Metallurgical Evaluation of Depainting Processes on Aluminum Substrate

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NOTICE

This material has been funded wholly or in part by Interagency Agreements among the U.S. Environmental Protection Agency (EPA), the National Aeronautics and Space Administration (NASA), and the U.S. Air Force (USAF). These agreements concern "Technical Assessment of Alternative Technologies for Aerospace Depainting Operations."

Mention of trade names or specific commercial products does not constitute endorsement or recommendation for their use.

EXECUTIVE SUMMARY

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In December 1993, the Environmental Protection Agency (EPA) Emission Standards Division and the National Aeronautics and Space Administration's (NASA's) Marshall Space Flight Center (MSFC) signed an Interagency Agreement (IA) initiating a task force for the technical assessment of alternative technologies for aerospace depainting operations. The United States Air Force (USAF) joined the task force in 1994. The mandates of the task force were:

- To identify available alternative depainting systems that do not rely on methylene chloride or other ozone-depleting, chlorinated, and volatile organic carbon solvents
- To determine the viability, applicability, and pollution prevention potential of each identified alternative
- To address issues of safety, environmental impact, reliability, and maintainability.

Through a Technical Implementation Committee (TIC), the task force selected and evaluated eight alternative paint stripping technologies: chemical stripping, carbon dioxide (CO_2) blasting, xenon flashlamp and CO_2 coatings removal (FLASHJET®), CO_2 laser stripping, plastic media blasting (PMB), sodium bicarbonate wet stripping, high-pressure water blasting (WaterJet), and wheat starch abrasive blasting (Enviro-Strip®). (The CO_2 blasting study was discontinued after the first depainting sequence.)

This final report presents the results of the Joint EPA/NASA/USAF Interagency Depainting Study. Significant topics include:

- Final depainting sequence data for the chemical stripping, PMB, sodium bicarbonate wet stripping, and WaterJet processes
- Strip rates for all eight technologies
- Sequential comparisons of surface roughness measurements for the seven viable depainting technologies
- Chronological reviews of and lessons learned in the conduct of all eight technologies
- An analysis of the surface roughness trends for each of the seven technologies
- Metallurgic evaluations of panels
- Summaries of corrosion and hydrogen embrittlement evaluations of chemical stripping panels, detailed descriptions of which appear in previous reports.

Because the requirements for alternative systems are diverse, as are initial setup, training, and on-going operational considerations, this study does not recommend a particular product or process. Users of this study will draw their own conclusions from the data presented herein.

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Brulin Corporation
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Carolina Equipment
Cold Jet, Inc.
Diversey Corporation
Dynacraft Industries
Ecolink, Inc.
Eldorado Chemical Company
Fine Organics Corporation
Gage Products Company
General Lasertronics Corporation
International Technical Associates
International Specialty Products
ManGill Chemical Company
Maxwell Laboratory
McGean-Rohco, Inc.
National Solvent Corporation
Orchem, Inc.
Pratt & Whitney
PyRock Chemical
Savogran Company
Silicon Alps
S&S Carbonic Industries
Titan Abrasive Systems
TOMCO$_2$ Equipment Company
Turco Products, Inc.

5. METALLURGIC EVALUATIONS

Metallurgic evaluations of corrosion potential, crack detectability, fatigue, and tensile strength were conducted on representative panels from each of the processes included in this study. Table 2.5.3 lists the processes and the specific evaluations each has undergone.

5.1 CORROSION TESTING

Several metallurgic evaluations were conducted to determine the corrosion potentials of the eight environmentally advantaged chemical strippers. The tests in this study were a subset of the prescribed corrosion evaluation tests listed in ISO/SAE MA4872 (draft 4), *Paint Stripping of Commercial Aircraft – Evaluation of Materials and Processes*. The following test methods were used to determine the corrosion and hydrogen embrittlement potentials that these chemicals may hold for clad and non-clad 2024-T3 aluminum substrates.

- American Society for Testing & Materials (ASTM) F483-90, *Standard Test Method for Total Immersion Corrosion Test for Aircraft Maintenance Chemicals*, was conducted to determine the corrosiveness of these chemicals with time on aircraft metals under conditions of total immersion by a combination of weight change measurements and visual qualitative determination of change. Since many aircraft maintenance chemicals are used on components and structures that would be affected adversely by excessive dimensional change, this test method screened the chemicals to ensure compliance with specified weight change criteria.
- ASTM F1110-90, *Standard Test Method for Sandwich Corrosion Test*, was conducted to evaluate the corrosivity of these chemicals on aluminum alloys commonly used for aircraft structures. This test method is used in the qualification and approval of compounds used in aircraft maintenance operations.
- ASTM F519-93, *Standard Test Method for Mechanical Hydrogen Embrittlement Testing of Plating Processes and Aircraft Maintenance Chemicals*, was conducted to evaluate any hydrogen embrittlement potential that may arise as various sources of hydrogen (plating processes, fluids, cleaning treatments, maintenance chemicals, gaseous environments that may contact the surface of steels) interact with substrates stripped with these chemicals.

Many aircraft maintenance chemicals are used on components and structures that are affected adversely by corrosion. Loss of material in a component because of corrosion can contribute to fatigue problems and reduce strength capability. Total immersion corrosion and sandwich corrosion are two test methods used in the qualification and approval of compounds used in aircraft maintenance operations to evaluate the corrosion potential of aircraft maintenance chemicals. Hydrogen embrittlement testing was performed to evaluate the potential of the paint stripping chemicals to embrittle cadmium-plated high-strength AISI 4340 steel.

The chemicals evaluated and their classification based on the manufacturers' reported pH levels were Gage Stingray 874B (neutral), Turco 6813 (alkaline), Turco 6813-E (alkaline), Turco 6840-S (alkaline), McGean-Rohco EZE 540[5]

[5]Calgon EZE 540 is now McGean-Rohco EZE 540.

(acidic), McGean-Rohco Cee-Bee E-1004B (acidic), Eldorado PR-2002 (acidic), and Turco 6776 (acidic). Two baseline methylene chloride chemicals, McGean-Rohco Cee-Bee R 256 (alkaline) and McGean-Rohco Cee-Bee A-202 (acidic) were also included. Manufacturers provided the chemicals reported in this study for evaluation. Mention of trade names or specific commercial products does not constitute endorsement or recommendation for or against their use. Clad aluminum tested was purchased in accordance with AMS 4041 and QQ-A-250/5 specifications. Non-clad aluminum tested was purchased in accordance with AMS 4037 and QQ-A-250/4 specifications. All aluminum substrates tested in this evaluation were 1.6 mm (0.064 in.) thick.

5.1.1 Total Immersion Corrosion Testing (ASTM F483-90)

The total immersion corrosion test is used to evaluate the corrosiveness of aircraft maintenance chemicals on aircraft metals. The test is conducted by immersing the substrate in the chemical for a prescribed time. Corrosiveness of the chemical is determined quantitatively by weight change and qualitatively by visual assessment. Photographs of total immersion samples are presented in Appendix 3.

Over 60 total immersion test coupons were fabricated with dimensions of 50.8 mm by 25.4 mm (2 in. by 1 in.) from 1.6-mm (0.064-in.) thick clad and non-clad 2024-T3 aluminum alloy. Non-clad material was anodized in accordance with MIL-A-8625C, Type 1 for chromic acid. All chemicals were tested in the as-received condition. The total immersion corrosion tests were conducted in accordance with ASTM F483-90; the samples were weighed 3 times: before testing, after 24 hours, and after 7 days of exposure.

Average weight loss rates for each of the chemicals are provided in Table 5.1.1-1. These measurements represent average weight loss di-

Table 5.1.1-1. Average Weight Loss Rates for Clad and Non-Clad 2024-T3 Test Coupons during Total Immersion Corrosion Testing

Chemical Tested	Weight Loss Rate ($mg/cm^2/24\ hr$)			
	Non-Clad 2024-T3		Clad 2024-T3	
	24-hr Exposure	168-hr Exposure	24-hr Exposure	168-hr Exposure
Turco 6813 (Alkaline)	0.0035	-0.0005	0.0000	-0.0025
Turco 6813-E (Alkaline)	0.0071	-0.0015	0.0000	-0.0020
Turco 6840-S (Alkaline)	0.0000	-0.0010	-0.0071	-0.0020
Stingray 874B (Neutral)	0.0000	-0.0005	0.0000	-0.0010
Cee-Bee R-256 (Alkaline baseline)	0.0000	0.0015	0.0000	-0.0015
Turco 6776 (Acidic)	0.3121	0.4189	0.2092	0.3440
EZE 540 (Acidic)	0.2943	0.2771	0.2624	0.2036
PR-2002 (Acidic)	0.0319	0.0709	0.0000	0.1054
Cee-Bee E-1004B (Acidic)	0.1986	0.1717	0.1773	0.1327
Cee-Bee A-202 (Acidic baseline)	0.2979	0.2594	0.1950	0.1753

vided by total coupon area (28.2 cm^2) expressed as loss in milligrams per square centimeter per 24 hours. The acceptable weight loss rate provided in the ISO/SAE MA4872 (draft) specification for non-clad 2024-T3 is 0.2 $mg/cm^2/24$ hr and for clad 2024-T3, 0.3 $mg/cm^2/24$ hr.

An assessment of these data suggests that almost no weight loss was exhibited over the test period by coupons treated with alkaline/neutral strippers. Negative numbers, indicating weight gains, are most likely related to the presence of remnant surface deposits, since these test coupons were not cleaned electrolytically.

Coupons treated with acid strippers showed significantly higher weight loss than coupons treated with alkaline/neutral strippers. Three of the five acidic strippers, including the methylene chloride baseline, had weight loss rates for non-clad material that exceeded the acceptable rate. For the clad material, one of the five chemicals, an alternative paint stripper, exhibited a weight loss rate exceeding the specification limits.

Summaries of the visual observations after 168 hours of exposure are shown in Tables 5.1.1-2 and 5.1.1-3 for non-clad and clad sub-

Table 5.1.1-2. Visible Changes in Non-Clad 2024-T3 Test Coupons after Total Immersion Corrosion Testing (168-hr Exposure)

Chemical Tested	Coupon Number	Discoloration or Dulling	Etching	Accretions Presence and Relative Amounts	Pitting	Selective or Localized Attack
Turco 6813 (Alkaline)	1, 2, 3	yes	no	no	no	no
Turco 6813-E Alkaline)	4, 5, 6	yes	no	no	no	no
Turco 6840-S (Alkaline)	7, 8, 9	no, small spots, no	no	no	no	no
Stingray 874B (Neutral)	10, 11, 12	very little, a little, no	no	no	no	no
Cee-Bee R-256 (Alkaline baseline)	13, 14, 15	very little, very little, no	no	no	no	no
Turco 6776 (Acidic)	16, 17, 18	yes (coupons whitened)	yes	no	no	no
EZE 540 (Acidic)	19, 20, 21	yes	yes	no	yes	yes
PR-2002 (Acidic)	22, 23, 24	yes (many spots)	yes	no	yes	yes
Cee-Bee E-1004B (Acidic)	25, 26, 27	yes	yes	no	yes	yes
Cee-Bee A-202 (Acidic baseline)	28, 29, 30	yes	yes	no	yes	yes

Table 5.1.1-3. Visible Changes in Clad 2024-T3 Test Coupons after Total Immersion Corrosion Testing (168-hr Exposure)

Chemical Tested	Coupon Number	Discoloration or Dulling	Etching	Accretions Presence and Relative Amounts	Pitting	Selective or Localized Attack
Turco 6813 (Alkaline)	49 50 51	some very little some	no	no	no	no
Turco 6813-E Alkaline)	52 53 54	some	no	no	no	no
Turco 6840-S (Alkaline)	55 56 57	very little	no	no	no	no
Stingray 874B (Neutral)	58 59 60	no	no	no	no	no
Cee-Bee R-256 (Alkaline baseline)	61 62 63	some very little very little	no	no	no	no
Turco 6776 (Acidic)	64 65 66	yes (coupons whitened)	yes	no	no	no
EZE 540 (Acidic)	67 68 69	yes	yes	no	no	no
PR-2002 (Acidic)	70 71 72	yes some yes	yes	no	yes no yes	yes no yes
Cee-Bee E-1004B (Acidic)	73 74 75	yes	yes	no	yes	no
Cee-Bee A-202 (Acidic baseline)	76 77 78	yes	yes	no	yes	yes

strates, respectively. The visual requirement set forth in the ISO/SAE MA4872 (draft 4) specification is that no evidence of corrosion be present on the samples. The alkaline/neutral strippers produced no visible etching, pitting, or accretions (corrosion product) on any samples.

The acidic strippers demonstrated signs of etching on all samples, both clad and non-clad. All acid chemicals, with one exception (Turco 6776), promoted pitting and localized attack of the non-clad substrate. With respect to the clad substrate, two acid chemicals (Turco 6776 and EZE 540) showed no signs of pitting or localized attack; three acid chemicals (Turco 6776, EZE 540, and Cee-Bee E-1004B) showed no signs of localized attack. No accretions were noted on any samples.

5.1.2 Sandwich Corrosion Testing (ASTM F1110-90)

Sandwich corrosion testing was performed to evaluate the corrosion potential of chemicals entrapped in faying surfaces. Sandwich corrosion test coupons were fabricated from 1.6-mm (0.064-in.) clad and non-clad 2024-T3 aluminum alloy. Non-clad material was anodized per

MIL-A-8625C, Type 1 for chromic acid. Testing was performed per ASTM F1110–90. Photographs of the sandwich corrosion test samples are provided in Appendix 3.

Four test coupon sandwiches were tested per chemical per alloy, each comprised of two individual test coupons sandwiched together in pairs of the same alloy and surface treatment. Both clad and non-clad sandwiched pairs were used to test all chemicals, and all chemicals were mixed thoroughly to ensure uniformity before being applied to the test coupons. Four coupon sandwiches were tested with reagent deionized water as controls for comparative purposes.

In each case, a piece of glass fiber filter paper was fit over one coupon of the sandwiched pair. The filter paper was then saturated with the as-received test solution, and the wet paper was covered with the second coupon of the sandwiched pair. The specimens were exposed alternately to warm air and warm humid air for 7 days. Each set was exposed individually (not stacked) in a horizontal position. After exposure, the panels were cleaned, examined under 10x magnification, and assigned a qualitative rating per ASTM F1110-90, as shown in Table 5.1.2-1.

Table 5.1.2-1. Rating Scale for Sandwich Corrosion Testing

Rating	Condition
0	No visible corrosion
1	Very slight corrosion or discoloration (up to 5% of the surface area corroded)
2	Slight corrosion (5 to10% of the surface area corroded)
3	Moderate corrosion (10 to 25% of the surface area corroded)
4	Extensive corrosion or pitting (25% or more of the surface area corroded)

Corrosion ratings were compared between coupons tested with chemicals and coupons tested with reagent water. These comparisons only considered the surfaces under the filter paper, and any corrosion at the edges was disregarded. In accordance with the ASTM specification, any corrosion in excess of that shown by the deionized water was considered cause for rejection.

Test results (ratings) from the sandwich corrosion testing are presented in Table 5.1.2-2. The coupons tested with reagent water showed significant discoloration and spotting over the surface. Pitting on coupons in reagent water was also evident. As a result, the coupons tested in reagent water were given a corrosion rating of 3. All alkaline/neutral chemicals performed better than the reagent water. On the non-clad material, the three alternate alkaline chemicals performed as well or better than the methylene chloride baseline. The neutral chemical did not perform as well as the baseline. On clad material, the methylene chloride baseline performed better than all four of the alternate alkaline/neutral chemicals.

On the non-clad material, the acidic chemicals caused more corrosion than the reagent water. The alternate chemicals performed the same as the methylene chloride baseline on the non-clad material. On clad material, four of the five acidic chemicals, including the methylene chloride baseline, performed as well or better than the reagent water. One of the four alternate chemicals performed the same as the methylene

Table 5.1.2-2. Sandwich Corrosion Test Results

Chemical Tested	Non-Clad 2024-T3		Clad 2024-T3	
	Sandwich Number	Rating	Sandwich Number	Rating
Deionized Water (per ASTM D1193, Type IV)	1	3	121	3
	3	3	123	3
	5	3	125	3
	7	3	127	3
Turco 6813 (Alkaline)	9	1	129	3
	11	2	131	3
	13	2	133	3
	15	3	135	3
Turco 6813-E (Alkaline)	17	2	137	2
	19	2	139	3
	21	2	141	2
	23	2	143	3
Turco 6840-S (Alkaline)	25	3	145	2
	27	3	147	3
	29	2	149	2
	31	2	151	3
Stingray 874B (Neutral)	33	3	153	3
	35	3	155	3
	37	3	157	3
	39	3	159	3
Cee-Bee R-256 (Alkaline baseline)	41	2	161	1
	43	3	163	2
	45	2	165	2
	47	3	167	1
Turco 6776 (Acidic)	49	4	169	3
	51	4	171	3
	53	4	173	3
	55	4	175	3
EZE 540 (Acidic)	57	4	177	3
	59	4	179	4
	61	4	181	3
	63	4	183	3
PR-2002 (Acidic)	65	4	185	3
	67	4	187	3
	69	4	189	3
	71	4	191	3
Cee-Bee E-1004B (Acidic)	73	4	193	3
	75	4	195	2
	77	4	197	3
	79	4	199	2
Cee-Bee A-202 (Acidic baseline)	81	4	201	3
	83	4	203	2
	85	4	205	2
	87	4	207	3

chloride baseline; the remaining three chemicals performed worse than the baseline.

5.1.3 Hydrogen Embrittlement Mechanical Testing (ASTM F519-93)

Hydrogen embrittlement testing was performed to evaluate the potential of the paint stripping chemicals to embrittle cadmium-plated, high-strength AISI 4340 steel. Test specimens were Type 1A notched round tensile specimens fabricated from AISI 4340 steel that was heat treated per MIL-H-6875 to obtain a hardness of 51 to 54 Rockwell C hardness (HR_C) with an ultimate tensile strength of 1800 to 1930 MPa (260 to 280 ksi). The sensitivity of the 4340 steel to embrittlement was determined using the methodology presented in ASTM F519-93. After machining, the notched round tensile specimens were degreased, dry abrasive blasted with alumina, rinsed with tap water and immediately electroplated using a low-embrittlement cadmium cyanide bath. After electroplating, the specimens were baked at 191 ±14 °C (375 ±25 °F) for 23 hours.

Each chemical was tested in the as-received condition at 20 to 30 °C (68 to 86 °F). The containment chamber was isolated around the test specimens, and the specimens were completely submerged in the chemical. Three specimens per chemical were assembled and loaded in tension to 45 percent of the notched ultimate tensile strength. Constant strain test fixtures (as opposed to constant load test fixtures) were used to conduct the tests. To ensure that no load relaxation occurred during the test, the recovered strain was measured upon unloading the non-failed specimens and compared to the initial strain required to load the specimen to confirm that the initial load was maintained. The loaded specimens were immersed in the chemicals, and the time to failure was recorded. The test was discontinued after 150 hours. According to ASTM F519-93, a chemical is considered non-embrittling under the conditions tested if no specimens fail within 150 hours after immersion in the chemical at 45 percent of the notch tensile strength. A chemical is considered embrittling under the conditions tested if 2 or more break in less than 150 hours.

Results of the hydrogen embrittlement testing, along with measured pH values of the chemicals, are presented in Table 5.1.3. Time to failure is listed either in actual hours or in the time interval in which the specimen failed. The failure ratio is the number of specimens that failed over the number of specimens tested under the same conditions.

The acidic chemicals, including the methylene chloride baseline, failed this test. All specimens failed within 48 hours of exposure; all, however, exhibited average failure times that exceeded that of the methylene chloride baseline. Scanning electron microscopy of failure surfaces revealed a large region of intergranular fracture. Metallographic cross sectioning of these samples revealed secondary cracking below the failure surface indicative of grain boundary attack.

Two of three Group 1 specimens tested in the neutral chemical (Stringray 874B) failed between 98 and 145 hours, indicating an embrittling chemical. Microscopy and metallography of these specimens revealed a region of the failure surface exhibiting an intergranular fracture with secondary cracking. The remaining specimen that passed the test was loaded to failure and exhibited a ductile failure surface.

Reports from independent laboratory tests indicated acceptable performance of Stingray 874B. One possible explanation for the discrepancy is that the measured pH level for the chemical used in this study was 5.7, which is slightly lower (more acidic) than the pH range for the chemical as reported by the manufacturer (6.5 - 7.0). The lower pH levels may explain why the Group 1 specimens failed and specimens from outside laboratory testing passed. In an effort to corroborate our results, three additional samples were tested and are listed in Table 5.1.3 as Group 2 specimens.

All Group 2 specimens met the 150-hour exposure requirement. For investigative purposes, exposure time was extended to 200 hours, and one specimen failed after 191 hours. HR_c measurements on the Group 2 specimens, however, indicated hardness values 3 to 4 points below those of the Group 1 samples. The sensitivity of 4340 steel to stress corrosion decreases with hardness; this reduction may account for the enhanced performance of the Group 2 specimens when compared with that of the Group 1 specimens.

All specimens tested in the alkaline chemicals passed the test with no failures. Test specimens loaded to failure after 150 hours of exposure exhibited ductile failure surfaces.

5.1.4 Conclusions

Test data indicate that alternate alkaline/neutral chemical paint strippers perform as well or better than a methylene chloride baseline with

Table 5.1.3. Results of Hydrogen Embrittlement Test

Chemical Tested	pH Values (as tested)	Failure Ratio	Time to Failure (hr or time interval)
Turco 6813 (Alkaline)	9.8	0/3	No Failures
Turco 6813-E (Alkaline)	9.9	0/3	No Failures
Turco 6840-S (Alkaline)	9.3	0/3	No Failures
Stingray 874B – Group 1 (Neutral)	5.7	2/3	98-145 128-143
Stingray 874B – Group 2 (Neutral)	5.7	1/3 (See note.)	191-198
Cee-Bee R-256 (Alkaline baseline)	8.0	0/3	No Failures
Turco 6776 (Acidic)	2.0	3/3	4.5 6 28-48
EZE 540 (Acidic)	2.5	3/3	0.5 8-24 8-24
PR-2002 (Acidic)	2.5	3/3	0.5 7-23 31-47
Cee-Bee E-1004B (Acidic)	2.4	3/3	1.75 1.75 1.75
Cee-Bee A-202 (Acidic baseline)	1.3	3/3	0.5 0.5 0.5

Note: Exposure time for the Group 2 specimens was extended to 200 hours.

respect to corrosion requirements. In general, these alternate alkaline/neutral chemical paint strippers also meet corrosion acceptance criteria as specified in ISO/SAE MA4872 (draft 4).

All alkaline chemical paint strippers and one group of the neutral chemical paint stripper met the specification requirements for hydrogen embrittlement. All four alternate acidic chemical paint strippers, tested with respect to corrosion and hydrogen embrittlement requirements, performed as well or better than the methylene chloride baseline. These chemicals, however, did not generally meet corrosion acceptance criteria for non-clad material or hydrogen embrittlement acceptance criteria as specified in ISO/SAE MA4872 (draft 4).

5.2 TENSILE TESTING (ASTM E8)

Tensile tests were performed on non-clad and clad baseline panels, non-clad and clad plastic media blasting panels, and non-clad FLASHJET® panels. (Tensile testing was planned for the remaining processed panels but was deleted to obtain additional fatigue data for the panels.)

A summary of the tensile results is provided in Table 5.2. The substrate material is aluminum alloy 2024-T3, and the tensile tests were conducted in the longitudinal direction. Data listed for each process and the clad baseline are based on one tensile test. Data listed for the non-clad baseline are averages of three tensile tests. Additionally, A-Basis design data values from MIL-HDBK-5G, *Metallic Materials and Elements for Aerospace Vehicles and Structures*, November 1994, are provided for comparison for non-clad and clad material.

Tensile properties of processed and baseline material exceeded the design values for the material, with the exception of the yield strength of FLASHJET® panel IV-15.10. The yield strengths for the panels tested, however, ex-

Table 5.2. Tensile Test Data Summary (2024-T3 Aluminum, Longitudinal Direction)

Depainting Process	Clad/Non-clad	Ultimate Tensile Strength (ksi)	Yield Strength (ksi)	Elongation (%)
Baseline	Non-clad	70.6	51.7	18.4
Xenon Flashlamp/CO_2				
Panel IV-15.7	Non-clad	71.0	51.1	15.7
Panel IV-15.10	Non-clad	67.3	45.6	14.7
Plastic Media Blasting				
Panel VII-VIII 29.16	Non-clad	71.9	52.1	15.9
Panel VII-21.28	Non-clad	71.4	51.5	17.7
MIL-HDBK-5G	Non-clad	64	47	(See note.)
Baseline	Clad	67.8	49.1	16.3
Plastic Media Blasting				
Panel VII-40.4	Clad	68.2	49.8	16.9
Panel VII-40.2	Clad	68.6	50.3	17.1
MIL-HDBK-5G	Clad	60	44	(See note.)

Note: Elongation data are not provided in MIL-HDBK-G.

ceeded the maximum stress amplitude (45 ksi) used in the fatigue testing.

5.3 FATIGUE TESTING (ISO/SAE MA4872)

Fatigue tests were performed on processed panels in an attempt to determine whether the process impacted fatigue life of the material. Baseline testing was performed to provide a measure of fatigue life for comparison. Unfortunately, only a limited number of process panel specimens were tested, making a statistical assessment of the process affect on fatigue life unfeasible. For completeness, however, the procedure for generating data and a summary of test results are provided.

Fatigue tests were run on non-clad and clad baseline panels, on non-clad and clad plastic media blasting panels, and on non-clad FLASHJET®, high-pressure water blasting, and EnviroStrip® wheat starch blasting panels. Figure 5.3-1 shows the fatigue life test setup. Markings on the test specimen assist in identifying the coupon segment in which a fatigue feature appears. A sketch of the fatigue specimen appears in appendix 3.2.

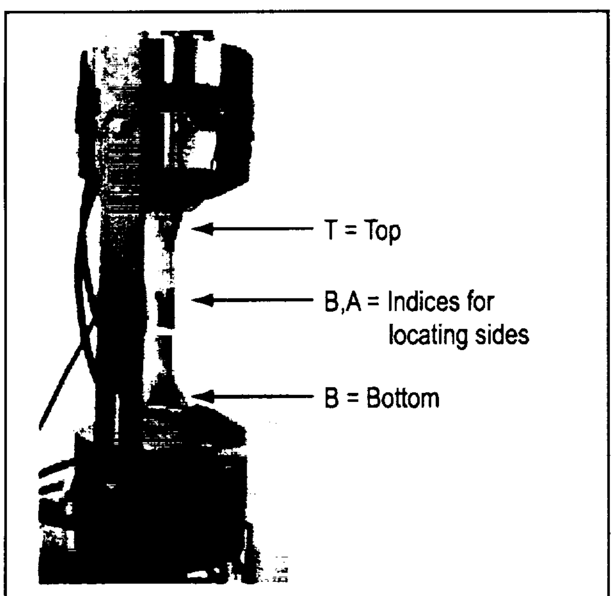


Figure 5.3-1. Fatigue Life Testing Setup

In general, specimens were machined conventionally from the panels. Specifically, they were sheared, stacked, and milled using a computer numerical control machine. The wheat starch specimens, however, were electro-discharge machined (EDM) from the panels.

Constant amplitude tension fatigue testing was performed at a maximum stress of 45 ksi, a stress ratio of R=0.1, and a frequency of 10 Hz. The 45-ksi maximum stress level for fatigue testing is below the measured yield strength of the baseline and test panels. Testing was performed in the longitudinal direction on 0.016-in. thick non-clad and clad 2024-T3 aluminum sheet.

To ensure proper alignment, a test coupon was instrumented with a series of 10 longitudinal strain gauges. This specimen was used to develop a standard loading methodology that would result in a uniform strain distribution across the specimen. Periodic checks were made with the instrumented specimen to verify alignment. Typically, strain readings across the specimen were within 1.5 percent.

The baseline data for clad and non-clad panels are shown in Figure 5.3-2. Baseline data for non-clad specimens were collected from 12 panels, each panel being cut from a different sheet of aluminum. Some non-clad baseline data panels were taken from sheets that were not subjected to depainting processes. Also, some non-clad sheets subjected to depainting processes did not have baseline fatigue test specimens cut from them. Baseline data for clad specimens were taken from the same sheet from which the processed panel fatigue data

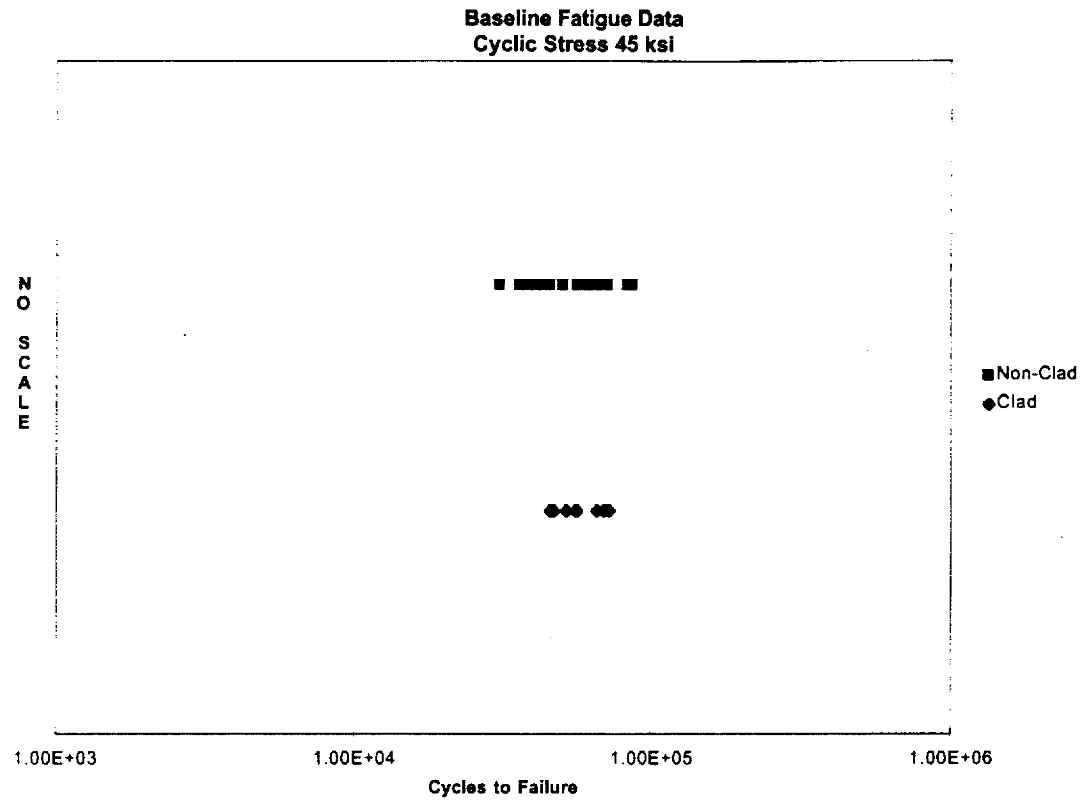


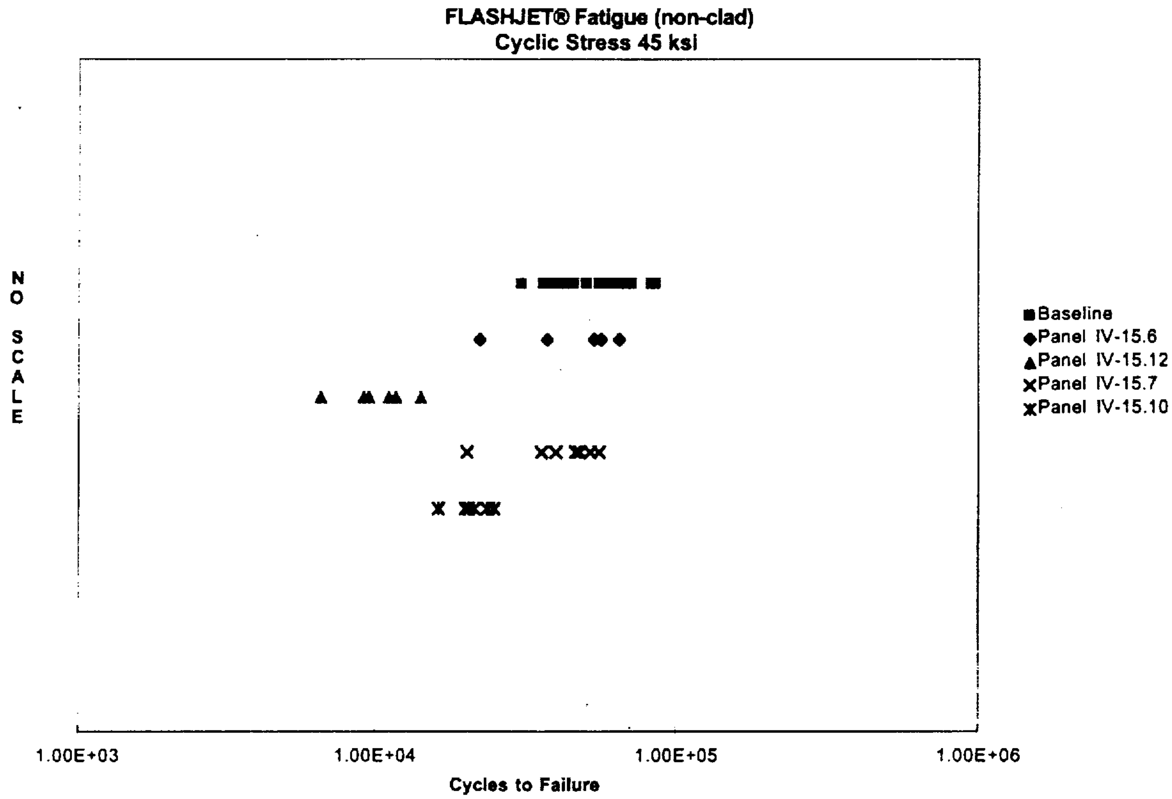
Figure 5.3-2. Baseline Fatigue Data, 2024-T3 Aluminum

were collected. Baseline fatigue data were screened only with respect to failure location. Test specimens that failed outside the gauge length, including specimens that failed at the radius of the specimen, were excluded from the baseline database.

Data for individual depainting processes appear in Figures 5.3-3 through 5.3-7. Figures 5.3-3, 5.3-4, 5.3-6, and 5.3-7 show the test panel data with respect to non-clad baseline data. Figure 5.3-5 shows processed PMB clad panel data with respect to PMB clad baseline data.

The mean fatigue life and standard deviation are shown in Table 5.3. These statistical values are based on an assumed log-normal distribution of the fatigue life. Additionally, the 95-percent confidence intervals for the mean value of each process are provided in Table 5.3. Fatigue data for individual panels appear in Appendix Table A-3.2. These data were generated to support statistical comparisons between baseline and processed data. Specifically, t-tests were performed to determine whether there was a statistically significant difference between the mean values of the baseline and the processed panel fatigue lives. The large standard deviation in the mean fatigue life and the small sample size precluded any significant statistical analysis, however.

The 95-percent confidence intervals for the mean fatigue life of FLASHJET® processed panels IV-15.6 and IV-15.7 overlapped the 95-percent confidence interval for the mean fatigue life of the baseline data. The 95-percent confidence intervals for the mean fatigue life of FLASHJET® panels IV-15.10 and IV-15.12 fell below the 95-percent confidence interval for the



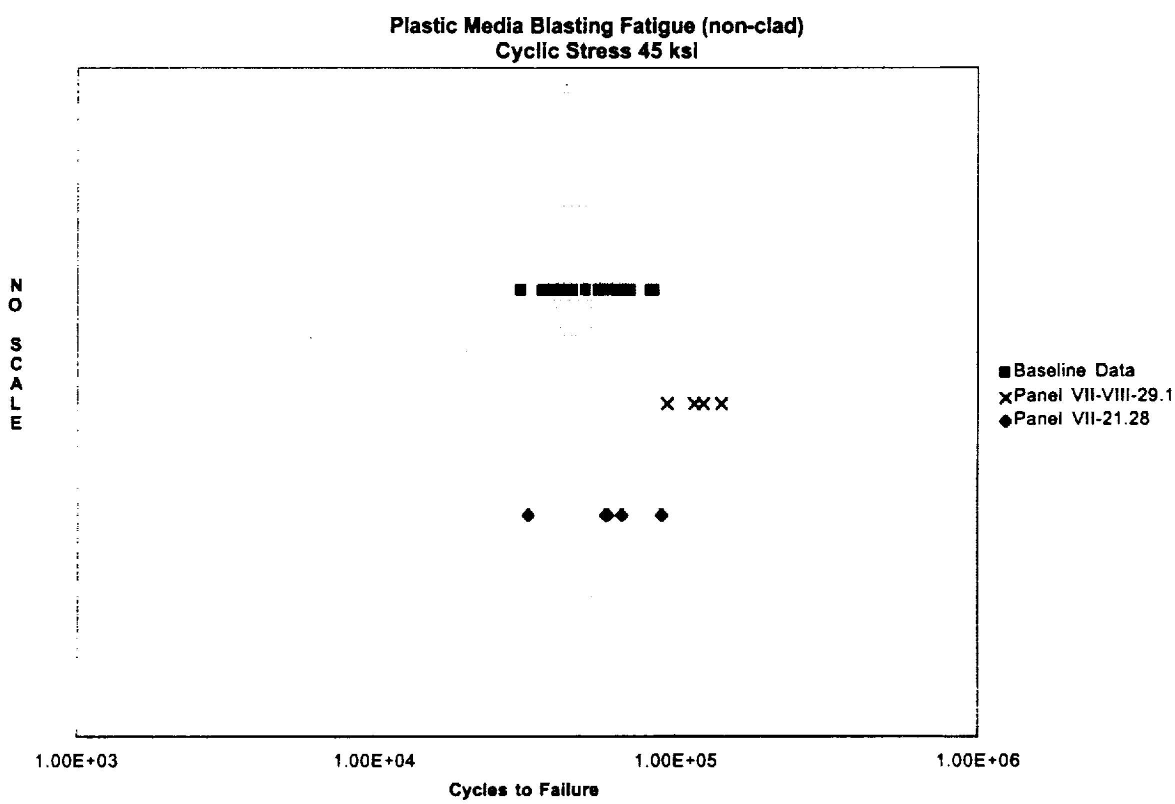


Figure 5.3-4. Fatigue Testing Results for Non-Clad Panels Depainted by the Plastic Media Blasting Process

Figure 5.3-3. Fatigue Testing Results for Panels Depainted by the FLASHJET® Process

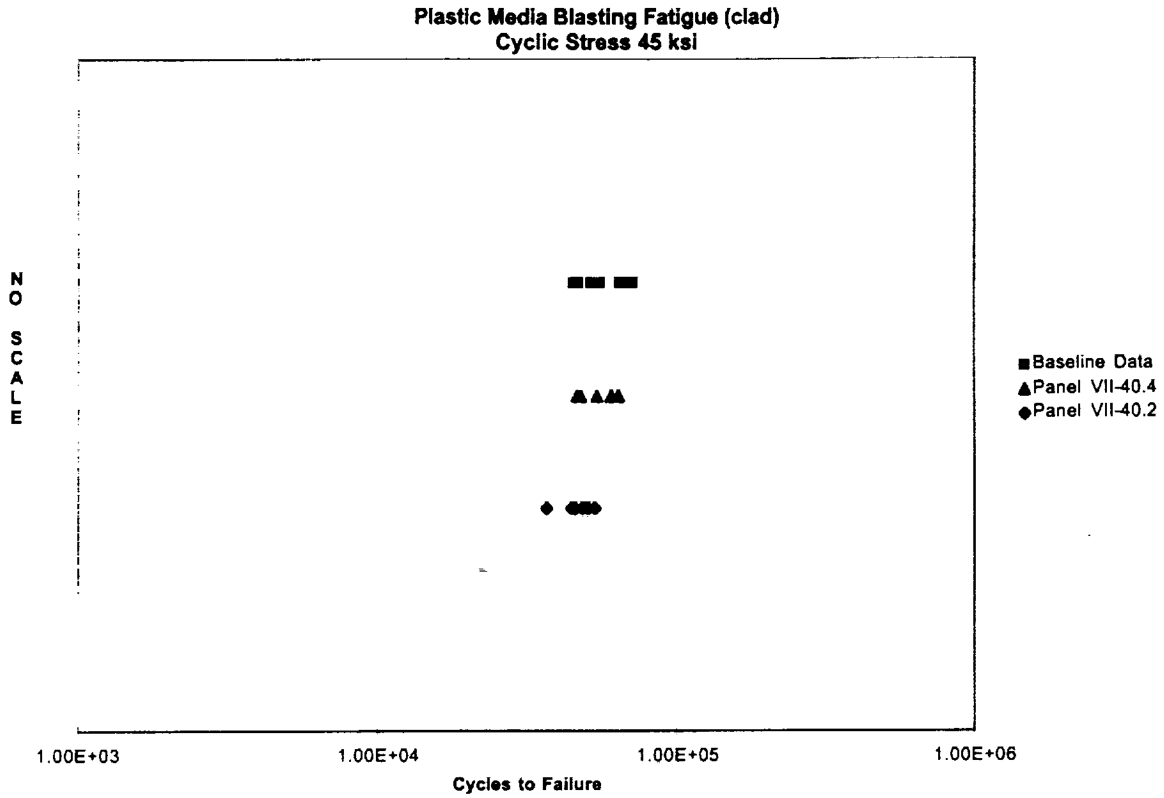


Figure 5.3-5. Fatigue Testing Results for Clad Panels Depainted by the Plastic Media Blasting Process

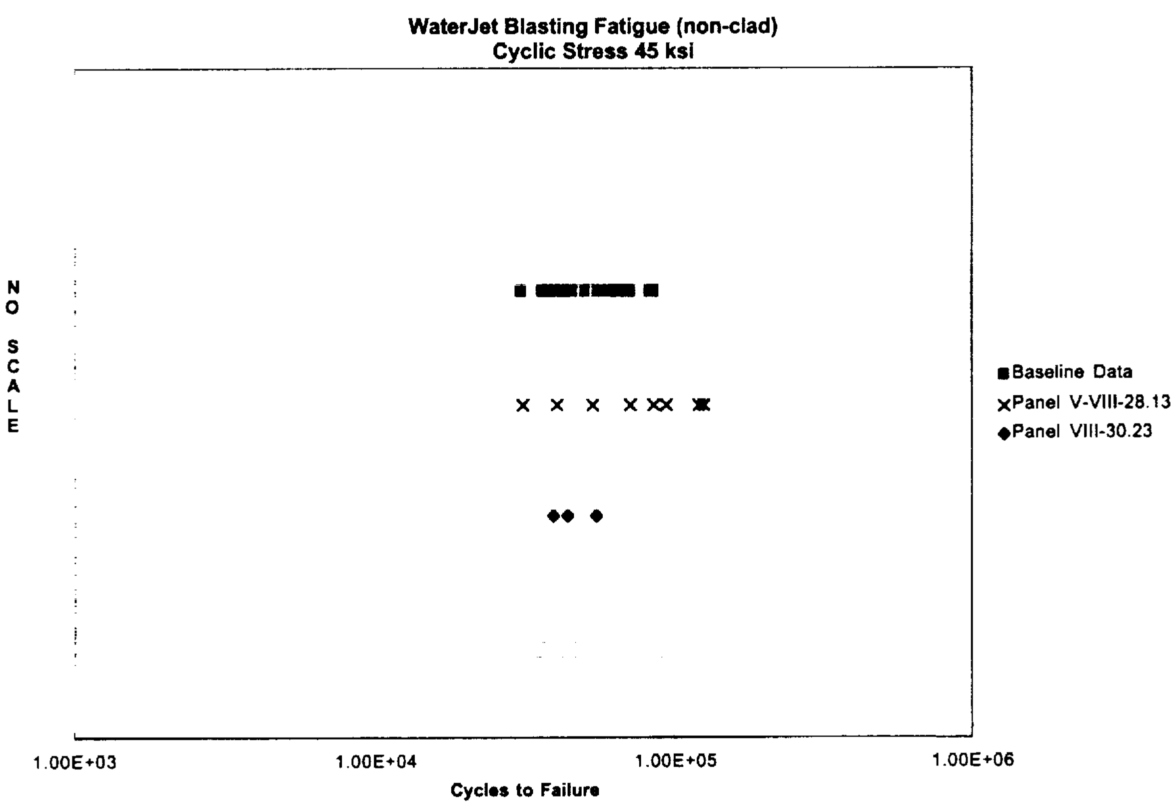


Figure 5.3-6. Fatigue Testing Results for Panels Depainted by the WaterJet Process

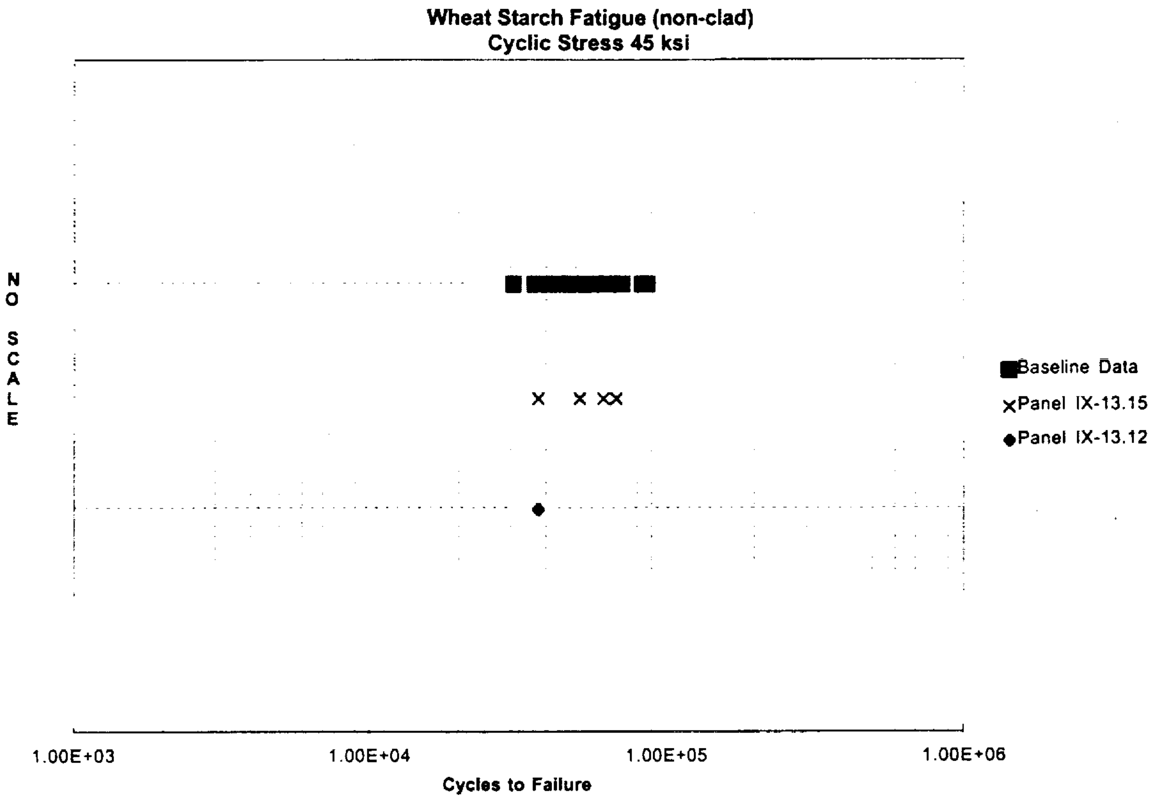


Figure 5.3-7. Fatigue Testing Results for Panels Depainted by the EnviroStrip® Wheat Starch Blasting Process

Table 5.3. Mean Fatigue Life and Standard Deviation from Fatigue Life Testing

Depainting Process	Clad or Non-clad	Number of Samples	Mean Fatigue Life (cycles)	Standard Deviation (cycles)	95% Confidence Intervals for Mean Fatigue Life (cycles)	
					Lower	Higher
Baseline	Non-clad	22	54,118	15,231	47,753	60,482
Xenon Flashlamp/CO_2						
Panel IV-15.6	Non-clad	5	47,804	21,478	28,978	66,630
Panel IV-15.7	Non-clad	7	43,058	15,298	31,725	54,390
Panel IV-15.10	Non-clad	6	21,048	3,124	18,549	23,543
Panel IV-15.12	Non-clad	6	10,351	2,779	8,128	12,575
Plastic Media Blasting						
Panel VII-VIII-29.16	Non-clad	4	119,249	20,852	98,815	139,683
Panel VII-21.28	Non-clad	5	62,173	23,901	41,224	83,123
High-Pressure Water Blasting						
Panel V-VIII-28.13	Non-clad	8	79,457	42,735	49,843	109,070
Panel VIII-30.23	Non-clad	3	46,112	8,038	37,016	55,208
Wheat Starch Blasting						
Panel IX-13.12	Non-clad	1	37048[1]	Note 2	Note 2	Note 2
Panel IX-13.15	Non-clad	4	54,827	14,704	40,418	69,238
Baseline	Clad	8	57,488	9,967	50,582	64,395
Plastic Media Blasting						
Panel VII-40.4	Clad	6	55,396	7,333	49,529	61,264
Panel VII-40.2	Clad	7	46,579	5,575	42,450	50,709

Notes: 1. Only one specimen from wheat starch blasting panel IX-13.12 failed in the gauge section; this figure is the actual number of cycles performed to fatigue the specimen.
2. No data are available for these categories since only one specimen from this panel failed in the gauge section.

baseline mean fatigue life. The low fatigue life in panel IV-15.12 is the result of extensive surface pitting of the material (Figure 5.3-8). As evident in the figure, pits along the failure surface served as crack initiation sites. Fatigue crack growth emanated from several of these sites until the critical fracture toughness or critical net section failure stress was reached.

No evidence suggests that the FLASHJET® process promotes surface pitting. The 2024-T3 alloy (non-clad) is sensitive to general corrosion, and the pitting on test specimens is characteristic of general corrosion. Figure 5.3-9 provides a visual comparison of the fracture surfaces of specimens from additional FLASHJET® panels. Note the absence of any corrosion pitting along these surfaces.

The reduction in fatigue life of panel IV-15.10 is likely related to the strength properties of this panel. Note from Table 5.2 that the yield strength of this panel was below the MIL-HDBK-5G minimum. The measured yield strength (45.6 ksi) is very close to the cyclic stress level used in the fatigue test (45 ksi). Panel IV-15.10 was cycled at 99 percent of its yield strength, in contrast to the baseline panels,

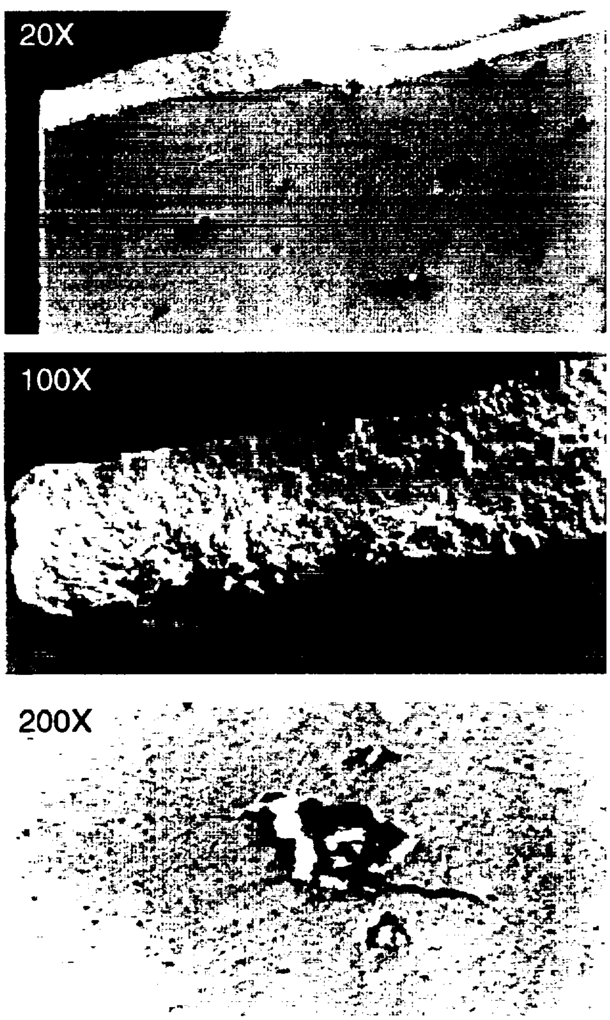


Figure 5.3-8. FLASHJET® Surface Pitting (Panel IV-15.12)

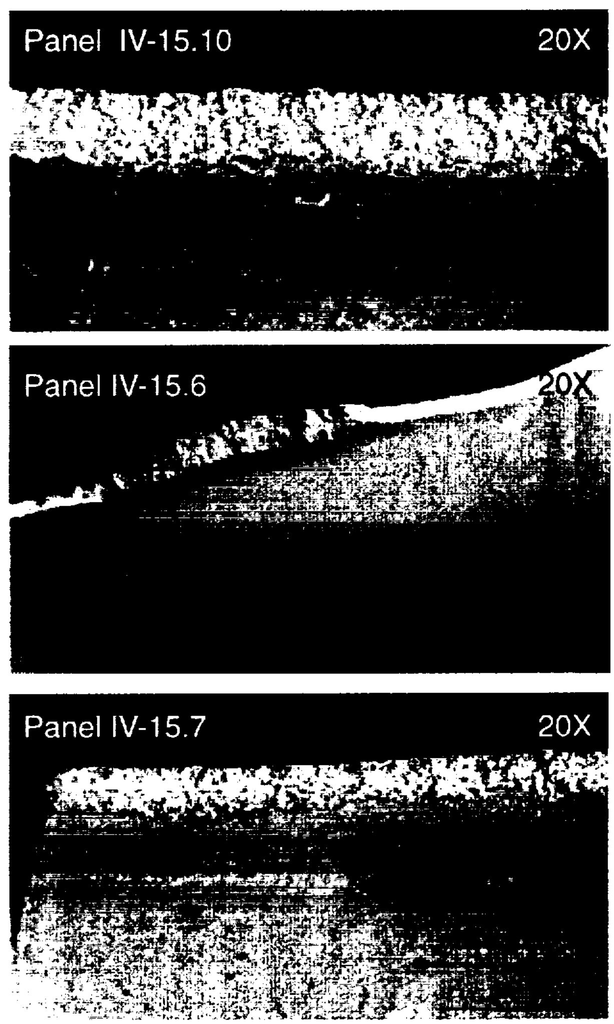


Figure 5.3-9. FLASHJET® Fracture Surfaces (Panels IV-15.10, IV-15.6, and IV-15.7)

which were cycled at approximately 87 percent of their yield strength.

Both non-clad plastic media blasting panels exhibited a mean fatigue life above the baseline mean fatigue life. This enhancement may be caused by residual compression on the surface of the specimen, a result of the PMB process. The 95-percent confidence interval for the mean fatigue life of the clad panels overlapped the baseline estimate for mean fatigue life intervals.

Wheat starch panel fatigue lives also overlapped the baseline estimates. Unfortunately, several of the wheat starch panel specimens failed at the radius of the test specimen gauge section. As previously noted, test specimens exhibiting failures outside the gauge length of the test specimen, including failures at the radius, were considered invalid. The preponderance of failures at the radius of the wheat starch specimens is likely the result of both test sample preparation and stress concentration at the radius. It was noted, after testing, that the wheat starch specimens had been electro-discharge machined from the test panels. EDM operations generally produce a small, brittle, recast layer at the edges of the cut. This layer was removed from the gauge section of the specimen by sanding but was not removed consistently from the radius section of the specimen. The combination of stress concentration and recast material resulted in failure initiation at the radius.

High-pressure water blasting fatigue data indicated fatigue lives comparable to baseline data for panel set VIII-30.23 but showed significantly higher lives for panel set V-VIII-28.13. The increased fatigue lives may be caused by residual compression in the surface of the substrate as a result of the water impact.

5.4 CRACK DETECTABILITY TESTING (ISO SAE MA4872)

Panels depainted by the plastic media blasting, WaterJet blasting, sodium bicarbonate wet stripping, and EnviroStrip® wheat starch blasting processes underwent crack detectability testing to determine whether the effects of these processes might inhibit the detection of substrate cracks. The crack detectability specimens (4 in. wide by 12 in. long) were cut from 0.064-in. thick 2024-T3 aluminum sheets. Testing for the plastic media blasting process was performed on clad and non-clad materials. Testing for the other processes was performed on clad material only.

After the panels were painted for the first time and cured for 24 hours at an elevated temperature [50 ±3 °C (122 ±5 °F)], the specimens were precracked using low stress intensities (less than 15 ksi$\sqrt{\text{in.}}$) to minimize plastic deformation at the crack tip. Cracks were then grown at least 1 in. out of each side of electro-discharge machined notches, and initial crack length measurements were made on each specimen, using high-frequency eddy current.

Crack length was measured again in cycle 1 after the test specimens were depainted. The same inspector made the initial and final crack length measurements. Crack length measurements were made to the nearest 1/64 inch. Cycle 1 crack length measurements were then compared to the initial measurements to assess crack closures and/or reductions in crack detectability. Table 5.4-1 presents results of the crack detectability testing. The data presented in Table 5.4-1 are represented graphically in Figure 5.4.

To assess the crack detectability data, a 95-percent confidence interval for the mean dif-

Table 5.4-1. Crack Detectability Results

Process	Specimen Number	Clad (y/n)	Crack Length (1/64 in.)		Process	Specimen Number	Clad (y/n)	Crack Length (1/64 in.)	
			Initial	Cycle 1				Initial	Cycle 1
Plastic Media Blasting	CD-10	n	158	164	Sodium Bicarbonate Wet Stripping	CD-2	n	162	154
	CD-11	n	158	168		CD-3	n	164	152
	CD-13	n	160	158		CD-20	n	177	170
	CD-15	n	162	162		CD-21	n	164	160
	CD-12	y	164	162		CD-22	n	160	158
	CD-14	y	164	176		CD-24	n	158	158
	CD-16	y	152	162		CD-25	n	160	160
	CD-17	y	161	162		CD-26	n	162	156
	CD-18	y	158	162		CD-27	n	160	158
	CD-19	y	173	170		CD-28	n	160	160
WaterJet	CD-30	n	166	160		CD-29	n	170	172
	CD-31	n	168	156	EnviroStrip® Wheat Starch	CD-40	n	160	166
	CD-32	n	143	156		CD-41	n	161	154
	CD-33	n	165	160		CD-42	n	160	160
	CD-34	n	170	162		CD-43	n	160	166
	CD-36	n	164	154		CD-44	n	163	164
	CD-37	n	160	158		CD-45	n	163	160
	CD-38	n	163	160		CD-46	n	157	160
	CD-39	n	154	152		CD-47	n	173	172

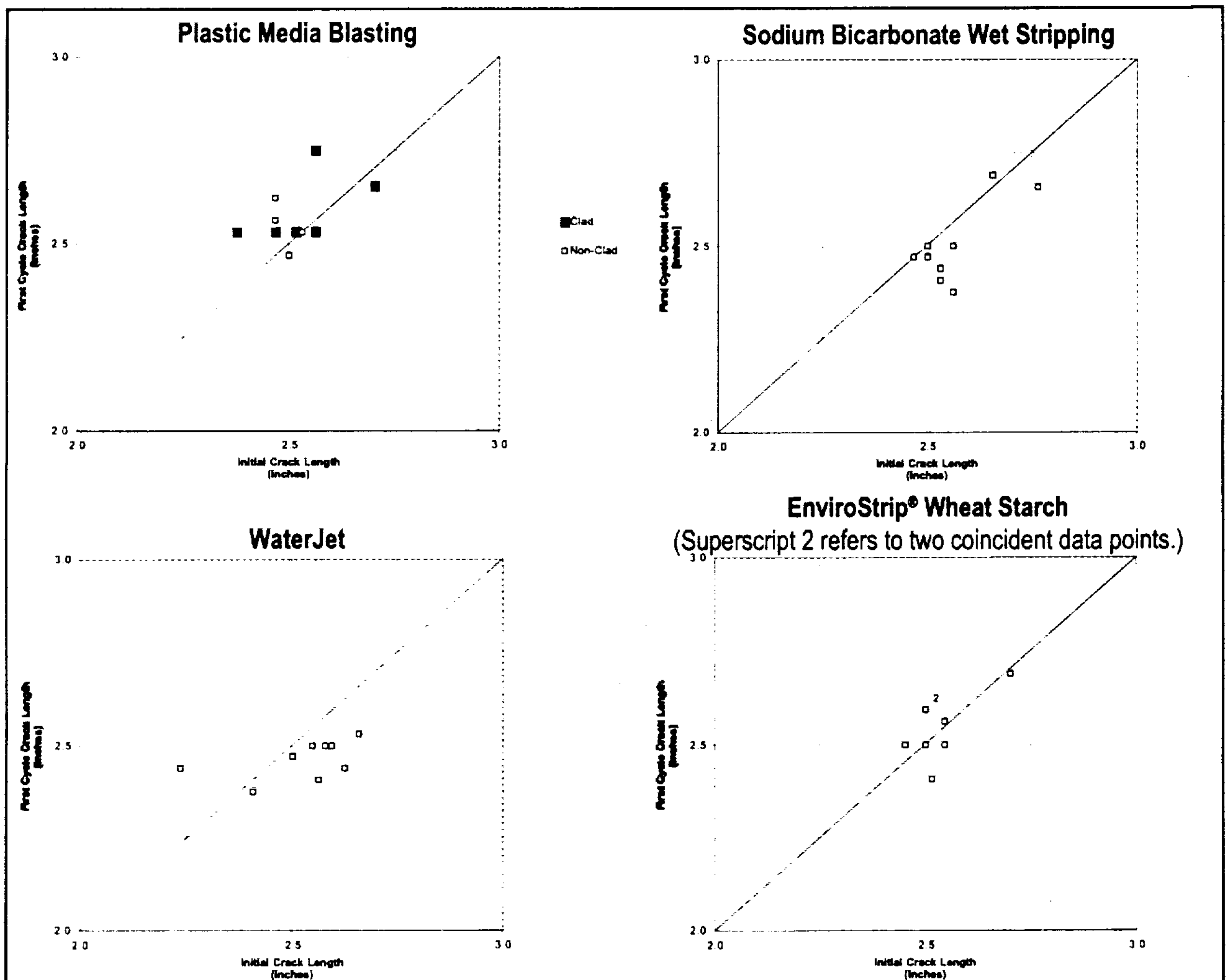


Figure 5.4 Initial versus First-Cycle (Poststrip) Crack Length Measurements

ference between initial and final crack lengths was calculated for each process. These intervals are shown in Table 4.5-2. Intervals containing zero indicate that, based on the limited data, there is no effect of processing on crack detectability. The sodium bicarbonate wet stripping process data indicated a non-zero mean, signifying a decrease in the detectable crack length of these processed panels.

5.5 ACKNOWLEDGMENTS

The MSFC points of contact for metallurgic evaluations have been ED33/Pablo Torres at (256) 544-2616, ED33/Dr. Preston McGill at (256) 544-2604, ED33/Hansel Gill at (256) 544-9027, and Pete Belcher (retired). The study team thanks Mr. Torres, Dr. McGill, Mr. Gill and Mr. Belcher for their contributions to the project.

Table 5.4-2. Differences in Pre- and Postprocessed Panel Crack Length

Process	Clad (y/n)	Average Difference (1/64 in.) (Cycle 1 - Initial)	Standard Deviation	Sample Size	95% Confidence Interval for Mean of the Difference	
Plastic Media Blasting	n	3.5	5.51	4	-1.9	8.9
	y	3.67	6.22	6	-1.31	8.64
Sodium Bicarbonate Wet Stripping	n	-3.55	4.27	11	-6.07	-1.02
WaterJet Blasting	n	-3.89	7.24	9	-8.62	0.84
EnviroStrip® Wheat Starch Blasting	n	0.63	4.44	8	-2.45	3.7

APPENDIX 3. METALLURGIC EVALUATION RESULTS

A-3.1 CORROSION RESULTS

Figures A-3.1.1 and A-3.1.2 show represemtative samples after sandwich corrosion testing.

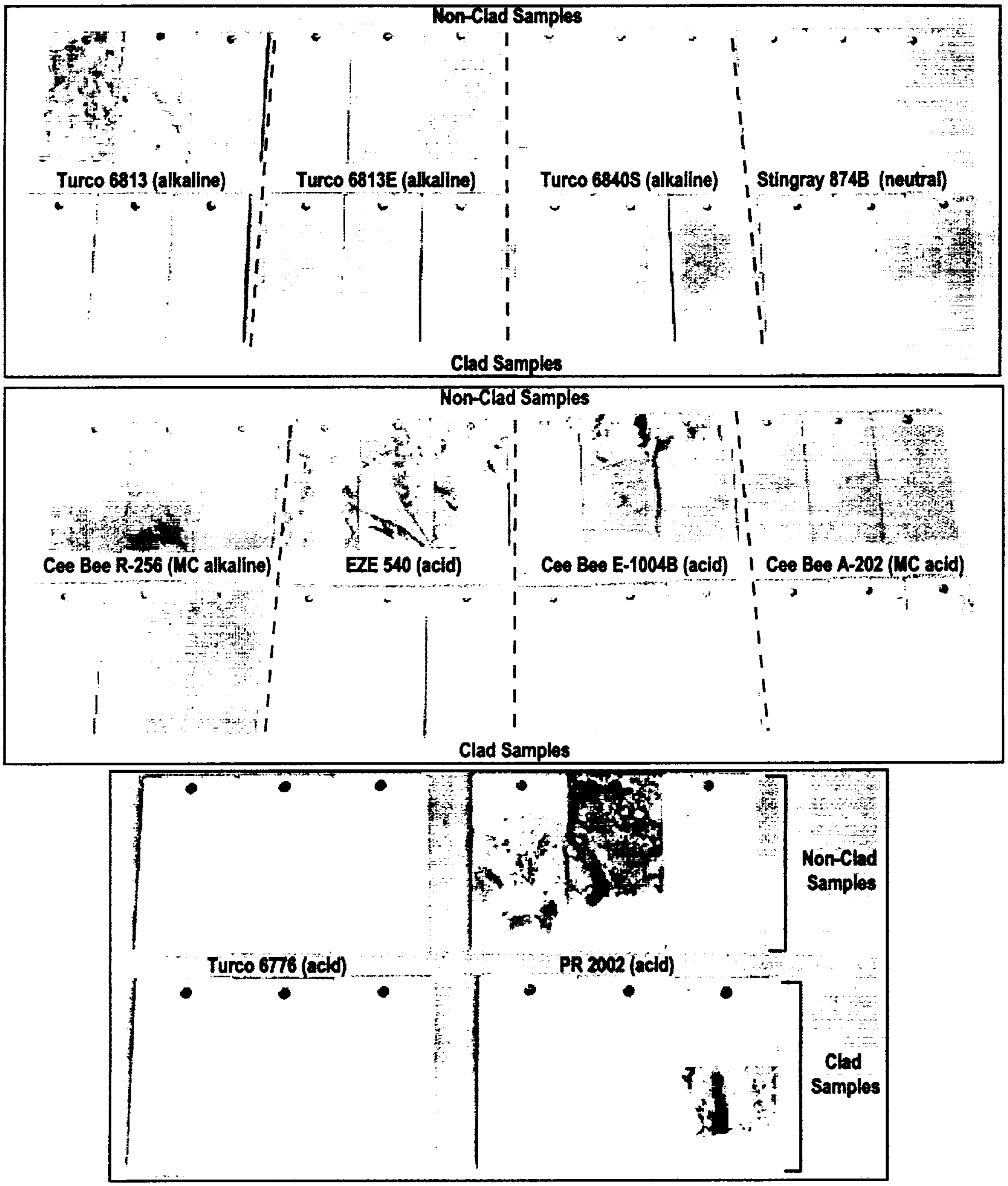


Figure A-3.1.1 Aluminum Alloy 2024-T3 Clad and Non-Clad Samples after 168 Hours of Total Immersion Corrosion Test per ASTM F483-90

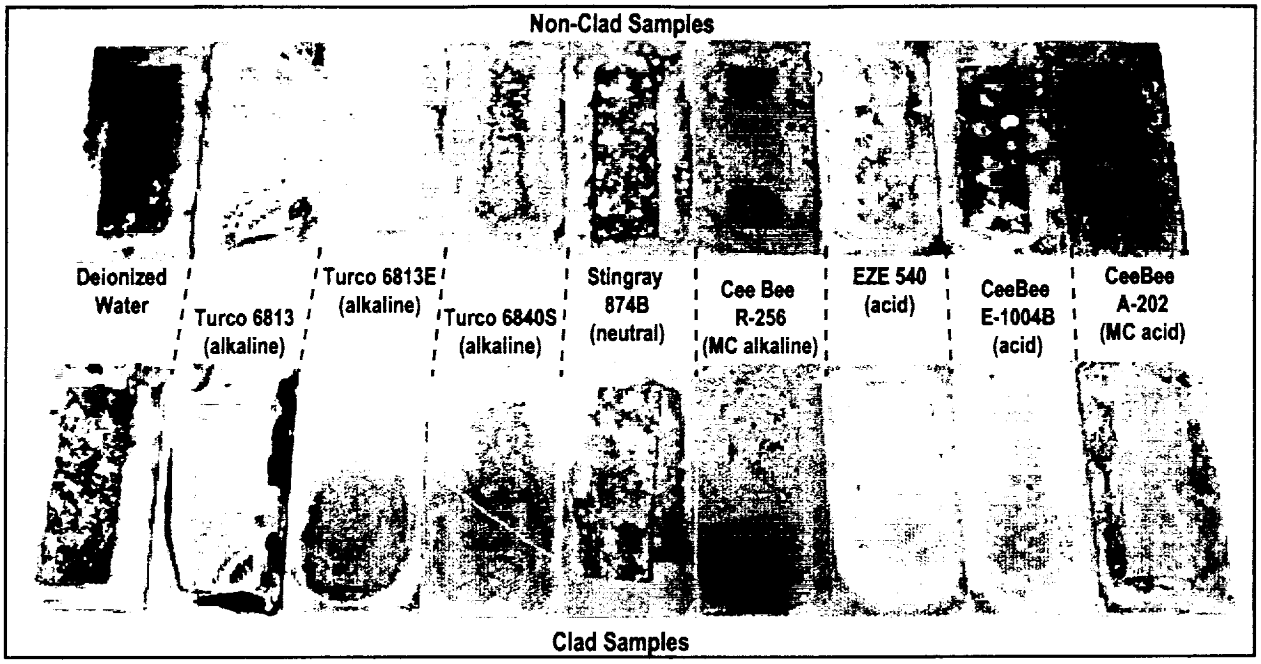


Figure A-3.1.2 Representative Aluminum Alloy 2024-T3 Non-Clad and Clad Samples after Sandwich Corrosion Test per ASTM F1110-90

A-3.2 FATIGUE LIFE TESTING RESULTS

Figure A-3.2 shows dimensions of the specimens that underwent fatigue testing, and Table A-3.2 lists the fatigue results by individual panel.

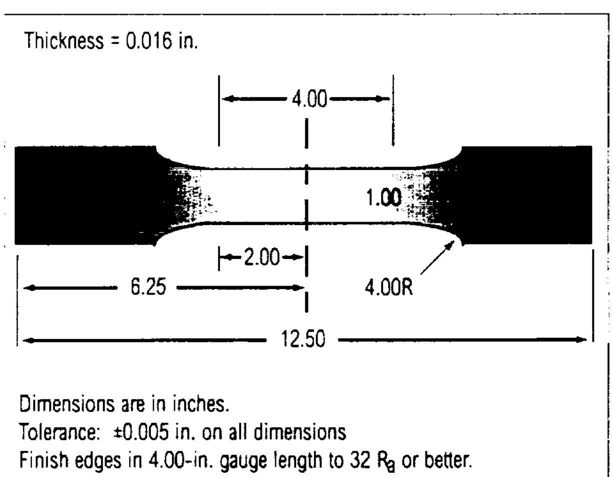


Figure A-3.2. Fatigue Test Specimen

Table A-3.2. Fatigue Life Testing Data

Process	Panel No.	Specimen ID	Cycles to Failure	Clad/ Non-Clad
Baseline	15.2	31721	57240	Non-clad
	17.1	31723	41273	Non-clad
	19.1	31725	30684	Non-clad
	20.2	31727	38904	Non-clad
	21.1	31728	41290	Non-clad
	21.2	31729	45325	Non-clad
	22.1	31730	41803	Non-clad
	22.4	31733	44832	Non-clad
	23.1	31734	55480	Non-clad
	23.2	31735	65164	Non-clad
	24.2	31737	85586	Non-clad
	25.2	31739	56620	Non-clad
	26.1	31740	61749	Non-clad
	26.2	31741	69295	Non-clad
	26.3	31742	82766	Non-clad
	26.4	31743	66116	Non-clad
	26.5	31744	70661	Non-clad
	27.1	31745	50246	Non-clad
	27.3	31747	35875	Non-clad
	27.5	31749	58761	Non-clad
	30.1	31750	50133	Non-clad
	30.2	31751	38611	Non-clad
	40.2	31887	55634	Clad
	40.2	31888	46647	Clad
	40.2	31889	71513	Clad
	40.2	31890	68613	Clad
	40.2	31892	64937	Clad
	40.2	31893	54789	Clad
	40.2	31894	51616	Clad
	40.2	31895	45317	Clad
WaterJet Blasting	VIII-30.23	31092	39177	Non-clad
		31093	43550	Non-clad
		31095	54944	Non-clad
	V-VIII-28.13	31125	40526	Non-clad
		31126	31157	Non-clad
		31127	84745	Non-clad
		31128	120722	Non-clad
		31129	53430	Non-clad
		31130	71289	Non-clad
		31131	124533	Non-clad
		31132	93838	Non-clad
EnviroStrip® Wheat Starch	IX-13.12	31309	37048	Non-clad
	IX-13.15	31317	61040	Non-clad
		31318	51108	Non-clad
		31319	37157	Non-clad
		31320	67846	Non-clad
Plastic Media Blasting	VII-VIII-29.16	31783	94087	Non-clad
		31784	115119	Non-clad
		31785	122952	Non-clad
		31786	142971	Non-clad
	VII-21.28	31811	65938	Non-clad
		31812	32179	Non-clad
		31814	89402	Non-clad
		31816	58500	Non-clad
		31817	59314	Non-clad
	VII-40.4	31819	46428	Clad
		31820	60402	Clad
		31821	47690	Clad
		31822	53729	Clad
		31823	63458	Clad
		31825	60158	Clad
	VII-40.2	31775	45536	Clad
		31776	50050	Clad
		31777	44170	Clad
		31778	36552	Clad
		31779	47979	Clad
		31780	48528	Clad
		31781	52832	Clad
FLASHJET®	IV-15.6	31134	55862	Non-clad
		31136	53087	Non-clad
		31138	64520	Non-clad
		31139	37119	Non-clad
		31140	22196	Non-clad
	IV-15.12	31116	9470	Non-clad
		31117	9087	Non-clad
		31118	6468	Non-clad
		31120	11628	Non-clad
		31121	14017	Non-clad
		31123	11007	Non-clad
	IV-15.7	31792	35775	Non-clad
		31793	20115	Non-clad
		31794	39497	Non-clad
		31796	47620	Non-clad
		31797	55686	Non-clad
		31798	52027	Non-clad
		31799	46159	Non-clad
	IV-15.10	31803	21412	Non-clad
		31804	24703	Non-clad
		31805	20367	Non-clad
		31806	16187	Non-clad
		31808	19983	Non-clad
		31809	23375	Non-clad