A	S/N Fatigue Test Data for "As Received" Anodized	C-5
C-2A	Fatigue Test Data for "As Received" 0.032 Anodized	C-5
C-2B	Fatigue Test Data for "As Received" 0.040 Anodized	C-6
C-2C	Fatigue Test Data for "As Received" 0.050 Anodized	C-6
C-3A	Fatigue Test Data for PMB Treated 0.032 Anodized	C-7
C-3B	Fatigue Test Data for PMB Treated 0.040 Anodized	C-7
C-3C	Fatigue Test Data for PMB Treated 0.050 Anodized	C-8
C-4A	S/N Fatigue Test Data for "As Received" Alclad	C-8
C-5A	Fatigue Test Data for "As Received" 0.032 Alclad	C-9

LIST OF TABLES (Continued)

Table		Page
C-5B	Fatigue Test Data for "As Received" 0.040 Alclad	C-9
C-5C	Fatigue Test Data for "As Received" 0.050 Alclad	C-10
C-6A	Fatigue Test Data for PMB Treated 0.032 Alclad	C-10
C-6B	Fatigue Test Data for PMB Treated 0.040 Alclad	C-11
C-6C	Fatigue Test Data for PMB Treated 0.050 Alclad	C-11

LIST OF ABBREVIATIONS

DPS Dense Particle Separator

EPA Environmental Protection Agency

FAA Federal Aviation Administration

FCP Fatigue Crack Propagation

PMB Plastic Media Blasting

S/N Stress versus Number of Cycles to Failure

GLOSSARY

Almen strip - A strip of metal cut to a specified size, usually 0.75 in x 3.0 in, which is used to measure the intensity of a blast.

Almen arc height - The arc caused by the residual stress imparted to an Almen strip by a blast. It is measured specifically by a dial indicator and is used to quantify the blast intensity. See figure 1.

Blast pressure - The air pressure, measured at the nozzle, used to propel abrasive media at the substrate.

Dwell time - The amount of time that a blast is constantly directed at the same impact point.

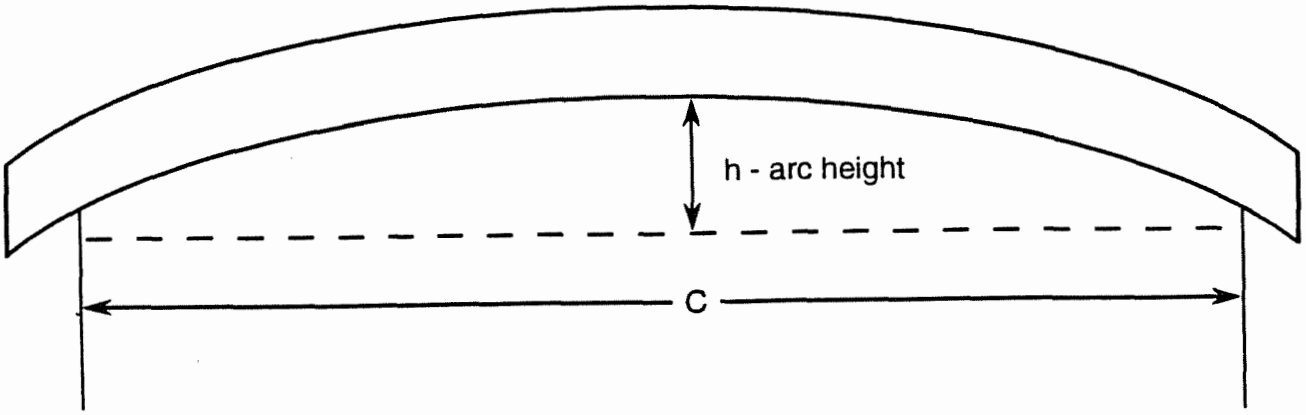
Impingement angle - The angle, measured relative to the blasted surface, at which the blast strikes the surface.

Media - The material used for paint removal due to its impact or abrasive qualities.

Mesh size - The screen size used to define the particle dimensions of the blasting material. See table 1.

Strip rate - The amount of coating/paint removed per unit time.

Substrate - The blasted material.



c = gage length = 2.25 in. (SAE Standard J442)

FIGURE 1. ALMEN STRIP MEASUREMENTS

TABLE 1. DEFINITION OF MESH SIZE BY PARTICLE DIAMETER

U.S. Mesh Size	Particle Diameter (inches)
12-20	0.033-0.067
20-30	0.024-0.033
30-40	0.016-0.024
40-60	0.010-0.016
60-80	0.007-0.010

Note: Table was obtained from reference 1.

EXECUTIVE SUMMARY

The goal of this program was to determine the effect of plastic media blasting (PMB), an alternative to chemical paint removal, on the fatigue life of 2024-T3 aluminum. Two surface treatments, anodized and alclad, and three thicknesses: 0.032 inch, 0.040 inch, and 0.050 inch were considered. A previous study sponsored by the Federal Aviation Administration (FAA) (reference 1) included a test program that focused primarily on the effect of PMB on the fatigue crack propagation (FCP) rates of the aforementioned treated 2024-T3 materials. This effort is a continuation of that program's to obtain data describing PMB's effects on the alloys with the surface treatments and thicknesses described above.

A quantity of alclad and anodized aluminum alloy panels of the specified thicknesses were subjected to four cycles of PMB. The blast parameters were identical to those used in a previous FAA program (reference 1) and Almen strips tests were performed to quantify the blast intensity. The Almen strip test results were compared with those of the previous program, and while differences were observed, these were attributed to variations in Almen strip test results that have been noted in other test programs.

A fatigue testing program was conducted on both the "as received" and the PMB treated material samples. The fatigue life results were then compared to determine whether any observed difference in fatigue lives was statistically significant. Reductions in mean fatigue life were observed for all materials tested after PMB treatment. These reductions were statistically significant for the 0.032 alclad and 0.040 anodized specimens.

1. INTRODUCTION.

The use of plastic media blasting (PMB) as an alternative to chemical removal of paint from aircraft skin has been driven primarily by increasingly stringent Environmental Protection Agency (EPA) regulations on the use and disposal of methylene chloride solvents. There is concern, however, that the use of blasting techniques may adversely affect the mechanical properties of the skin material. A previous study sponsored by the Federal Aviation Administration (FAA) (reference 1) focused primarily on the effect of PMB on the fatigue crack propagation (FCP) rates of thin alclad and anodized 2024-T3 aluminum sheet materials commonly used as aircraft skin. Also investigated were industry specifications for the use of PMB. Data on the specific thicknesses and surface treatments of interest proved to be scarce. Therefore, a limited FCP test program was conducted to provide data for the thicknesses of concern to the FAA, namely, 0.032, 0.040, and 0.050 inch thicknesses. This most recent program is a continuation of the previously referenced effort to obtain data describing PMB's effects on these specific substrates.

The goal of this program was to determine the effect of plastic media blasting on the fatigue life of 2024-T3 aluminum. To achieve this goal the following tasks were conducted:

- Task I - PMB Treatment of 2024-T3 Material - A quantity of anodized and alclad 2024-T3 aluminum panels were subjected to four cycles of PMB utilizing identical blast parameter specifications to those used in reference 1.

- Task II - Conduct Fatigue Testing Program - A fatigue testing program was conducted on both "as received" and PMB treated material.

- Task III - Evaluate Fatigue Test Results - The results of the fatigue testing program were evaluated to determine the effect that PMB had on the fatigue life of the test materials.

This report documents the results of this investigation into the fatigue properties of PMB treated 2024-T3 material. Background information is given on the PMB process, including industry specifications and methods of assessing the process effect on the substrate being stripped. The technical approach used in accomplishing the test program is also presented. The results of the PMB treatment on the test material and the fatigue tests are presented and discussed. Conclusions based on the results of this program are given. The appendices contain raw data, specimen dimensions, and equipment descriptions for the PMB treatment, tensile, and fatigue tests that were performed.

2. BACKGROUND.

The major concern with the use of PMB as an aircraft paint removal method has centered on its effect on the mechanical properties of aircraft skin, such as its fatigue life and fatigue crack propagation rate. It has been determined in previous research (reference 1) that PMB can cause damage by two main mechanisms: surface damage and residual stress. The presence of dense particle contaminants in the media (defined as having a greater specific gravity than the media) can cause pitting of the surface during the blasting process. This pitting has been found to cause decreased fatigue life and accelerated crack growth (references 3 and 4). Aggressive use of even virgin media free of dense particle contaminants can increase the surface roughness of the substrate (reference 1). Both alclad and anodized surfaces can be damaged, with the soft alclad surfaces being deformed and shifted into "peaks and valleys" by the blast. The blast also induces a surface layer of residual compressive stresses that can affect the crack growth rate.

Industry uses various means of measuring and assessing the effects of the blasting process on the substrate being stripped. The method commonly used by industry is the Almen strip test that was originally developed to measure the intensity of shot-peening operations. A piece of substrate material, cut to a specified size (ASTM), is clamped in a holding frame by four bolts and then blasted. The substrate material, known as an Almen strip, is then removed from the holding frame. The residual stresses imparted by the blast cause the Almen strip to become convex on the blasted side. The arc height of this curvature is measured with a specified dial gauge indicator. This method allows the blast intensity to be quantified. These results may then be correlated with the amount of the residual stress imparted to the substrate.

Almen strips are used to ensure that the residual stress induced in the substrate does not exceed the level at which it would increase the fatigue crack propagation rate. The arc heights measured from each Almen strip after each blast cycle when blasted with the same blast parameters can be used to plot a curve of arc height versus blast cycle. This produces a saturation curve that becomes asymptotic as it approaches the saturation arc height level for that substrate. Saturation should be below the level that will cause increased fatigue crack propagation rates. Then, for any additional blast cycles using the same parameters, no further significant residual stress will be caused in the substrate by the same blast. The theoretical number of stripping cycles that may be performed after a proper saturation level is reached, therefore, is unlimited.

It should be mentioned that other research has found that some significant variability in Almen strip test results may be observed, even when the same blast parameters and substrates are used. Other methods, in addition to Almen strips of the substrate material, are being used to quantify the effect of a particular set of blast parameters on the substrate being considered. In MIL-STD 85-891, magnesium strips are specified to be blasted using the PMB parameters of interest. The amount of material lost during the blasting process is then measured and used to give an order of magnitude indication of the blast intensity.

Test data have been obtained to assess the effect of PMB on the fatigue crack growth rate of thin 2024-T3 sheet material (reference 1). Among the materials that have undergone four blast cycles, the anodized material suffered more than the alclad material from residual stress as determined from the Almen arc heights. However, the crack growth rates of the PMB treated anodized material were not significantly affected. But the crack growth rates of the PMB treated alclad material were greater than the "as received" material. This result showed that Almen strips cannot be used alone to assess blast damage and that further investigation to characterize the blast effects was desirable. To further characterize the effect of PMB treatment on thin 2024-T3 aluminum, it is necessary to experimentally determine how blast parameters identical to those used in the FCP tests effect the material fatigue life.

3. TECHNICAL APPROACH.

This effort is a continuation of a previous investigation into the effects of PMB on thin 2024-T3 aluminum sheet. The previous investigation included a limited FCP test program to determine the effects of PMB on the fatigue crack propagation rate of this material. The PMB treated material in that test program was blasted utilizing a combination of parameters that were selected as a "worst case" combination of those parameters specified by industry (reference 1). A complete description of the current program is shown in figure 3.1. The organization of this program, including the number of specimens used for each test condition, follows the procedures recommended in reference 6 for testing the effects of PMB on material fatigue life.

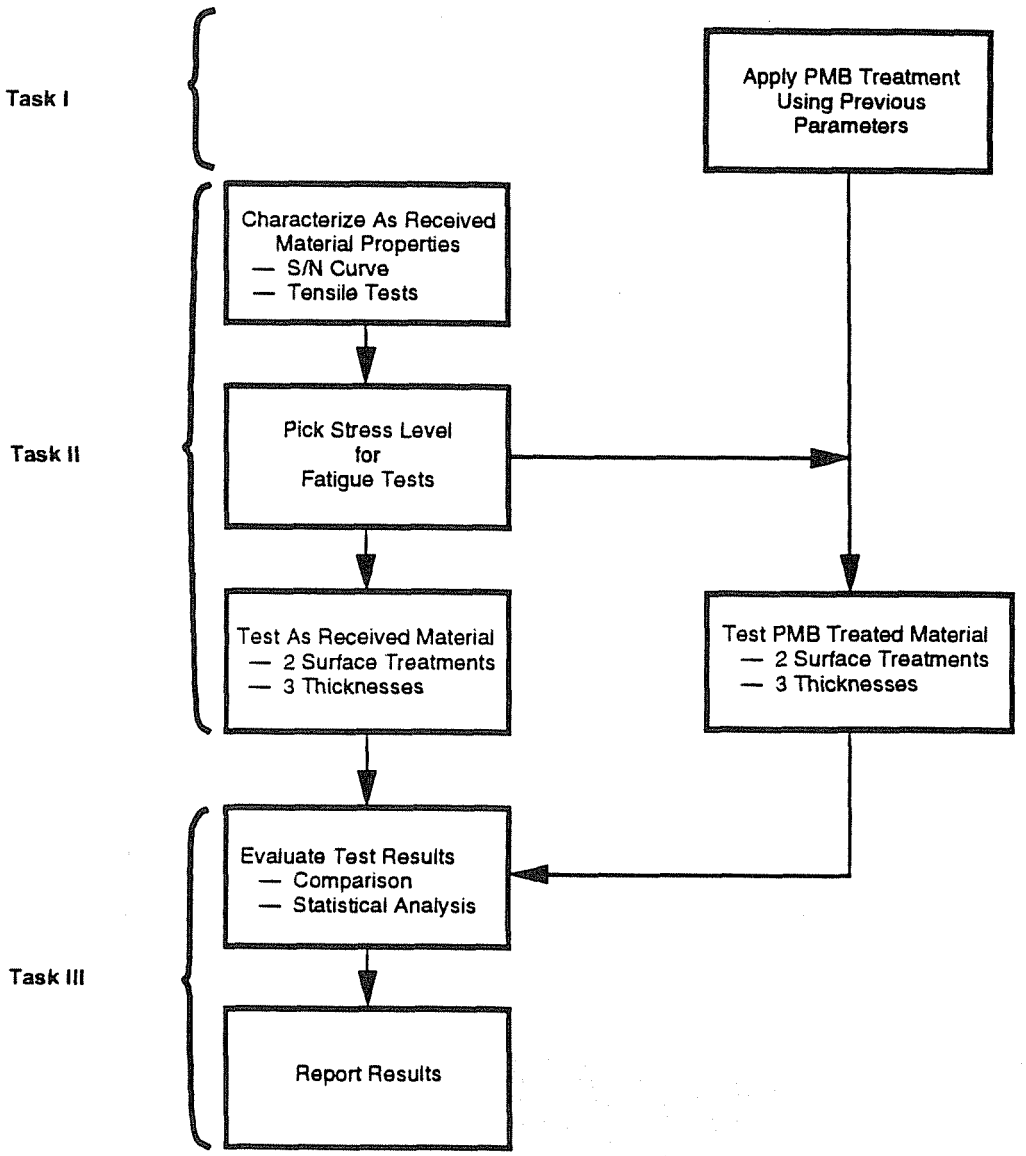


FIGURE 3-1. OVERALL DESCRIPTION OF ANODIZED AND ALCLAD ALUMINUM TEST PROGRAM

3.1 PMB TREATMENT OF MATERIALS.

The goal of this investigation was to test for fatigue life differences using the same material and PMB treatment as in the previous program (reference 1). It was intended that the material being tested in the current program be exposed to a blast intensity similar to that experienced by the material in the previous test program. Therefore blast parameters identical to those used in that program were specified for this current test program. Table 3.1-1 contains these blast parameters. Almen strip tests were performed as a means of assessing the blast intensity experienced by the aluminum sheet and comparing it with the blast intensity experienced by the test materials in the FCP test program. The results of the Almen strip tests are discussed in section 4.1.

TABLE 3.1-1. BLAST PARAMETER SPECIFICATIONS

Blast Parameter	Specified Value
Media Type	Type II, size 30/40
Nozzle Pressure	35 psi
Distance	12 inches
Nozzle Diameter	0.5 inch
Media Flowrate	870 lb/hr
Impingement Angle	90°
Number of Blast Cycles	4 (1 initial stripping, then 3 subsequent blastings)

3.2 TENSILE TESTS.

Tensile tests were performed on both the anodized and the alclad material to characterize the sample material properties. These tests were conducted according to reference 2. The results of the tensile tests are discussed in section 4.2.

3.3 FATIGUE TEST PROGRAM.

To determine the effects of PMB treatment on the fatigue life of the subject material, a stress level at which to test the material had to be chosen. A procedure used in previous PMB research was used to determine this stress level for both the anodized and alclad material (references 3, 4, and 6). First, a separate S/N plot was established for the "as received" anodized and alclad 2024-T3 material. A stress level was then chosen from the S/N plots that would be expected to cause failure at approximately 100,000 cycles for each of these materials. A series of fatigue tests, performed according to reference 5, was then performed on "as received" and PMB treated material at the chosen stress level for all three thicknesses for both the anodized and alclad materials. Statistical t-tests were performed to determine the

significance of any observed differences in the fatigue lives of the two samples. The results of the fatigue test program are discussed in section 4.3.

4. RESULTS AND DISCUSSION.

The arc heights obtained from Almen strip tests, performed to measure the intensity of the PMB treatment, are presented and compared with the arc heights determined for the previous FCP test program (reference 1). The S/N plots established for this test program are presented. The results of the fatigue tests performed for the baseline and PMB treated material are presented and discussed to determine the effect of PMB treatment on the fatigue life of the material.

4.1 PMB TREATMENT OF MATERIALS.

The materials used in this program were anodized and alclad 2024-T3 aluminum in 0.032, 0.040, and 0.050 inch thicknesses. It should be noted that the aluminum used in this effort was from different material lots than those used in the previous FCP test program. Panels of these materials were subjected to the PMB process utilizing the parameters defined for the FCP test program conducted previously (see table 3.1-1). Appendix A describes in the detail the PMB process applied to the test material and presents all of the raw arc height data.

The results of the current PMB treatment were compared with the FCP test results to assess the degree of similarity in the blasting treatments. Almen strip arc heights were the primary means of comparison, with consideration also being given to the media breakdown rates, media lots, media purity, and dwell time.

A comparison of the average arc heights for the current anodized aluminum with the previous arc height data according to thickness and blast cycle is shown in table 4.1-1. Similar information is presented in table 4.1-2 for the alclad aluminum. In both test efforts, trends in arc height results concerning surface treatment and material thickness were similar. Anodized material had greater average arc heights than alclad material for a given thickness in both test programs. This result is reasonable because the anodized material is not cushioned against the blast as the alclad is by a soft surface layer. Also, as material thickness decreased the average arc heights increased in both test programs. Comparison by blast cycle shows that for identical surface treatment, material thickness, and blast cycle, the arc height magnitudes in the current sample were consistently greater than those of the previous test program. These differences were most apparent in the alclad 0.050 inch thick material where arc heights were greater than those in the previous program by as much as a factor of five.

It should be noted that all three thicknesses of anodized material were blasted simultaneously with the intent of eliminating the variability caused by the blasting process. The same holds true for the alclad material, which was blasted separately.

TABLE 4.1-1. COMPARISON OF AVERAGE ARC HEIGHTS IN MILS OBTAINED FOR 2024-T3 ANODIZED ALUMINUM

Material Thickness (inches)	Blast Cycle							
	1		2		3		4	
	current	FCP	current	FCP	current	FCP	current	FCP
0.032	14	11	15	13	17	15	17	16
0.040	9	4	10	4	12	5	13	5
0.050	8	4	8	4	9	4	10	5

Note: FCP represents arc height data obtained from reference 1.

TABLE 4.1-2. COMPARISON OF AVERAGE ARC HEIGHTS IN MILS OBTAINED FOR 2024-T3 ALCLAD ALUMINUM

Material Thickness (inches)	Blast Cycle							
	1		2		3		4	
	current	FCP	current	FCP	current	FCP	current	FCP
0.032	9	5	13	8	14	8	15	9
0.040	6	3	10	4	11	4	11	5
0.050	3	1	5	1	5	1	5	1

Note: FCP represents arc height data obtained from reference 1.

An examination of other measurements taken during the two PMB treatments demonstrates that the process was applied similarly. The dwell times for both programs were comparable. Paint removal rates for the FCP test program were 0.34 and 0.56 min/ft^2 for the anodized and alclad, respectively. In the current program, paint removal rates were 0.35 and 0.50 min/ft^2, respectively. The media breakdown rates were also comparable for the two programs. A media breakdown rate of 19.3 percent per blast cycle was recorded for the FCP program, while rates of 19.3 and 15.7 percent were recorded for the anodized and alclad materials in the current program. Two breakdown rates were recorded in the current program because two different lots of media were used. The flowrate recorded for the FCP test program was 900 lb./hr while that for the current program was 900 and 845 lb./hr, for the anodized and alclad materials, respectively.

The above discussion demonstrates that although similar parameter values are used to apply the PMB process, variability may still be found in arc height results. Since the PMB treatment was applied in essentially the same manner for both programs, these differences in arc height magnitudes may be attributed to differences in the substrate materials. The material lots differed

between the previous FCP program and the current fatigue program. Any variations in the materials, such as the depth of the alclad layer or differences in the microstructure may have introduced the discrepancies observed in the arc heights.

4.2 TENSILE TESTS.

A series of axial tension tests were performed according to reference 2, for both the anodized and the alclad baseline material. The tests were conducted in an environmentally controlled laboratory. Three specimens of 0.050 inch thickness were tested for each of the two surface treatments. The tests were conducted in strain control with a 0.005 in/in/sec strain rate until specimen fracture. Appendix B describes the specimens and the test equipment used.

The yield strength at 0.2 percent offset and the ultimate strength, modulus of elasticity, and elongation were determined for each specimen. The mean values obtained for these parameters are presented in table 4.2-1. Magnitudes of these properties taken from reference 7 are presented for clad 2024-T3 sheet for comparison purposes.

TABLE 4.2-1. RESULTS OF TENSILE TESTS ON "AS RECEIVED" 2024-T3 ANODIZED AND ALCLAD ALUMINUM

Material	Tensile Ultimate Strength, ksi	Tensile Yield Strength, ksi	Elongation, percent	Modulus, Mpsi
Anodized 0.050	66.8	52.5	13.3	9.9
Alclad 0.050	66.5	54.2	11.2	8.9
Clad 0.0100 - 0.062	60	44	15.0	10.5

4.3 STRESS/CYCLE TESTS.

A series of fatigue tests were performed at various stress levels to obtain a plot of the stress versus the number of cycles to failure (S/N). This was done for both the anodized and alclad 2024-T3 aluminum being used in this program. A total of ten fatigue tests were performed, for both surface treatments, according to reference 5. The tests were conducted in an environmentally controlled laboratory. The specimens were all 0.050 inches thick and were subjected to a stress ratio of 0.1.

The raw data obtained from the S/N fatigue tests are presented in Appendix C. Plots of the S/N data for the anodized and alclad aluminum are shown in figures 4.3-1 and 4.3-2, respectively.

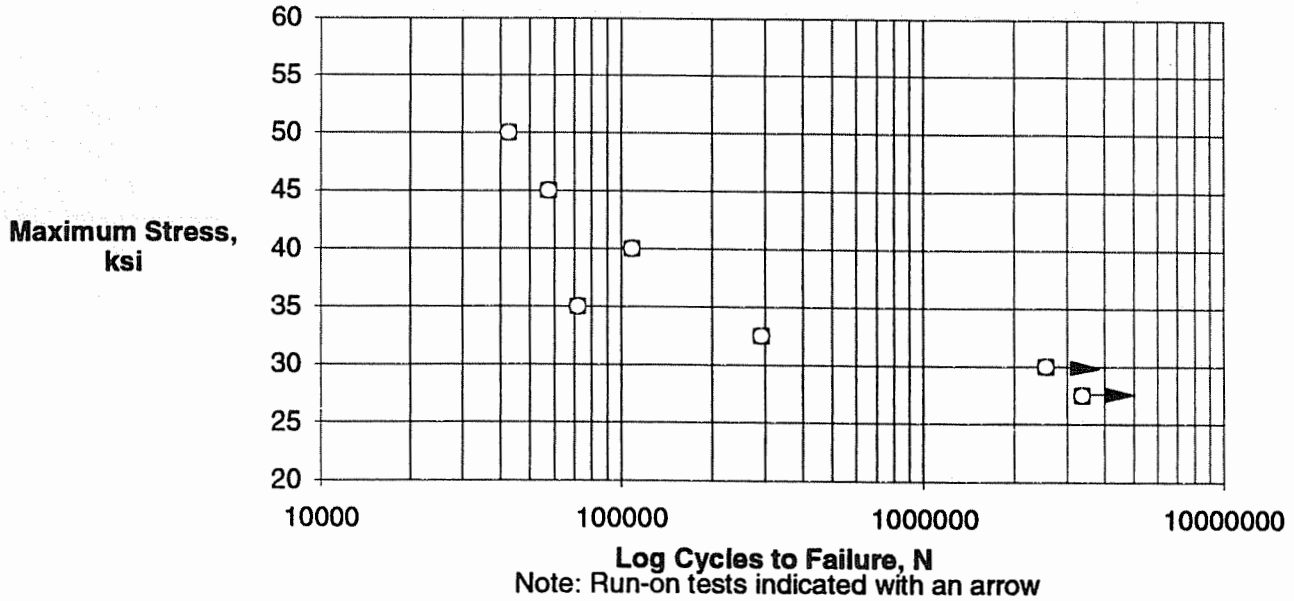


FIGURE 4.3-1. S-N DIAGRAM FOR 2024-T3 ANODIZED ALUMINUM

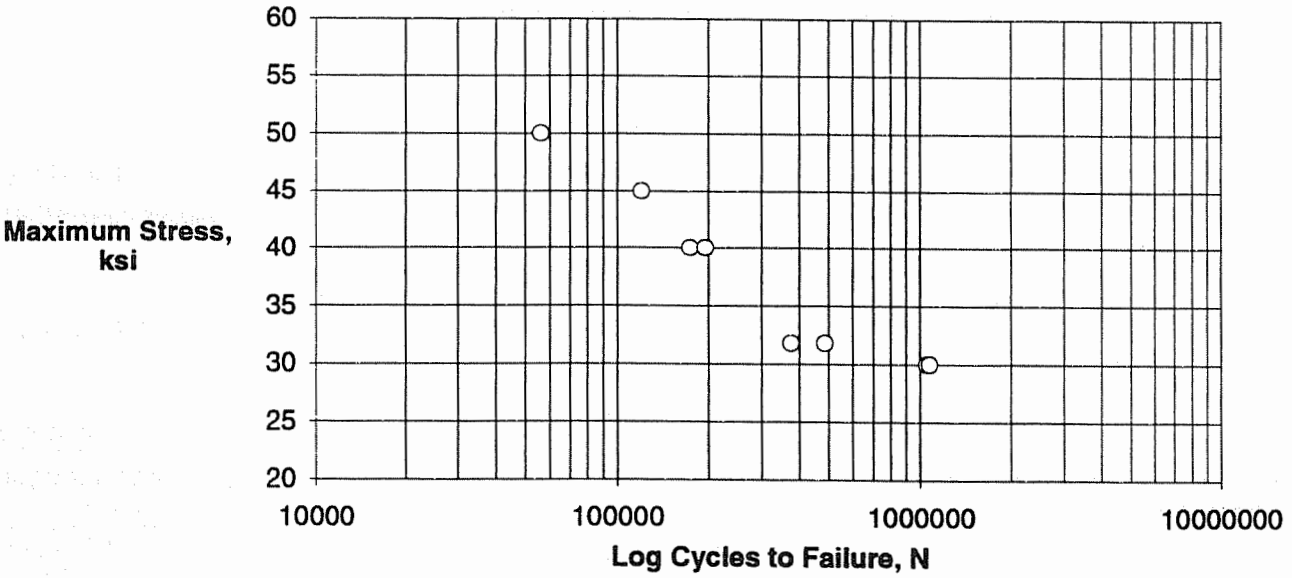


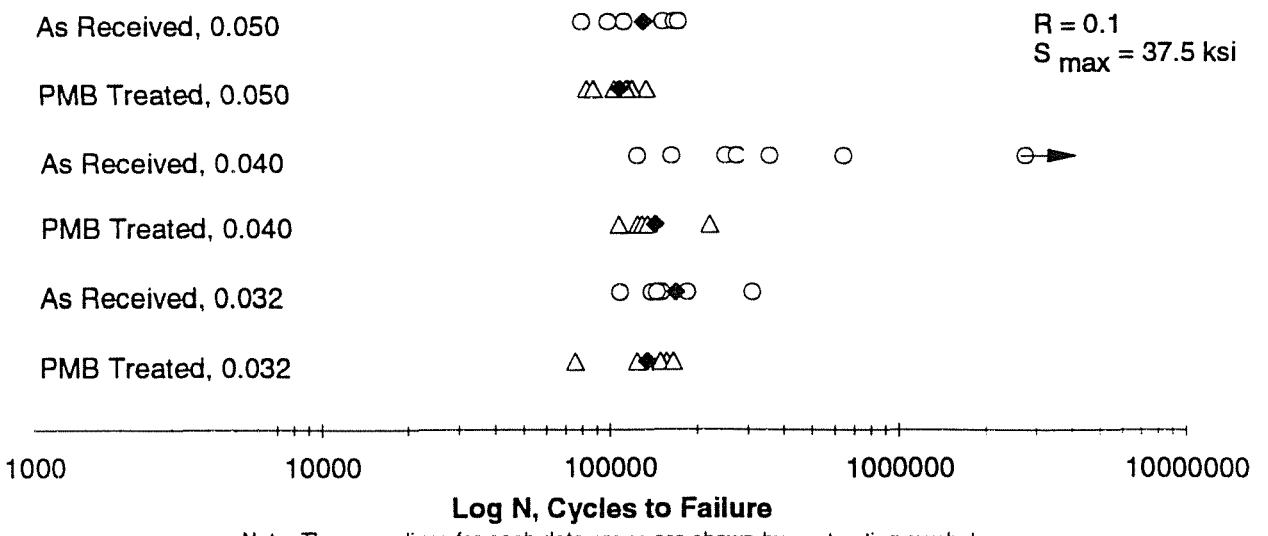
FIGURE 4.3-2. S-N DIAGRAM FOR 2024-T3 ALCLAD ALUMINUM

4.4 FATIGUE TESTS.

Two sets of fatigue tests were conducted for each thickness and surface treatment: one for the "as received" material and one for the PMB treated material. The procedures used to perform these tests are described in Appendix C and were done according to reference 5. Appendix C also contains all of the raw fatigue data obtained in this project.

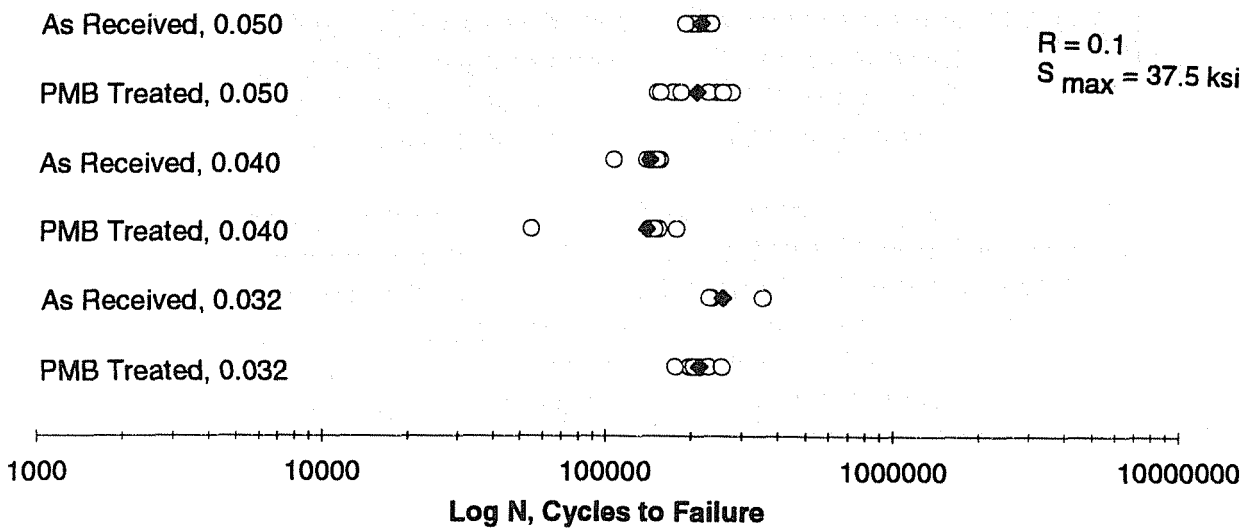
Once the tests had been completed, the fatigue lives of the "as received" material were compared to those of the PMB treated material to determine whether significant differences could be determined. Figures 4.4-1 and 4.4-2 contain logarithm plots of the fatigue lives of the PMB treated and "as received" anodized and alclad aluminum, respectively. In these two figures, the mean fatigue life for each group of tests is indicated by a contrasting diamond symbol. In figure 4.4-1 the median fatigue life is given instead of the mean fatigue life for the "as received" 0.040 anodized aluminum because the data contains a run-out. Reference 3 uses this treatment of fatigue data samples containing run-outs.

A statistical summary of the fatigue tests is given in tables 4.4-1 and 4.4-2 for the anodized and alclad materials, respectively. Several observations may be made regarding the data contained in these two tables. It can be seen that the mean fatigue lives for the alclad material, for both "as received" and PMB treated conditions, were generally greater then the mean fatigue lives for the anodized aluminum. For the anodized aluminum, it can be seen from table 4.4-1 that the mean fatigue lives for the PMB treated material was generally lower than the "as received" material.



Note: The mean lives for each data group are shown by contrasting symbol

FIGURE 4.4-1. FATIGUE LIFE DISTRIBUTIONS FOR THREE THICKNESSES OF "AS RECEIVED" AND PMB TREATED 2024-T3 ANODIZED ALUMINUM



Note: The mean lives for each data group are shown by contrasting symbol

FIGURE 4.4-2. FATIGUE LIFE DISTRIBUTIONS FOR THREE THICKNESSES OF "AS RECEIVED" AND PMB TREATED 2024-T3 ALCLAD ALUMINUM

TABLE 4.4-1. SUMMARY OF FATIGUE DATA FOR 2024-T3 ANODIZED ALUMINUM

Thickness	Treatment	No. of Valid Tests	No. of Run- Outs	Fatigue Life (Log Cycles) Mean	Fatigue Life (Log Cycles) Std. Dev.	Fatigue Life (Kilocycles) Mean	Fatigue Life (Kilocycles) Std. Dev.
.032	As Received	7	0	5.21	0.144	171	66.7
.032	PMB Treated	5	0	5.11	0.140	135	36.4
.040	As Received	7	1	5.44*	0.451	279*	95.5
.040	PMB Treated	5	0	5.15	0.118	145	44.9
.050	As Received	6	0	5.11	0.138	134	39.8
.050	PMB Treated	7	0	5.04	0.076	111	18.3

* median used where run-outs exist.

For the alclad material, the mean fatigue lines of the PMB treated material was generally lower than the "as received" material, as seen in table 4.4-2. Examination of the standard deviations for the fatigue lives of the two materials reveals another observation. For the anodized material, the standard deviation was generally reduced for the PMB treated material when compared to the "as received" material. For the alclad aluminum the reverse effect was observed, with the standard deviation in fatigue life being greater for the PMB treated material when compared to the "as received" material. These results seem to suggest that the PMB treatment may affect

fatigue life scatter. Similar results were observed for 7075-T6 clad and anodized aluminum in reference 4.

TABLE 4.4-2. SUMMARY OF FATIGUE DATA FOR 2024-T3 ALCLAD ALUMINUM

Thickness	Treatment	No. of Valid Tests	No. of Run- Outs	Fatigue Life (Log Cycles) Mean	Fatigue Life (Log Cycles) Std. Dev.	Fatigue Life (Kilocycles) Mean	Fatigue Life (Kilocycles) Std. Dev.
.032	As Received	5	0	5.41	0.079	259	54.6
.032	PMB Treated	6	0	5.33	0.055	214	27.8
.040	As Received	8	0	5.16	0.054	145	15.5
.040	PMB Treated	8	0	5.13	0.160	141	36.4
.050	As Received	6	0	5.34	0.032	218	16.2
.050	PMB Treated	8	0	5.32	0.104	212	49.4

Statistical t-tests were performed to determine whether differences observed in the fatigue lives of the "as received" and PMB treated materials were statistically significant. Tables 4.4-3 and 4.4-4 contain the results of these t-tests, for the anodized and alclad material, respectively. The results of the t-tests are presented in the form of confidence intervals for the percent gain (or loss) in fatigue life. These tables also contain the percent gain in mean fatigue life of the materials tested. The percent gain in fatigue life is considered significant if zero lies outside the bounds of the corresponding 90 percent confidence interval. Appendix D describes how the t-test statistic is computed.

TABLE 4.4-3. STATISTICAL T-TEST AND CONFIDENCE INTERVALS SHOWING EFFECTS OF PMB TREATMENT ON 2024-T3 ANODIZED ALUMINUM

Thickness inches	Max. Stress (ksi)	Mean Fatigue Life (kilocycles) As Received	Mean Fatigue Life (kilocycles) PMB Treated	Percent Fatigue Life Gain Mean	Percent Fatigue Life Gain 90 % Confidence Interval	Mann-Whitney Test Observed Significance Level[2]
.032	37.5	171	135	-21.1	-76.8 to 12.0	.378
.040	37.5	279[1]	146	-	-	.015
.050	37.5	134	111	-17.2	-49.7 to 9.17	.267

(1) Median used where run-outs exist.
(2) An observed significance level less than 0.05 indicates a significant loss in fatigue life.

The analysis shows that the percent gain in mean fatigue life was negative for all materials in the test program. This means that all materials experienced a reduction in mean fatigue life after being subjected to the PMB treatment. Using the t statistic, this loss in fatigue life was found

to be significant only for the 0.032 inch alclad material. The confidence interval for the percent reduction in mean fatigue life for the 0.032 alclad was computed to be -1.63 to -30.1 percent. For the remaining materials for which confidence intervals could be computed, the intervals contained zero and therefore indicated that for 90 percent confidence both positive and negative percentage differences in mean fatigue life could be expected.

TABLE 4.4-4. STATISTICAL T-TEST AND CONFIDENCE INTERVALS SHOWING EFFECTS OF PMB TREATMENT ON 2024-T3 ALCLAD ALUMINUM

Thickness inches	Max. Stress (ksi)	Mean Fatigue Life (kilocycles)		Percent Fatigue Life Gain		Mann-Whitney Test Observed Significance Level[1]
		As Received	PMB Treated	Mean	90 % Confidence Interval	
.032	37.5	259	214	-17.4	-30.1 to -1.63	.026
.040	37.5	145	141	-2.76	-34.3 to 15.0	.520
.050	37.5	218	212	-2.75	-21.5 to 10.1	.207

(1) An observed significance level less than 0.05 indicates a significant loss in fatigue life.

The t-test could not be used for the 0.040 inch anodized aluminum because the sample contained a run-out. A statistical test based on ranks, the Mann-Whitney test, is appropriate for this type of data. Appendix D describes how the Mann-Whitney statistic is computed. This test was applied to all of the anodized and alclad fatigue data for comparison with the t-test results.

Table 4.4-3 and 4.4-4 contain the results of the Mann-Whitney tests for the anodized and alclad specimens, respectively. The observed significance level for the 0.040 inch anodized material is less than 0.05, which indicates that for the 90 percent confidence level the loss in fatigue life is significant. For the other two thicknesses of anodized material, the observed significance level indicates that the loss in fatigue life is not statistically significant, which corresponds with the t-test results for these specimen thicknesses. The observed significance levels for the alclad specimens agree completely with the t-test statistics in finding no significant loss in fatigue life except for the 0.032 inch alclad.

5. CONCLUSIONS.

1. Reductions in mean fatigue life were observed for all thicknesses and surface coatings tested after PMB treatment. Statistical analysis using the t test showed that these reductions in mean fatigue life were not significant because of the data scatter, except for the 0.032 inch alclad. Confidence intervals computed from the t test results indicated that for 90 percent confidence, both positive and negative percent differences in fatigue life could be expected. The t test could not be applied to the 0.040 inch anodized specimens because the data contained a run-out. The Mann-Whitney test indicated that for 90 percent confidence, the reduction in fatigue life for the 0.040 inch anodized material was significant. The PMB treatment did not appear to significantly reduce the fatigue life of the tested material except for the 0.032 inch alclad and 0.040 inch anodized material.

2. The anodized material treated with PMB was observed to have a reduction in the fatigue life scatter when compared to the "as received" anodized material. PMB treatment may act to reduce fatigue life variability in thin anodized substrates.

3. The alclad material treated with PMB was observed to have an increase in fatigue life scatter when compared to the "as received" alclad material. Because of the surface damage observed, to occur to the clad layer during the blasting process, PMB treatment may introduce greater variability to the fatigue life of thin alclad substrates.

4. Notable differences were observed in the Almen strip arc height results obtained for this program when compared to results from a test (reference 1). This observation suggests that even when the PMB treatment is applied identically, notable variability in results may be found.

6. REFERENCES.

1. Chen, Charles C. T., Muller, Mark, and Reinhardt, John W., Effects of Plastic Media Blasting on Aircraft Skin, DOT/FAA/CT-91/27, November 1993.

2. ASTM Standard E8, "Tension Testing of Metallic Materials," Part 7: Die Cast Metals; Aluminum and Magnesium Alloys, pp. 722-742, 1979.

3. Galliher, R. D., Deel, O. L., and Taylor, G. C., Plastic Bead Blast Materials Characterization Study, Battelle Columbus Division, July 1986.

4. Galliher, R. D., Deel, O. L., and Taylor, G. C., Plastic Bead Blast Materials Characterization Study - Follow-on Effort, Battelle Columbus Division, November 1987.

5. ASTM Standard E466, "Constant Amplitude Axial Fatigue Tests of Metallic Materials," Part 10: Metals, Mechanical, Fracture, and Corrosion Testing; Fatigue; Erosion; Effect of Temperature, pp. 574-579, 1979.

6. Childers, Sidney, Watson, David. C., Stumpff, Patricia, Tirpak, Jon, Evaluation of the Effects of a Plastic Bead Paint Removal Process on Properties of Aircraft Structural Materials, Materials Laboratory, Air Force Wright Aeronautical Laboratories, AD-A165 289, December 1985.

7. Metallic Materials and Elements for Aerospace Vehicle Structures, MIL-HD-5F, Vol. 1, November 1990.

8. Kvanli, Alan H., Guynes, Stephen C., and Pavur, J. Introduction to Business Statistics, 3rd edition, West Publishing Co., 1992.

APPENDIX A - PLASTIC MEDIA TREATMENT OF MATERIAL

Aluminum Panel Preparation

The preparation of the aluminum panels was performed identically to that used in the previous program documented in reference 1. Six panels of bare and nine panels of alclad 2024-T3 aluminum were processed. The six bare aluminum panels were anodized according to Military Specification 8625 before painting and blasting. The process of treating the panels then consisted of surface cleaning each panel by abrading the surface with distilled water and a nylon web obtaining a water-break-free surface, application of an epoxy-polyamide primer conforming MIL-P-23377, application of an aliphatic polyurethane topcoat conforming to MIL-C-83286, and artificially aging the painted panels in an oven maintained at 210 degrees Fahrenheit for 100 hours. Three anodized panels and six alclad panels designated for the fabrication of fatigue specimens were stripped using plastic media blasting. The remaining six panels were sheared into Almen strip specimens.

All test panels and Almen strip specimens were blasted with virgin 30-40 mesh Type II (Urea Formaldehyde - Thermoset) plastic media obtained from Composition Materials, Inc. It should be noted that the alclad panels were blasted with media from a different lot number than the anodized panels. Insufficient media remained from the first lot after blasting the anodized panels; therefore, additional media was procured from the same manufacturer and of the same type and grade.

TABLE A-1 MEDIA TYPE

Type II (Urea Formaldehyde)

Grade: A

For treatment of anodized panels

Ship Date: March 18, 1991
Lot Number: 43

For treatment of alclad panels

Ship Date: February 1, 1993
Lot Number: Not Specified

Manufacturer: Composition Materials, Inc.
1375 Kings Highway East
Fairfield, Connecticut 06430

All test panels and Almen strip specimens were blasted using the following set of parameters:

TABLE A-2 BLAST PARAMETERS

35 - psi nozzle pressure
12 - inch nozzle distance from substrate
90 degree nozzle angles (from horizontal)
1/2 - inch diameter straight nozzle
845 lb./hr media flow rates

The nozzle pressure was measured before and after blasting the panels and Almen strip specimens by using a needle pressure gage. The pressure was measured in the blast hose approximately one inch from the nozzle. Figure A-1 shows the dimensions of the Almen strips used in the test program. Figure A-2 Show the test fixture used to hold the Almen strips during the blasting process as well as the gauge used to measure the arch heights.

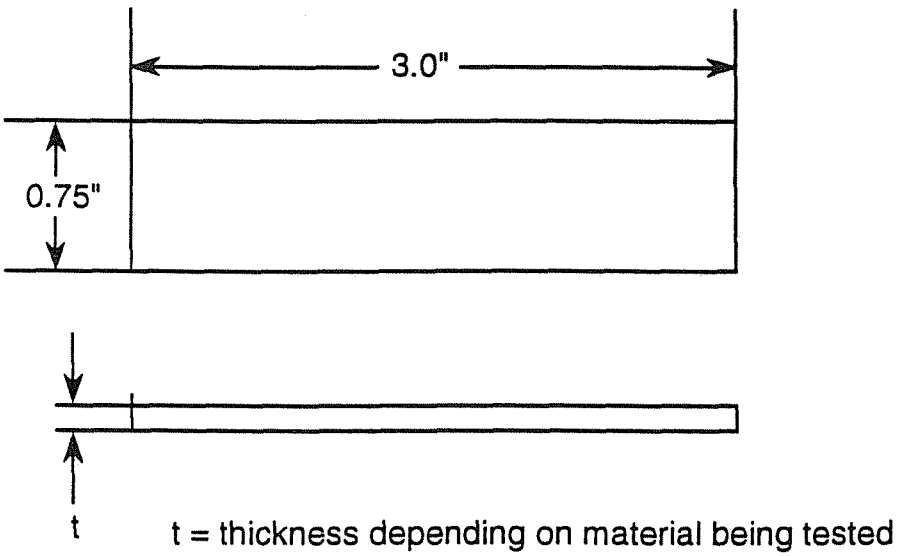


FIGURE A-1. ALMEN STRIP SPECIFIED DIMENSIONS

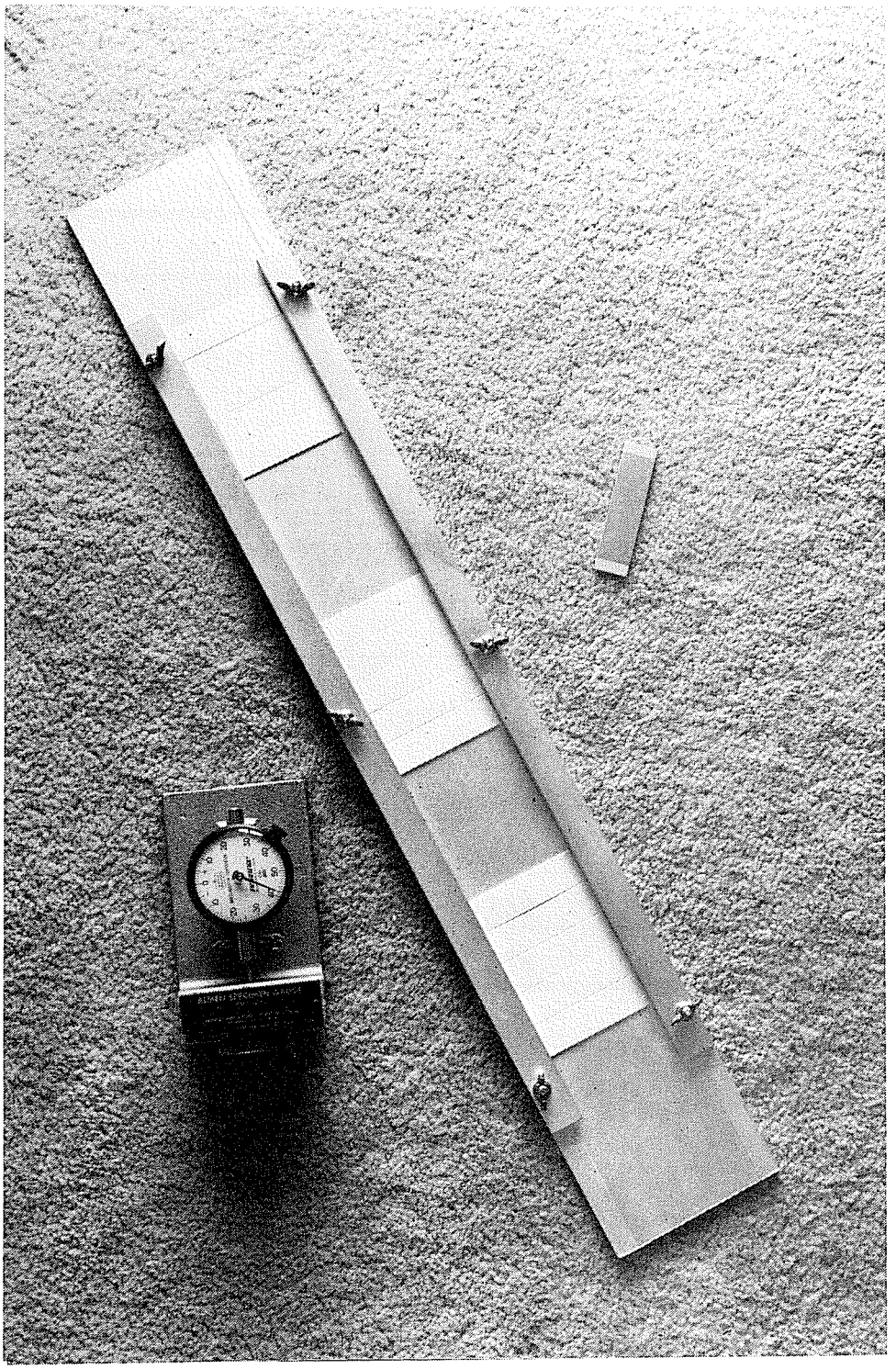


FIGURE A-2. ALMEN STRIP TEST FIXTURE AND ALMEN ARCH HEIGHT GAUGE

TABLE A-3. PAINT STRIPPING RATE AND DWELL TIME FOR 2024-T3 ANODIZED ALUMINUM

Test Panel Number	Paint Removal Area, ft^2	Paint Removal Time, sec	Paint Removal Rate, ft^2/min	Dwell Time min/ft^2
AN32-1	1.36	25	3.26	0.31
AN40-1	1.36	30	2.72	0.37
AN50-1	1.36	30	2.72	0.37
AVERAGE	-	-	2.90	0.35

TABLE A-4. VIRGIN MEDIA PARTICLE SIZE DISTRIBUTION FOR 2024-T3 ANODIZED ALUMINUM

Sieve Size	Pan Weight with Media (grams)	Empty Sieve or Pan Weight (grams)	Media Weight (grams)	Percent by Weight
12	440.0	440.0	0.0	0.0
16	435.9	435.9	0.0	0.0
20	398.9	398.9	0.0	0.0
30	404.3	393.0	11.3	11.2
40	446.0	377.6	68.4	68.0
60	376.8	355.9	20.9	20.8
80	347.4	347.4	0.0	0.0
PAN	372.0	372.0	0.0	0.0
TOTAL	-	-	100.6	100.0

TABLE A-5. PARTICLE SIZE DISTRIBUTION AFTER FOUR PMB CYCLES ON 2024-T3 ANODIZED ALUMINUM

Sieve Size	Pan Weight with Media (grams)	Empty Sieve or Pan Weight (grams)	Media Weight (grams)	Percent by Weight
12	440.0	440.0	0.0	0.0
16	435.9	435.9	0.0	0.0
20	398.9	398.9	0.0	0.0
30	394.0	393.0	1.0	1.0
40	494.7	377.6	17.1	17.1
60	494.2	355.9	38.3	38.3
80	366.2	347.4	18.8	18.8
PAN	396.7	372.0	24.7	24.7
TOTAL	-	-	99.9	99.9

TABLE A-6. MEDIA BREAKDOWN RATE CALCULATION AFTER TREATMENT OF 2024-T3 ANODIZED ALUMINUM

(Product retained on 40 Mesh Sieve)

$$\text{Consumption} = \frac{\text{Virgin media weight - 4 PMB cycle media weight}}{\text{Virgin media weight x 4 PMB cycles}}$$

$$\text{Consumption} = \frac{11.3 + 68.4 - 1.0 - 17.1}{(11.3 + 68.4) \times 4} \times 100 = 19.3 \text{ percent/blast cycle}$$

TABLE A-7. PAINT STRIPPING RATE AND DWELL TIME FOR 2024-T3 ALCLAD ALUMINUM

Test Panel Number	Paint Removal Area, ft^2	Paint Removal Time, sec	Paint Removal Rate, ft^2/min	Dwell Time min/ft^2
AL32-1	1.36	38	2.15	0.47
AL32-2	1.36	35	2.33	0.43
AL40-1	1.36	43	1.90	0.53
AL40-2	1.36	45	1.81	0.55
AL50-1	1.36	45	1.81	0.55
AL50-2	1.36	40	2.04	0.49
AVERAGE	-	-	2.01	0.50

TABLE A-8. VIRGIN MEDIA PARTICLE SIZE DISTRIBUTION FOR 2024-T3 ALCLAD ALUMINUM

Sieve Size	Pan Weight with Media (grams)	Empty Sieve or Pan Weight (grams)	Media Weight (grams)	Percent by Weight
16	435.9	435.9	0.0	0.0
20	398.9	398.9	0.0	0.0
30	402.9	393.0	9.9	9.9
40	452.9	377.6	75.3	75.1
60	371.0	355.9	15.1	15.1
80	347.4	347.4	0.0	0.0
100	359.6	359.6	0.0	0.0
PAN	372.0	372.0	0.0	0.0
TOTAL	-	-	100.3	100.1

TABLE A-9. PARTICLE SIZE DISTRIBUTION AFTER FOUR PMB CYCLES ON 2024-T3 ALCLAD ALUMINUM

Sieve Size	Pan Weight with Media (grams)	Empty Sieve or Pan Weight (grams)	Media Weight (grams)	Percent by Weight
16	435.9	435.9	0.0	0.0
20	398.9	398.9	0.0	0.0
30	395.3	393.0	2.3	1.4
40	428.4	377.6	50.8	30.2
60	419.1	355.9	63.2	37.6
80	368.7	347.4	21.3	12.7
100	367.4	359.6	7.8	4.6
PAN	394.6	372.0	22.6	13.5
TOTAL	-	-	168.0	100.0

TABLE A-10. MEDIA BREAKDOWN RATE CALCULATION AFTER TREATMENT OF 2024-T3 ALCLAD ALUMINUM

(Product Retained on 40 Mesh Sieve)

$$\text{Consumption} = \frac{\text{Virgin media weight - 4 PMB cycle media weight}}{\text{Virgin media weight x 4 PMB cycles}}$$

$$\text{Consumption} = \frac{9.9 + 75.1 - 1.4 - 30.2}{(9.9 + 75.1) \times 4} \times 100 = 15.7 \text{ percent/blast cycle}$$

TABLE A-11. ALMEN STRIP ARC HEIGHTS IN MILS FOR 2024-T3 ANODIZED ALUMINUM 0.032-INCH THICKNESS

Specimen Number	Blast Cycle			
	1	2	3	4
AN32-1	15	16	17	17
AN32-2	15	17	18	18
AN32-3	14	14	17	17
AN32-4	14	14	16	16
AN32-5	13	13	16	16
Average	14	15	17	17

TABLE A-12. ALMEN STRIP ARC HEIGHTS IN MILS FOR 2024-T3 ANODIZED ALUMINUM 0.040-INCH THICKNESS

Specimen Number	Blast Cycle			
	1	2	3	4
AN40-1	9	10	12	13
AN40-2	10	11	13	13
AN40-3	9	10	12	13
AN40-4	9	10	12	12
AN40-5	10	11	13	13
Average	9	10	12	13

TABLE A-13. ALMEN STRIP ARC HEIGHTS IN MILS FOR 2024-T3 ANODIZED ALUMINUM 0.050-INCH THICKNESS

Specimen Number	Blast Cycle			
	1	2	3	4
AN50-1	7	8	9	10
AN50-2	8	8	9	10
AN50-3	7	7	8	9
AN50-4	8	8	9	10
AN50-5	9	8	9	10
Average	8	8	9	10

TABLE A-14. ALMEN STRIP ARC HEIGHTS IN MILS FOR 2024-T3 ALCLAD ALUMINUM 0.032-INCH THICKNESS

Specimen Number	Blast Cycle			
	1	2	3	4
AL32-1	10	11	14	16
AL32-2	9	13	13	16
AL32-3	11	14	14	15
AL32-4	10	14	15	16
AL32-5	8	12	13	14
AL32-6	9	13	13	14
AL32-7	9	13	12	14
AL32-8	9	12	14	14
AL32-9	10	13	13	16
AL32-10	9	13	14	15
Average	9	13	14	15

TABLE A-15. ALMEN STRIP ARC HEIGHTS IN MILS FOR 2024-T3 ALCLAD ALUMINUM 0.040-INCH THICKNESS

Specimen Number	Blast Cycle			
	1	2	3	4
AL40-1	6	9	10	11
AL40-2	6	10	11	13
AL40-3	6	9	10	11
AL40-4	6	9	11	11
AL40-5	7	10	10	11
AL40-6	6	9	10	11
AL40-7	6	9	9	10
AL40-8	7	10	11	11
AL40-9	6	10	11	11
AL40-10	7	11	12	12
Average	6	10	11	11

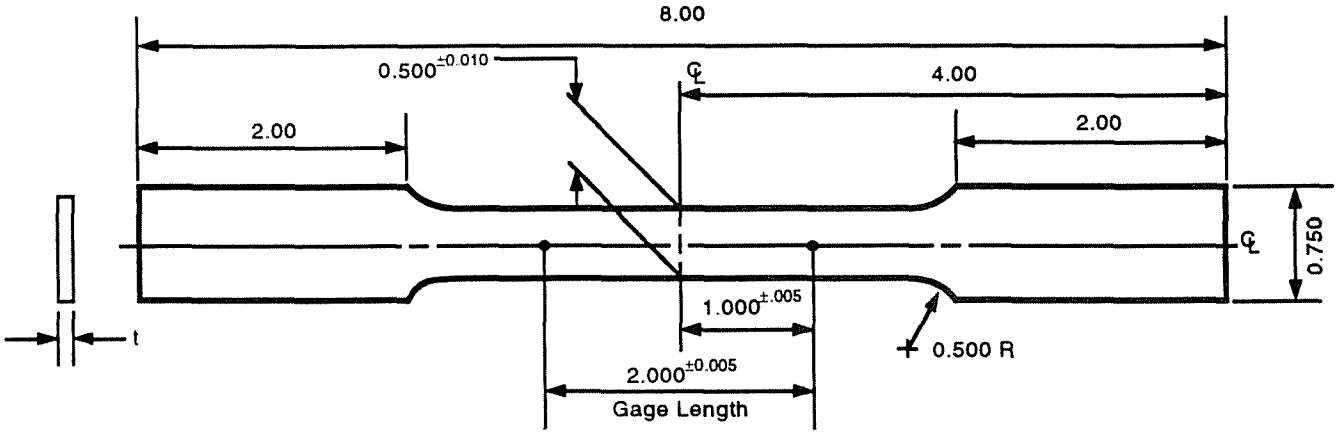
TABLE A-16, ALMEN STRIP ARC HEIGHTS IN MILS FOR 2024-T3 ALCLAD ALUMINUM 0.050-INCH THICKNESS

Specimen Number	Blast Cycle			
	1	2	3	4
AL50-1	3	5	6	6
AL50-2	3	6	6	6
AL50-3	3	4	5	5
AL50-4	4	5	5	6
AL50-5	4	5	5	5
AL50-6	4	5	6	6
AL50-7	2	4	5	5
AL50-8	2	4	5	4
AL50-9	2	5	5	5
AL50-10	2	5	5	6
Average	3	5	5	5

APPENDIX B - TENSILE TESTS

TABLE B-1. TENSILE TEST PARAMETERS

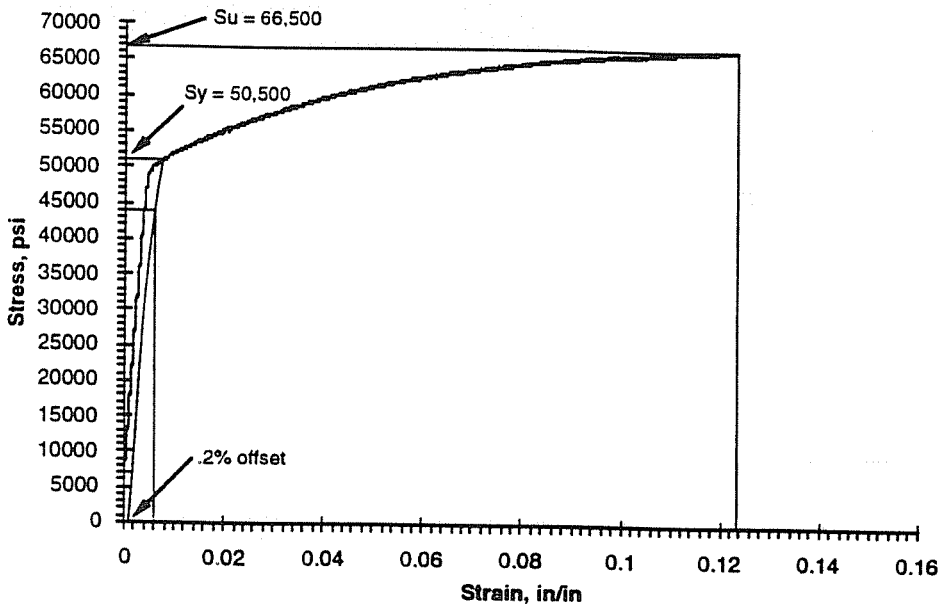
Yield Rate:	0.005 in/in/min until failure
Control Mode:	Strain
Equipment:	MTS Model 810.23 TestStar Closed-Loop Testing System
Laboratory Temperature:	69.8 - 77 °F
Laboratory Humidity:	45 - 55 %



Note: All dimensions shown in inches.

Reference
ASTM Designation E8

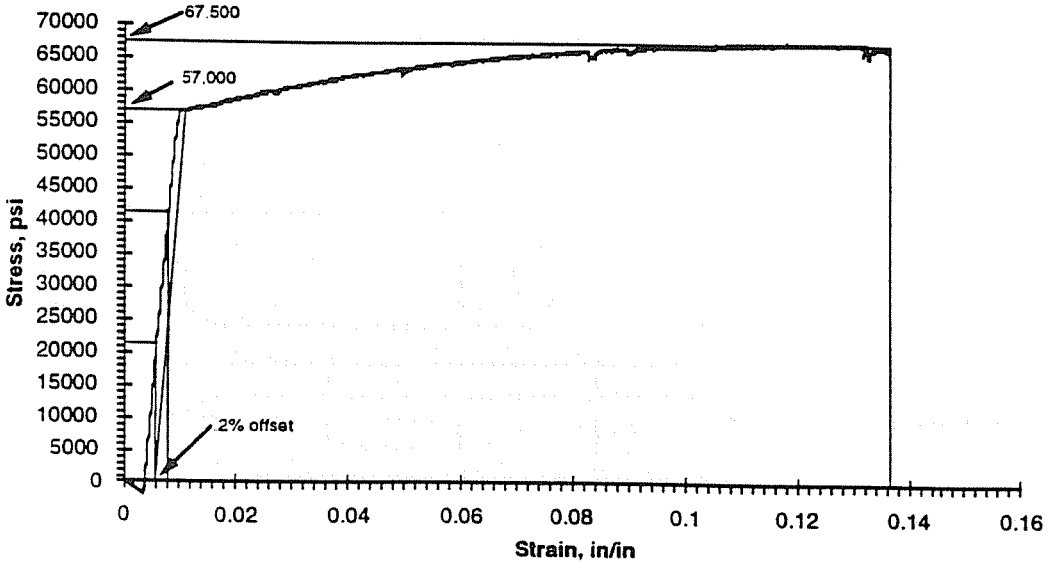
FIGURE B-1. TENSILE TEST SPECIMEN DIMENSIONS



$$E = \frac{44{,}000 - 7{,}000}{.006 - .002} = 9.25 \text{ Mpsi}$$

% EL = .123 x 100% = 12.3%

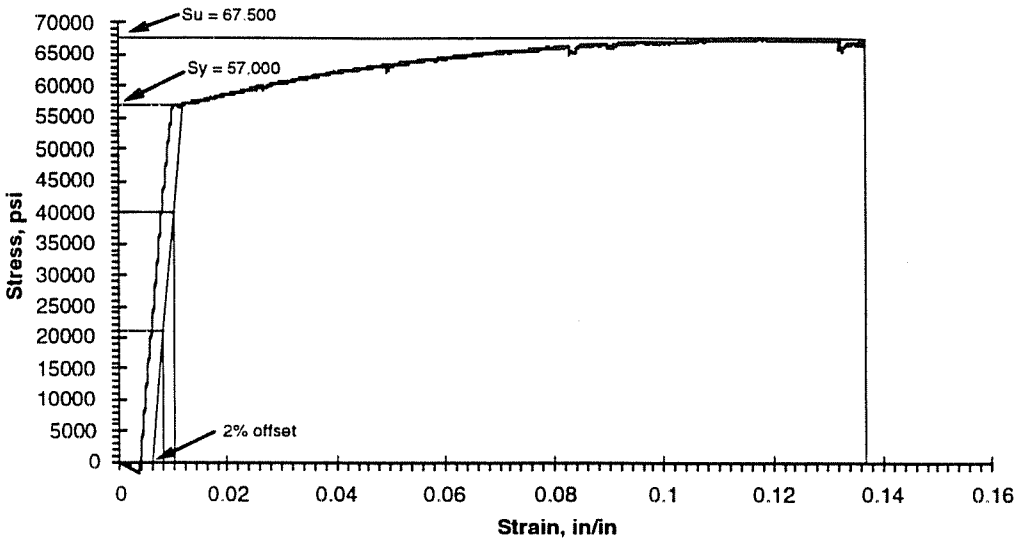
FIGURE B-2. PLOT OF STRESS VS. STRAIN FOR 2024-T3 ANODIZED ALUMINUM SPECIMEN 1



$$E = \frac{41{,}300 - 21{,}300}{.008 - .006} = 10.0 \text{ Mpsi}$$

% EL = .137 x 100% = 13.7%

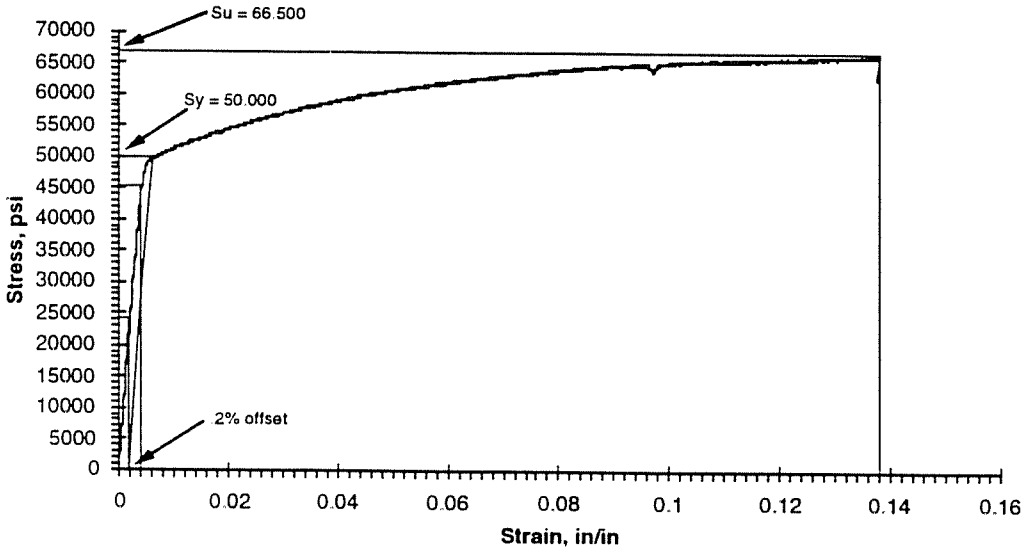
FIGURE B-3. PLOT OF STRESS VS. STRAIN FOR 2024-T3 ANODIZED ALUMINUM SPECIMEN 2



$$E = \frac{39{,}900 - 21{,}000}{01 - 008} = 9.45 \text{ Mpsi}$$

% EL = .1365 x 100% = 13.7%

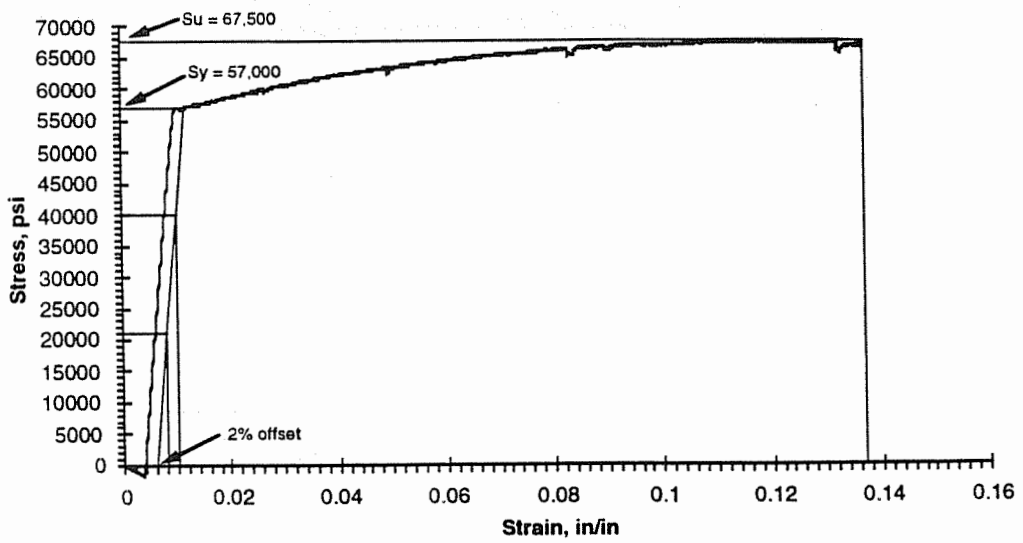
FIGURE B-4. PLOT OF STRESS VS. STRAIN FOR 2024-T3 ANODIZED ALUMINUM SPECIMEN 3



$$E = \frac{45{,}000 - 24{,}000}{004 - 002} = 10.5 \text{ Mpsi}$$

% EL = .1382 x 100% = 13.8%

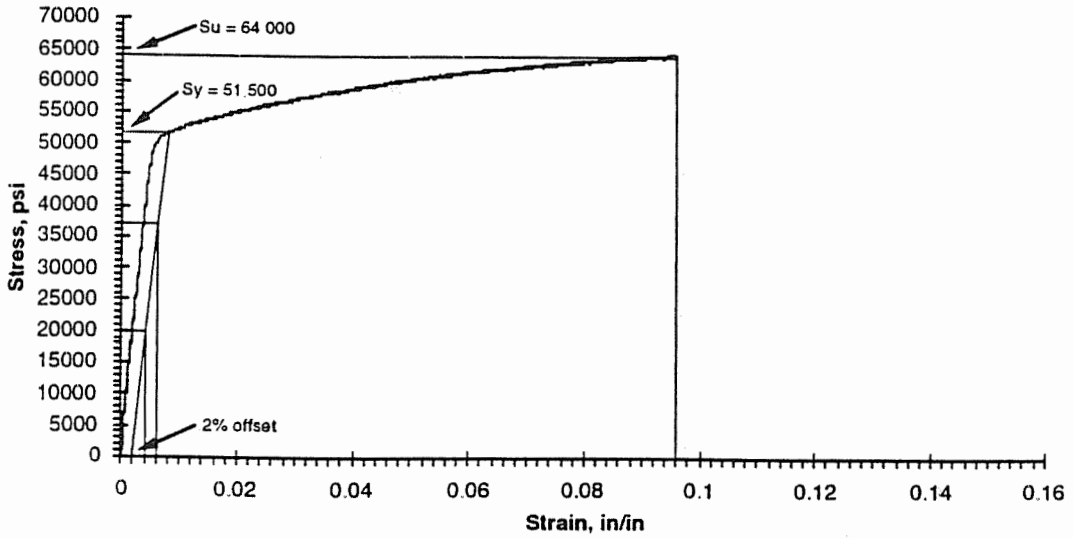
FIGURE B-5. PLOT OF STRESS VS. STRAIN FOR 2024-T3 ALCLAD ALUMINUM SPECIMEN 1



$$E = \frac{39.900 - 21.000}{.01 - .008} = 9.45 \text{ Mpsi}$$

% EL = .1365 x 100% = 13.7%

FIGURE B-6. PLOT OF STRESS VS. STRAIN FOR 2024-T3 ALCLAD ALUMINUM SPECIMEN 2



$$E = \frac{37.000 - 20.000}{.006 - .004} = 8.50 \text{ Mpsi}$$

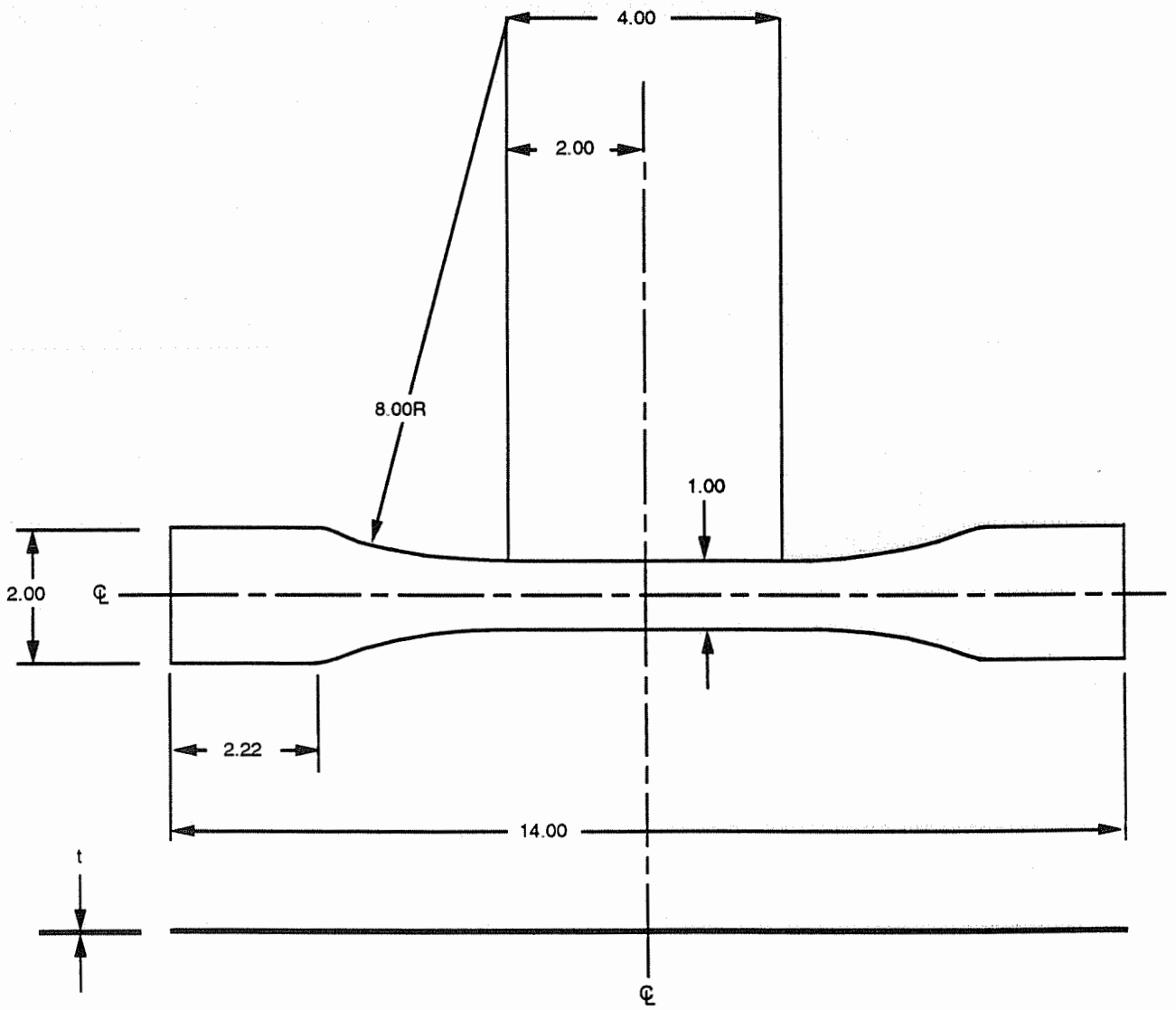
% EL = .0955 x 100% = 9.6%

FIGURE B-7. PLOT OF STRESS VS. STRAIN - 2024-T3 ALCLAD ALUMINUM SPECIMEN 3

APPENDIX C - FATIGUE TESTS

TABLE C-1, FATIGUE TEST PARAMETERS

Fatigue Testing Machine:	MTS Model 810.23
Type of Test:	Axial
Number of Machines Used:	1
Test Frequency:	10 Hz
Control Mode:	Load
Failure Criterion:	complete fracture
Run-out:	2 million cycles
Stress Ratio R:	.1
Laboratory Temperature:	69.8 - 77 °F
Laboratory Humidity:	45 - 55 %



Note: All dimensions shown in inches.

FIGURE C-1. FATIGUE TEST SPECIMEN DIMENSIONS

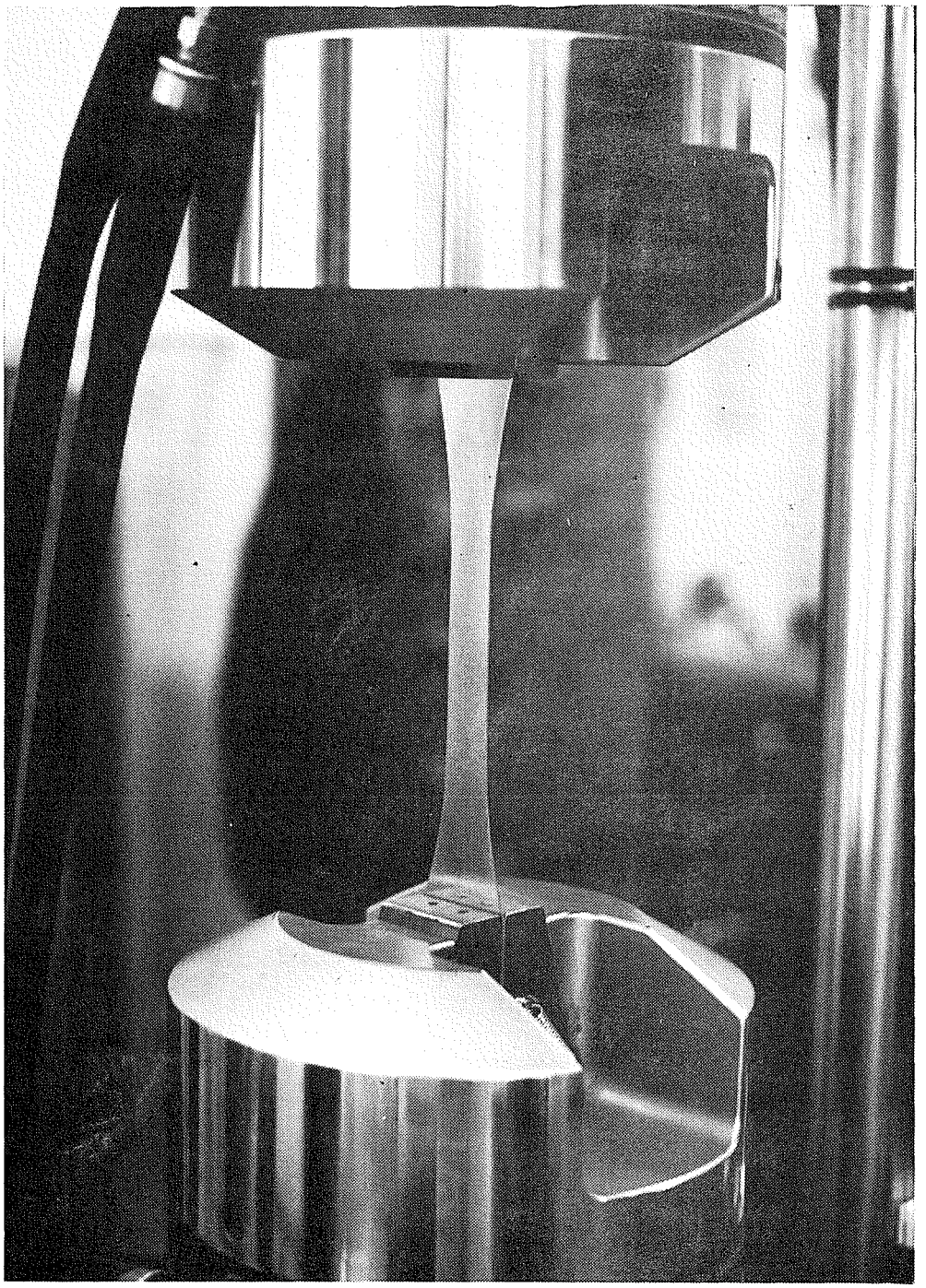


FIGURE C-2. MOUNTED FATIGUE SPECIMEN IN TEST MACHINE GRIPS

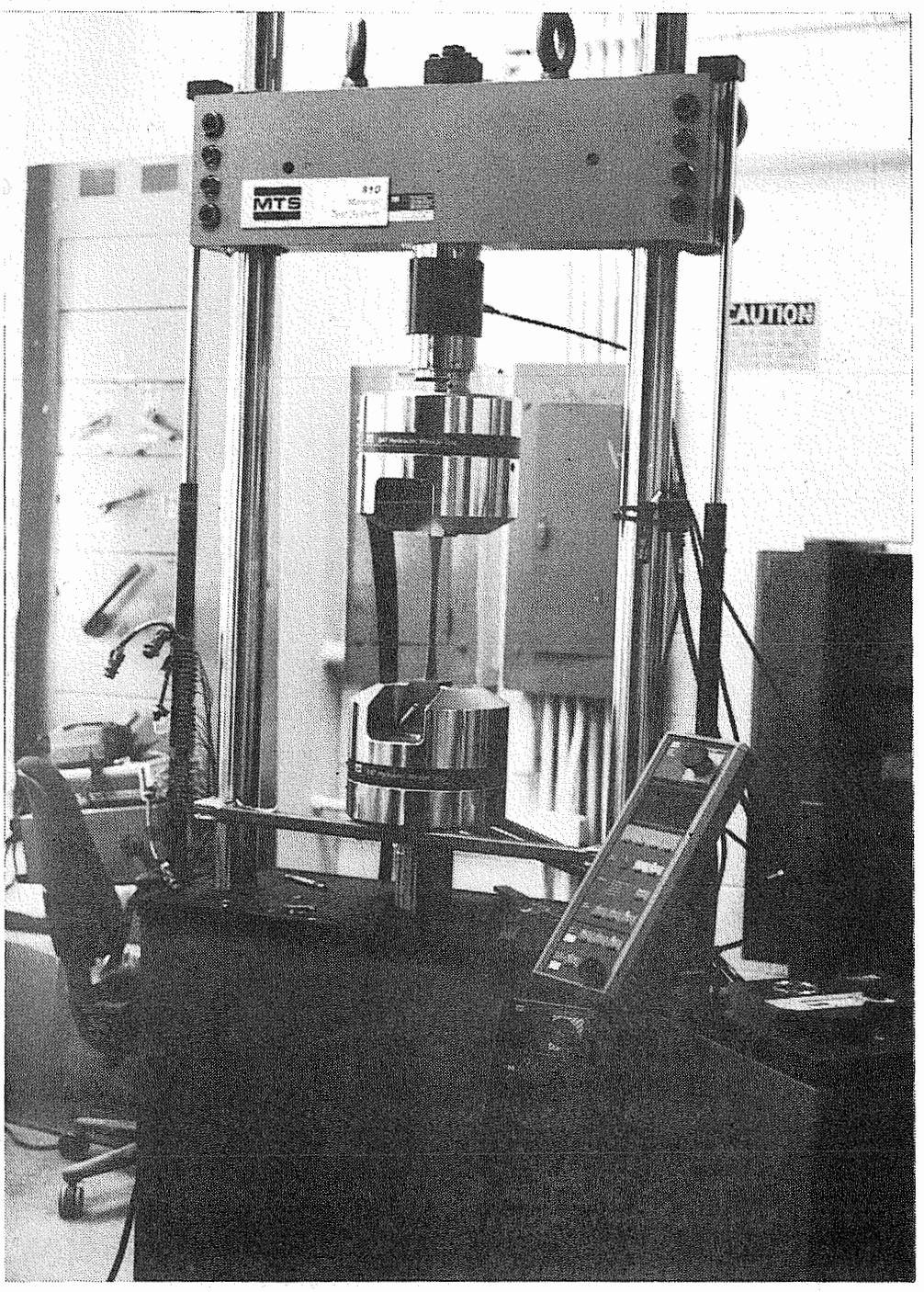


FIGURE C-3. MATERIAL TESTING MACHINE

TABLE C-1A. S/N FATIGUE TEST DATA FOR "AS RECEIVED" ANODIZED

Test Sequence	Specimen Number	Dynamic Stresses		Fatigue Life, kilocycles	Remarks
		Maximum, ksi	Minimum, ksi		
1	SN-AN50-1	50.0	5.0	42360	
2	SN-AN50-2	45.0	4.5	57368	
3	SN-AN50-3	40.0	4.0	-	invalid test
4	SN-AN50-4	37.5	3.75	-	invalid test
5	SN-AN50-5	35.0	3.5	71695	
6	SN-AN50-6	32.5	3.25	290398	
7	SN-AN50-7	30.0	3.0	2540223	run-on
8	SN-AN50-8	27.5	2.75	3356476	run-on
9	SN-AN50-9	25.0	2.5	108565	
10	SN-AN50-10	20.0	2.0	-	invalid test

TABLE C-2A. FATIGUE TEST DATA FOR "AS RECEIVED" 0.032 ANODIZED

Test Sequence	Specimen Number	Dynamic Stresses		Fatigue Life, kilocycles	Remarks
		Maximum, ksi	Minimum, ksi		
1	BL-AN32-1	37.5	3.75	312873	
2	BL-AN32-2	37.5	3.75	152227	
3	BL-AN32-3	37.5	3.75	186730	
4	BL-AN32-4	37.5	3.75	109139	
5	BL-AN32-5	37.5	3.75	145008	
6	BL-AN32-6	37.5	3.75	140718	
7	BL-AN32-7	37.5	3.75	146765	

TABLE C-2B. FATIGUE TEST DATA FOR "AS RECEIVED" 0.040 ANODIZED

Test Sequence	Specimen Number	Dynamic Stresses		Fatigue Life, kilocycles	Remarks
		Maximum, ksi	Minimum, ksi		
1	BL-AN40-1	37.5	3.75	361512	
2	BL-AN40-2	37.5	3.75	254661	
3	BL-AN40-3	37.5	3.75	165814	
4	BL-AN40-4	37.5	3.75	278554	
5	BL-AN40-5	37.5	3.75	126606	
6	BL-AN40-6	37.5	3.75	651572	
7	BL-AN40-7	37.5	3.75	2792401	run-on

TABLE C-2C. FATIGUE TEST DATA FOR "AS RECEIVED" 0.050 ANODIZED

Test Sequence	Specimen Number	Dynamic Stresses		Fatigue Life, kilocycles	Remarks
		Maximum, ksi	Minimum, ksi		
1	BL-AN50-1	37.5	3.75	81908	
2	BL-AN50-2	37.5	3.75	156277	
3	BL-AN50-3	37.5	3.75	171266	
4	BL-AN50-4	37.5	3.75	114735	
5	BL-AN50-5	37.5	3.75	101016	
6	BL-AN50-6	37.5	3.75	177106	

TABLE C-3A. FATIGUE TEST DATA FOR PMB TREATED 0.032 ANODIZED

Test Sequence	Specimen Number	Dynamic Stresses		Fatigue Life, kilocycles	Remarks
		Maximum, ksi	Minimum, ksi		
1	PT-AN32-1	37.5	3.75	76032	
2	PT-AN32-2	37.5	3.75	157254	
3	PT-AN32-3	37.5	3.75	124178	
4	PT-AN32-4	37.5	3.75		invalid test
5	PT-AN32-5	37.5	3.75	150270	
6	PT-AN32-6	37.5	3.75	166041	

TABLE C-3B. FATIGUE TEST DATA FOR PMB TREATED 0.040 ANODIZED

Test Sequence	Specimen Number	Dynamic Stresses		Fatigue Life, kilocycles	Remarks
		Maximum, ksi	Minimum, ksi		
1	PT-AN40-1	37.5	3.75	126412	
2	PT-AN40-2	37.5	3.75	131462	
3	PT-AN40-3	37.5	3.75	223671	
4	PT-AN40-4	37.5	3.75	109040	
5	PT-AN40-5	37.5	3.75	94260	invalid test
6	PT-AN40-6	37.5	3.75	137220	

TABLE C-3C. FATIGUE TEST DATA FOR PMB TREATED 0.050 ANODIZED

Test Sequence	Specimen Number	Dynamic Stresses		Fatigue Life, kilocycles	Remarks
		Maximum, ksi	Minimum, ksi		
1	PT-AN50-1	37.5	3.75	118519	
2	PT-AN50-2	37.5	3.75	136595	
3	PT-AN50-3	37.5	3.75	122168	
4	PT-AN50-4	37.5	3.75	85106	
5	PT-AN50-5	37.5	3.75	89692	
6	PT-AN50-6	37.5	3.75	105951	
7	PT-AN50-7	37.5	3.75	116657	

TABLE C-4A. S/N FATIGUE TEST DATA FOR "AS RECEIVED" ALCLAD

Test Sequence	Specimen Number	Dynamic Stresses		Fatigue Life, kilocycles	Remarks
		Maximum, ksi	Minimum, ksi		
1	SN-AL50-1	50.0	5.0	56059	
2	SN-AL50-2	50.0	5.0	56167	
3	SN-AL50-3	31.8	3.18	373889	
4	SN-AL50-4	40.0	4.0	174042	
5	SN-AL50-5	30.0	3.0	1048660	
6	SN-AL50-6	30.0	3.0	1074711	
7	SN-AL50-7	40.0	4.0	194859	
8	SN-AL50-8	31.8	3.18	485671	
9	SN-AL50-9	40.0	4.0	142168	invalid test
10	SN-AL50-10	45.0	4.5	120206	
11	SN-AL50-11	45.0	4.5	120146	

TABLE C-5A. FATIGUE TEST DATA FOR "AS RECEIVED" 0.032 ALCLAD

Test Sequence	Specimen Number	Dynamic Stresses		Fatigue Life, kilocycles	Remarks
		Maximum, ksi	Minimum, ksi		
1	BL-AL32-1	37.5	3.75	234107	
2	BL-AL32-2	37.5	3.75	-	invalid test
3	BL-AL32-3	37.5	3.75	-	invalid test
4	BL-AL32-4	37.5	3.75	356533	
5	BL-AL32-5	37.5	3.75	-	invalid test
6	BL-AL32-6	37.5	3.75	233897	
7	BL-AL32-7	37.5	3.75	237311	
8	BL-AL32-8	37.5	3.75	232883	

TABLE C-5B. FATIGUE TEST DATA FOR "AS RECEIVED" 0.040 ALCLAD

Test Sequence	Specimen Number	Dynamic Stresses		Fatigue Life, kilocycles	Remarks
		Maximum, ksi	Minimum, ksi		
1	BL-AL40-1	37.5	3.75	152770	
2	BL-AL40-2	37.5	3.75	157504	
3	BL-AL40-3	37.5	3.75	147718	
4	BL-AL40-4	37.5	3.75	140927	
5	BL-AL40-5	37.5	3.75	108377	
6	BL-AL40-6	37.5	3.75	151226	
7	BL-AL40-7	37.5	3.75	145759	
8	BL-AN50-8	37.5	3.75	153408	

TABLE C-5C. FATIGUE TEST DATA FOR "AS RECEIVED" 0.050 ALCLAD

Test Sequence	Specimen Number	Dynamic Stresses		Fatigue Life, kilocycles	Remarks
		Maximum, ksi	Minimum, ksi		
1	BL-AL50-1	37.5	3.75	-	invalid test
2	BL-AL50-2	37.5	3.75	-	invalid test
3	BL-AL50-3	37.5	3.75	226481	
4	BL-AL50-4	37.5	3.75	230778	
5	BL-AL50-5	37.5	3.75	236530	
6	BL-AL50-6	37.5	3.75	215081	
7	BL-AL50-7	37.5	3.75	206152	
8	BL-AL50-8	37.5	3.75	193656	

TABLE C-6A. FATIGUE TEST DATA FOR PMB TREATED 0.032 ALCLAD

Test Sequence	Specimen Number	Dynamic Stresses		Fatigue Life, kilocycles	Remarks
		Maximum, ksi	Minimum, ksi		
1	PT-AL32-1	37.5	3.75	198820	
2	PT-AL32-2	37.5	3.75	214726	
3	PT-AL32-3	37.5	3.75	201647	
4	PT-AL32-4	37.5	3.75	230171	
5	PT-AL32-5	37.5	3.75	256966	
6	PT-AL32-6	37.5	3.75	176237	

TABLE C-6B. FATIGUE TEST DATA FOR PMB TREATED 0.040 ALCLAD

Test Sequence	Specimen Number	Dynamic Stresses		Fatigue Life, kilocycles	Remarks
		Maximum, ksi	Minimum, ksi		
1	PT-AL40-1	37.5	3.75	151575	
2	PT-AL40-2	37.5	3.75	149363	
3	PT-AL40-3	37.5	3.75	179003	
4	PT-AL40-4	37.5	3.75	143413	
5	PT-AL40-5	37.5	3.75	155263	
6	PT-AL40-6	37.5	3.75	55188	
7	PT-AL40-7	37.5	3.75	144263	
8	PT-AL40-8	37.5	3.75	150407	

TABLE C-6C. FATIGUE TEST DATA FOR PMB TREATED 0.050 ALCLAD

Test Sequence	Specimen Number	Dynamic Stresses		Fatigue Life, kilocycles	Remarks
		Maximum, ksi	Minimum, ksi		
1	PT-AL50-1	37.5	3.75	174770	
2	PT-AL50-2	37.5	3.75	154204	
3	PT-AL50-3	37.5	3.75	186057	
4	PT-AL50-4	37.5	3.75	157875	
5	PT-AL50-5	37.5	3.75	279496	
6	PT-AL50-6	37.5	3.75	148586	
7	PT-AL50-7	37.5	3.75	231919	
8	PT-AL50-8	37.5	3.75	261295	

APPENDIX D - STATISTICAL METHODS

The statistical methods used in this program for data analysis are described in this Appendix. The equations for the mean $\bar{x}$ and standard deviations are as follows:

$$\bar{x} = \frac{\Sigma x}{n} \qquad \text{equation A-1}$$

$$s = \sqrt{\frac{\Sigma (x - \bar{x})^2}{n - 1}} \qquad \text{equation A-2}$$

where x represents individual specimen fatigue lives and n represents the number of fatigue specimens in each sample.

The percent fatigue life gain was calculated using the following equation:

$$\text{GAIN \%} = \frac{100 (\bar{x}_2 - \bar{x}_1)}{\bar{x}_1} \qquad \text{equation A-3}$$

where $\bar{x}_2$ is the mean fatigue life, in kilocycles, of the PMB treated specimens and $\bar{x}_1$ is the mean fatigue life, in kilocycles, of the "as received" specimens.

Two statistical methods were used to determine the significance of differences observed between the fatigue lives of the "as received" and the PMB treated specimens. These two methods were the t-test and the Mann-Whitney U test.

The T-Test

The t-test used for this analysis is for comparing small samples from two populations assumed to be normally distributed. The t-test was performed using the log values of the specimen fatigue lives, as described in references 3 and 4. The t statistic may be computed either by using the standard deviations of the two samples or by using a pooled sample variance. Using the pooled sample variance is considered a more powerful test but requires that the standard deviations of the two samples be equal ($s_1 = s_2$). The procedure for testing this assumption uses the F statistic described in reference 8. Both methods of computing the t statistic are described below. Equations A-4 through A-7 are used to compute the t statistic when $s_1 \neq s_2$ and equations A-8 through A-12 are used with a pooled sample variance ($s_1 = s_2$).

For $s_1 \neq s_2$:

The following equation is used to calculate the t statistic:

$$t' = \frac{\bar{x}_2 - \bar{x}_1}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}} \qquad \text{equation A-4}$$

where $\bar{x}_1$ is the mean fatigue life, in log cycles, of the PMB treated specimens and $\bar{x}_2$ is the mean fatigue life, in log cycles, of the "as received" specimens.

The degrees of freedom are then calculated as follows:

$$df = \frac{\left[\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}\right]^2}{\frac{\left(\frac{s_1^2}{n_1}\right)^2}{n_1 - 1} + \frac{\left(\frac{s_2^2}{n_2}\right)^2}{n_2 - 1}} \qquad \text{equation A-5}$$

Then, to calculate the upper (U) and lower (L) bounds of an interval for 90 percent confidence, where confidence equals $(1-\alpha)x100$ percent, the following equations are used:

$$U = (\bar{x}_2 - \bar{x}_1) + t_{\frac{\alpha}{2}, df} \sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}} \qquad \text{equation A-6}$$

$$L = (\bar{x}_2 - \bar{x}_1) - t_{\frac{\alpha}{2}, df} \sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}} \qquad \text{equation A-7}$$

where df is from equation A-5 and $t_{\frac{\alpha}{2}, df}$ is obtained from a table containing the t distribution for different levels of confidence.

For $s_1 = s_2$:

The following equation is used to calculate the t statistic:

$$t' = \frac{\bar{x}_2 - \bar{x}_1}{\sqrt{\frac{s_P^2}{n_1} + \frac{s_P^2}{n_1}}} \qquad \text{equation A-8}$$

where $\overline{x_1}$ is the mean fatigue life, in log cycles, of the PMB treated specimens and $\overline{x_2}$ is the mean fatigue life, in log cycles, of the "as received" specimens. The pooled variance s_p is calculated as follows:

$$S_p = \frac{(n_1 - 1)\ S_1^2 + (n_2 - 1)S_2^2}{n_1 + n_2 - 2} \qquad \text{equation A-9}$$

The degrees of freedom are found by the following equation:

$$df = n_1 + n_2 - 2 \qquad \text{equation A-10}$$

To calculate the upper (U) and lower (L) bounds of the 90% confidence interval, the following two equations are used where confidence equals $(1-\alpha)x100$ percent.

$$U = (\bar{x}_2 - \bar{x}_1) + t_{\frac{\alpha}{2},\,df} \sqrt{\frac{S_P^2}{n_1} + \frac{S_P^2}{n_2}} \qquad \text{equation A-11}$$

$$L = (\bar{x}_2 - \bar{x}_1) - t_{\frac{\alpha}{2},\,df} \sqrt{\frac{S_P^2}{n_1} + \frac{S_P^2}{n_2}} \qquad \text{equation A-12}$$

The value for $t_{\frac{\alpha}{2},\,df}$ is obtained from a table containing the t distribution for different levels of confidence.

The 90 percent confidence intervals computed for this analysis were used to describe the difference in the mean fatigue lives between the PMB treated and the "as received" specimens. In cases where zero is contained within the confidence interval, the difference in the mean fatigue lives is not considered to be statistically significant.

The 90 percent confidence intervals were presented in Tables 4.4-3 and 4.4-4 as upper and lower bounds for the percentage fatigue life gain. These upper and lower bounds were computed using the following equations:

$$UC = 100\left(10^{U} - 1\right) \qquad \text{equation A-13}$$

$$LC = 100\left(10^{L} - 1\right) \qquad \text{equation A-14}$$

where UC is the upper confidence bound, LC is the lower confidence bound, U is the upper level of confidence computed by equations A-6, A-11, and L is the lower level of confidence computed by equations A-7 and A-12.

Because the t-test requires that both populations being compared are normally distributed, it is not considered an appropriate means of comparing fatigue test samples that contain run-on tests. Therefore the Mann-Whitney U test was also used.

The Mann-Whitney Test

The Mann-Whitney test determines significance based on a ranking of the magnitudes of the sample values, rather than the values themselves and does not require a normal distribution. This test assumes that random samples have been obtained from each population, that the two samples are independent, and that the sample data are at least ordinal.

The procedure for administering the Mann-Whitney test is to assume $n_1 \leq n_2$ so that n_1 is the smaller sample size. The values for each sample are then combined into a padded sample and ranked by magnitude. The rankings of the two respective samples are summed, where T_1 is the sum of the n_1 rankings and T_2 is the sum of the n_2 rankings. Values for U_1 and U_2 are then determined according to the following equations:

$$U_1 = n_1 \bullet n_2 + \frac{n_1(n_1+1)}{2} - T_1 \qquad \text{equation A-15}$$

$$U_2 = n_1 \bullet n_2 + \frac{n_2(n_2+1)}{2} - T_2 \qquad \text{equation A-16}$$

These U values are then used to find a value from a table containing the distribution function for the Mann-Whitney statistic. If the value obtained from the table is less than the determined significance level then the two populations may be said to be statistically differing in location. The significance level, $\frac{\alpha}{2}$ is defined by the required confidence, where confidence equals $(1-\alpha)x100$ percent. For this analysis, 90 percent confidence or a significance level of 0.05 was used. The descriptions of these statistical methods are excerpted from reference 8.

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