Joint EPA/NASA/USAF Interagency Depainting Study

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INTRODUCTION

Environmental regulations such as National Emission Standards for Hazardous Air Pollutants (NESHAPs) are drivers for the implementation of environmentally compliant methodologies in the manufacture of aerospace hardware. In 1995, the Environmental Protection Agency (EPA) promulgated the NESHAP for the Aerospace Manufacture and Rework (Aerospace NESHAP) industry. Affected facilities were to be in compliance by September 1998. Several aerospace manufacturing operations are regulated within the Aerospace NESHAP including Depainting operations.

The National Aeronautics and Space Administration (NASA), EPA, and United States Air Force (USAF) combined resources to evaluate the performance of nine (9) alternative depainting processes. The seven alternative depainting processes were: Chemical stripping (non- methylene chloride), Carbon Dioxide Blasting, Xenon Flashlamp, Carbon Dioxide Laser Stripping, Plastic Media Blasting, Sodium Bicarbonate Wet Stripping, Waterjet Blasting and Wheat Starch Blasting. An epoxy primer and polyurethane top coat system was applied to 2024-T3 clad and non-clad aluminum test specimens.

Approximately 200 test specimens were evaluated in this study. Each coupon was subjected to three (3), four (4), or five (5) complete depainting cycles. This paper discusses the conclusions from the study including the test protocol, test parameters, and achievable strip rates for the alternative depainting processes. Test data includes immersion corrosion testing, sandwich corrosion testing and hydrogen embrittlement testing for the non-methylene chloride chemical strippers. Additionally, the cumulative effect of the alternative depainting processes on the metallurgical integrity of the test substrate is addressed with the results from tensile and fatigue evaluations.

REGULATORY BACKGROUND

Methylene Chloride was traditionally utilized for chemical stripping of coating systems. Methylene Chloride is listed as a Hazardous Air Pollutant (HAP) by the EPA. This chemical is also a suspected carcinogen.

The National Emission Standards for Hazardous Air Pollutants for Aerospace Manufacturing and Rework Facilities (Aerospace NESHAP) regulates depainting operations. The Aerospace NESHAP limits the amount of methylene chloride for coating removal operation in affected facilities. The limit is 26 gallon/craft/year for commercial operations and 50 gallons/craft/year for military operations.

The initial Aerospace NESHAP was promulgated in September 1995 however subsequent versions exist. The first substantive compliance date for existing sources is September 1998. The Occupational Safety and Health Administration (OSHA) established stringent Permissible Exposure Limits (PEL) that were effective in April 1997.

OBJECTIVE OF STUDY

The overall objective of the study was to evaluate nine (9) alternative depainting methodologies per ISO/SAE MA4872, Revision # 5 “Paint Stripping of Aircraft – Evaluation of Materials and Processes”. Additionally, three (3) to five (5) cycles of panel preparation and depainting were performed for each alternative depainting methodology to determine cumulative metallurgical effects of the alternative processes on the substrate. The nine (9) alternative depainting processes are:

1 Chemical Stripping (non-methylene chloride)
2 Carbon Dioxide Blasting (Coldjet™)
3 Carbon Dioxide Blasting (TOMCO_2)

4 Xenon Lamp/Carbon Dioxide Blasting (Flashjet™)
5 Laser Stripping
6 Plastic Media Blasting
7 Sodium Bicarbonate Wet Stripping
8 Water Stripping
9 Wheat Starch Blasting

SCOPE OF STUDY

The specimens for evaluation were fabricated from 2024 -T3 clad and non-clad aluminum. The specimen thicknesses were 16, 32, 51, and 64 mil. The paint system utilized for the first depainting cycle contained a MIL-P-23377F , Type 1, Class 2 primer and a MIL –C-83286B urethane topcoat. The primer remained the same for all subsequent depainting cycles. The vendor discontinued the availability of the MIL-C-83286B urethane topcoat after the first depainting cycle due to the high Volatile Organic Content (VOC) of the material. The MIL-C-85285B topcoat was implemented for subsequent depainting cycles. This material contained a high solids, low VOC formulation.

SPECIMEN PROCESSING & DEPAINTING

The depainting specimens were processed per the following 9 steps:

1. Coating Application of Paint System
2. Coating thickness measurements
3. Environmental Aging
4. Depainting (Coating Removal)
5. Measurements: substrate thickness, surface roughness
6. Specimen Cleaning: Water Break Free Surface
7. Chromate Conversion (Iridite 14-2)
8. Measurements: substrate thickness and weight, surface roughness
9. Repeat for next cycle of specimen processing

SPECIMEN CLEANING

The cleaning of the test specimens (per Step 6 above) encompassed the following:

- Methyl Ethyl Ketone (MEK) handwipe
- Perchloroethylene Vapor Degreasing for 10 minutes
- Immersion in Turco 4215 for 25 minutes
- Hot Water Deionized Rinse for 5 minutes
- Immersion in Turco Smut-Go #1 for 11 minutes
- Cold Water Deionized Rinse for 5 minutes
- Water Break Free Test with Deionized Water.

ENVIRONMENTAL AGING OF SPECIMENS

The specimens were aged according to ISO/SAE MA4872. The specimen aging in cycle one required approximately 90 days. The installation of liquid nitrogen lines accelerated the aging cycle. The environmental aging consumed 35 – 50 days for the remaining cycles. The specimens were thermally cycled for 800 times. The environmental aging cycle is described below.

- Precondition : 12 hours @ 120 ^{o}F and 95% RH
- Hold at –65 ^{o}F for 1 hour
- Thermally cycle from –65 ^{o}F to 160 ^{o}F for 400x
- Return chamber to ambient temperature.
- Repeat steps 1 – 3.

MATERIAL EVALUATION TESTING

Material evaluation testing was performed on the test specimens. Sandwich corrosion testing, immersion corrosion testing and hydrogen embrittlement testing was performed on the non-methylene chloride chemical strippers. Baseline surface roughness measurements, post-cleaning surface roughness measurements, and post-stripping surface roughness measurements were taken for each test specimens. Crack Detectability measurements were performed on all Plastic Media Blast test specimens and on non-clad test specimens for Sodium Bicarbonate Wet Stripping, High-Pressure Water Blasting, and Wheat Starch Blasting.. Tensile testing was performed on non-clad specimens that were depainted with the Xenon Flashlamp/CO_2 process, and clad/non-clad specimens depainted with the Plastic Media Blast process. Fatigue testing was performed on non-clad specimens that were depainted with the following processes: Xenon Flashlamp CO_2, Plastic Media Blasting, High Pressure Water Blasting, and Wheat Starch Blasting.

DEPAINTING STRIP RATES & OPERATING PARAMETERS

This section of the technical paper discusses the strip rates that were achieved during the evaluation of the alternative depainting methodologies.

1. Chemical Stripping

A total of five (5) depainting cycles were completed with non-methylene chloride chemical strippers. The non-methylene chloride strippers contained acid and alkaline/neutral formulations. The specimen dimensions were 12” x12” with a 64 mil thickness. Initially, low strip rates were obtained in the 1st depainting cycle prior to process optimization. Fortunately, a site visit to Raytheon in Selma, Alabama provided guidance on chemical stripping optimization.

The following operating conditions were recommended by Raytheon and implemented during the four (4) remaining depainting cycles for evaluation of the non-methylene chloride containing chemical strippers:

- Maintain environment at an RH of 34% and a temperature between 80 and 86 °F.
- Apply fine mist of stripper over panel.
- Apply heavier mist 30 minutes later.
- Check at 2 hour intervals.
- When coating is released, brush panel and reapply stripper as before.

Initially, 40 candidate strippers were evaluated for stripping efficiency. A down-selection process yielded the eight (8) chemical strippers listed in Table 1.

Table 1. Non-Methylene Chloride Chemical Strippers

Alkaline/ Neutral Chemical Strippers	*Acid Strippers*
Gage 874B	Cee-Bee-E-1004B
Turco 6813	EZE 540
Turco 6813-E	PR-2002
Turco 6840-S	Turco 6770

The aforementioned chemical strippers were highly effective and removed 100% of the topcoat and 100% of the primer from the specimens. The average “time to strip” for all eight (8) non-methylene chemical strippers is provided in Table 2. Additionally, two (2) methylene chloride containing strippers were used as controls during the evaluation.

Table 2. Strip Times for Non-Methylene Chloride Chemical Strippers and Control Chemical Strippers

Chemical Strippers	*Average Dwell Time*
Methylene Chloride Baseline for Alkaline Neutral : Cee Bee R-256	5.0 minutes
Alkaline Neutral Candidates	3.5 hours
Methylene Chloride Baseline Acid : Cee Bee A-202	5.0 minutes
Acid Candidates	3.1 hours

2. Carbon Dioxide Blasting

Two Carbon Dioxide (CO_2) Blast systems were evaluated during this study. The two systems were the COLDJET™ Model 62-250 and the $TOMCO_2$ DI-250. The COLDJET™ system caused significant deformation on 16 mil specimens. Surface damage was evident on some of the 64 mil specimens. The $TOMCO_2$ system was capable of some coating removal but the allowable pressure was ineffective for efficient stripping. The CO_2 Blast systems were removed from the study after completion of the 1st depainting cycle. The CO_2 Blast systems were effective for cleaning of specimens versus coating removal. The operating parameters for the COLDJET™ and the $TOMCO_2$ systems are provided below.

COLDJET ™

- Area Stripped : 12 in^2 - 45.5 in^2
- Angle of Attack : 75°
- Stand-Off Distance: 5 in - 6in (16 mil non-clad) & 1" to 3" (64 mil non-clad)
- Media Flow Rate: 350 lb/hr
- Nozzle: 5 in diameter
- Pressure : 120 -300 psi
- Stripping Passes : 4 maximum
- Effectiveness: 100% topcoat, 80% primer

$TOMCO_2$ System

- Area Stripped : 144 in^2 maximum
- Angle of Attack: 10 °
- Stand-Off Distance: 1in
- Media Feed Rate : 200 - 400 lb
- Nozzle : 1.5 -in diameter (fan nozzle)
- Pressure: 150 psi
- Stripping Passes: 1 to 2
- Effectiveness: 45% topcoat & 10% primer (144 in^2), 100% topcoat & 98% primer (36 in^2)

3. Xenon Flashlamp/ Carbon Dioxide (Flashjet)

A total of three (3) depainting cycles were completed for the Xenon/ Flashlamp CO_2 coating removal system. The Boeing Company in St. Louis, MO, donated generous time and effort during the evaluation of this depainting system.

The Flashjet system utilizes pulsed light and a CO_2 particle stream to remove the coating from the substrate. Boeing chose to remove 100% of the topcoat and 57-74% of the primer. Many of the Boeing customers allow a portion of the primer to remain on the craft after depainting. Typically, six (6) to twenty-two (22) passes were needed to achieve the desired coating removal.

The study team regarded data from the 3rd depainting cycle as representative of the capabilities of the Flashjet system. This data is provided in Table 3.

Table 3. Strip Rates for Flashjet System

Substrate Dimensions (in.)	Substrate Thickness (in.)	Strip Rate (in.^{2}/min)
22 x22	0.016	70.0
22 x 22	0.051	132.0
22 x 22	0.064	100.8
12 x 12	0.064	91.9

The following operating parameters were utilized to achieve the aforementioned strip rates:

Operating Parameters:

- Stand-off Distance: 2 to 3 inches
- Angle of Attack : 21 to 29^o
- Media Flow Rate: 500 to 1000 lb/hr
- Input Pressure to nozzle : 90 to 180 psi CO_2
- Input Voltage : 1900 to 2300 Volts
- Repetition Rate: 3 to 5 flashes/sec
- Translational Velocity: 0.75 to 1.4 in/sec

4. Carbon Dioxide Laser Stripping

A total of three (3) depainting cycles were completed for the evaluation of the CO_2 Laser Stripping process. The first depainting cycle was performed by International Technical Associates of Santa Clara, California. A 50 watt demonstration unit was utilized to remove the coating from the specimens. The second depainting cycle was performed by Silicon Alps of Santa Clara, California. A 2kW production unit was utilized. CO_2 lasers were used for coating removal during the first and second depainting cycles. General Lasertronics Corporation of Milpitas, California, performed the 3rd depainting cycle. A Neodium –doped Yttrium Aluminum Garner laser was utilized during the 3rd depainting cycle. Processing anomalies at MSFC skewed the strip rates for the 3rd depainting cycle.

The strip rates for Laser Stripping are provided in Table 4. The stripping effectiveness is 100% removal for topcoat and 99% removal for primer. An area of 60 in^2 was stripped during the first depainting cycle and an area of 30in^2 was stripped during the second depainting cycle.

Table 4. Strip Rates for CO_2 Laser Stripping

Substrate Dimensions (in.)	**Sequence**	**Time to Strip**	**Strip Rate (in^2/min)**
12 x 13	1	10 min	6.0
12 x 13	2	38 sec	47.4

The following operating parameters were utilized:

- Scan Rate : 15 Hz
- Pulse Width : 6 microseconds
- Laser Power: 50 W (Sequence 1), 2kW (Sequence 2)
- Maximum Energy: 5 Joules/pulse
- Stripping Fluence: 4.5 Joules/cm
- Footprint Size: 5.5mm x 5.5mm
- Stand-off Distance : 12 inches

5. Plastic Media Blast (PMB)

A total of four (4) depainting cycles were conducted at MSFC for the evaluation of the Plastic Media Blast (PMB) process. A manual PMB system was used in the study. Strip rates from this system were not comparable to strip rates achieved by industry. Substrate thickness was 16, 32, 51 and 64 mils. Clad and non-clad specimens were evaluated. Specimen dimensions were 12" x 12" and 22" x 22". The strip rates provided in Table 5 are an average of all four depainting cycles. One stripping pass removed 100% of the primer and 80% of the topcoat.

Table 5. – Strip Rates for Plastic Media Blast Process

Substrate Thickness (inches)	**Clad/ Non-Clad**	**Average Strip Rate (in^2/min)**
0.016	Non-clad	22.4
0.016	clad	25.0
0.032	clad	26.7
0.051	Non-clad	26.4
0.064	Non-clad	22.0

The following operating parameters were implemented to achieve the strip rates provided above:

- Nozzle Diameters: 0.5 inches @ throat, 1.0 inch @ exit
- Stand-off Distance: 9 inches to 12 inches
- Angle of Attack : 30°, 30° – 45° (64mil)
- Mesh size: 20/20 (80%), 16/20 (20%)
- Media Flow Rate: 250 – 500 lb/hour
- Pressure: 30 psi – 40 psi

6. Sodium Bicarbonate Wet Stripping

A total of three (3) depainting cycles were conducted using manual and automated Sodium Bicarbonate Wet Stripping systems at the MSFC. The first cycle was performed manually and the remaining two cycles were performed with an automated system. Aquamiser and Carolina Equipment Company were the two manufacturers of the Bicarbonate of Soda System (BOSS) equipment. The substrate thickness of the clad test specimens was 16 mil and 32 mil. The substrate thicknesses of the non-clad test specimens were 51 mil and 64 mil. The specimen dimensions were 22” x 22”.

The 16 mil specimens were removed from the study after the first depainting cycle. The Sikorsky Company generously donated 10 clad specimens for the 3rd depainting cycle. The data in Table 6 represents the strip rates that were obtained with the BOSS equipment. The coating removal efficiency for the 2nd and 3rd depainting cycles was 100% of the topcoat and 90% of the primer.

Table 6. BOSS Strip Rates

Substrate Thickness (inches)	Clad/ Non-Clad	Average Strip Rate (in^2/min)	Average Strip Rate (in^2/min)	Average Strip Rate (in^2/min)
		Sequence 1	**Sequence 2**	**Sequence 3**
0.016	**Non-Clad**	**120.8**	**N/A**	**N/A**
0.016	**Clad**	**69.8**	**N/A**	**N/A**
0.032	**Clad**	**118.8**	**N/A**	**N/A**
0.051	**Non-Clad**	**96.41**	**170.0**	**162.0**
0.064	**Non-Clad**	**N/A**	**166.9**	**135.0**

The following operating parameters were implemented to achieve the strip rates in Table 6. :

- Nozzle : 7° fan nozzle
- Stand-off Distance : 2 inches
- Angle of Attack: 90 °
- Media Feed Rate: 2 to 3 lb/min
- Media Flow Rate: 3.2 gallons/minute
- Pressure : 14,000 psi
- Translational Velocity: 9 to 29 in/sec

7. High Pressure Water Blast Stripping

A total of three (3) depainting cycles were conducted at MSFC utilizing the High Pressure Water Blast technology. The clad specimens were donated by Sikorsky and were 16 and 32 mils in thickness. The substrate thickness of the non-clad specimens was 16, 51 and 64 mils. The dimensions of the clad specimens were 22” x 22” and the dimensions of the non-clad specimens were 12” x 12”. 12’ x 13”, and 22” x 22”. Three depainting cycles were conducted on the non-clad specimens while one depainting cycle was conducted on the clad specimens.

The stripping effectiveness of the High Pressure Water Blast technology removed 100% of the topcoat and 100% of the primer. The aforementioned stripping efficacy was achieved with one to three stripping passes. The strip rates are provided in Table 7.

Table 7. Strip Rates for High Pressure Water Blast Stripping

Specimen Thickness (in)	Clad/ Non-Clad	Average Strip Rate (in^2/min)	Average Strip Rate (in^2/min)	Average Strip Rate (in^2/min)
		Sequence 1	Sequence 2	Sequence 3
0.016	Non-clad	85.0	173.1	
0.016	Clad	174.3	See note	See note
0.032	Clad	617.2	See note	See note
0.051	Non-clad	223.9	593.4	880.2
0.064	Non-clad	285.1	494.5	713.1

Note: Sequence 1 for clad panels occurred concurrently with sequence 3 for non-clad panels.

The operating parameters for the High Pressure Water Blast Stripping technology is as follows:

- Nozzle : Hammelmann Rotary Nozzle
- Rotational Velocity: 900 rpm
- Stand-off Distance: 2 inches
- Angle of Attack: 90^o
- Water Flow Rate: 7-11.5 gal/min
- Pressure: 20,000 – 30,000 psi
- Translational Velocity: 1.2 – 6 in/sec
- Stripping Passes: 1-3
- Overlap: 0.5 – 1.75 in

8. Wheat Starch Stripping

A total of three (3) depainting cycles were performed with the EnviroStrip Wheatstarch technology. Thirty (30) specimens were stripped with the Wheat Starch technology. Generous time and support was donated by ADM Ogilvie and CAE Electronics (Montreal, Canada). Manual and semi-automated systems were utilized. The pure wheat starch media is used with this technology. The wheat starch can be recycled a maximum of 20 times. This technology can be implemented on aluminum, composite and steel materials. The workpiece is grounded to prevent ignition of media dust.

The specimens were a thickness of 16, 51 and 64 mils. The strip rates provided in Table 8 yielded 100% removal of the topcoat and 99% removal of the primer with one pass.

Table 8. Strip Rates for Wheat Starch Stripping Technology

Specimen Thickness (in)	Manual/ Automated	Average Strip Rates (in^2/min)	Average Strip Rates (in^2/min)	Average Strip Rates (in^2/min)
		Sequence 1	Sequence 2	Sequence 3
0.016	Manual	55.2	98.0	71.0
0.051	Manual	69.2	124.6	105.3
0.064	Manual	50.0	104.9	110.0
0.016	Semi-automated	180.0	293.3	293.3
0.051	Semi-automated	382.5	484.5	535.5
0.064	Semi-automated	382.5	484.5	535.3

The following operating parameters provided the strip rates in Table 8:

- Manual Operating Parameters:
    - Area Stripped : 216 in^2
    - Nozzle : 0.5 inch double venturi

- Angle of Attack: 30 to 60 ^{o}
- Stand – Off Distance : 4 to 8 inches
- Media Flow Rate: 12 to 18 lb/min
- Pressure : 20-30 psi

- Automated Operating Parameters:
  - Area Stripped : 204 in^2, 216 in^2
  - Nozzle: 4 inch flat nozzle
  - Projection Angle: 45^0
  - Stand-Off Distance: 3 inches
  - Media Flow Rate: 12-18 lb/min
  - Pressure: 20-40 psi
  - Translational Velocity: 0.8-2.1 in/sec

SURFACE ROUGHNESS

The ISO/SAE M8472 standard requires that the cumulative surface roughness value not exceed 125 microinches after 5 (five) depainting cycles. A Giddings & Lewis profilometer and a Hommelwerke T500 profilometer were used to determine the surface roughness of the specimens. Table 9 lists the cumulative surface roughness measurements after the 3rd depainting cycles.

Table 9. – Surface Roughness Measurements

Depainting Process	Baseline (microinches)	Sequence 3 , After Cleaning (microinches)
Chemical Stripping	1.6	10.5
Xenon/Flashlamp	1.9	15.2
CO_2 Laser	2.3	-
Plastic Media Blast	2.5	16.2
Sodium Bicarbonate w Water	1.8	*28.3
High Pressure Water	1.9	*26.0
Wheat Starch Blasting	1.3	16.8

* Represents surface roughness before cleaning.

CONCLUSION

The evaluation of the alternative depainting methodologies demonstrated that all processes are viable for coating removal with the exception of CO_2 Blasting. Many factors should be taken into consideration when selecting an alternative depainting methodology. The factors are as follows:

- Capital Costs
- Operating Costs
- Specialized Training
- Facility Space
- Manual vs. Automatic
- Ease of Use
- Strip Rates
- Compatibility with Existing Systems
- Waste Generation
- Substrate Characteristics
- Hardware Characteristics
- Paint/Primer System

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REFERENCES

Joint EPA/NASA/AF Interagency Study – Final Report, December 1999.