Environmentally-Preferred and Improved (Rapid) Laser Coating Removal Process for the Safe Removal of Coatings from Composite Substrates

ESTCP Project WP-201709

Dwight Maness
AFLCMC/RO

Final Debrief

24 SEPTEMBER 2020

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
24/09/2020

2. REPORT TYPE
ESTCP Project Outbrief

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Environmentally Preferred and Improved (Rapid) Laser Coating Removal Process for the Safe Removal of Coatings from Composite Substrates

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

5d. PROJECT NUMBER
WP-201709

5e. TASK NUMBER

5f. WORK UNIT NUMBER

6. AUTHOR(S)
Dwight Maness, Connor Eviston, Randall Straw, Jesse Holdaway: AFLCMC/RO
Bryan Pavlich: University of Dayton Research Institute
Marylee Dunphy, Hannah Easton, Natasha Voevodin: UDRI
Mike Rigney: Southwest Research Institute
Andy Strat: Titan Robotics

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Air Force Life Cycle Management Center
n/a

8. PERFORMING ORGANIZATION REPORT NUMBER
WP-201709

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Environmental Security Technology Certification Program
4800 Mark Center Drive, Suite 16F16
Alexandria, VA 22350-3605

10. SPONSOR/MONITOR'S ACRONYM(S)
ESTCP

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
WP-201709

12. DISTRIBUTION/AVAILABILITY STATEMENT
DISTRIBUTION STATEMENT A. Approved for public release: distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Technical objectives of this project:

-Validate and qualify 1 kW nano-pulsed fiber (NPF) laser for thin advanced composites coated with traditional and non-traditional military paint colors such as gloss white.

-The outcome of the qualification will be to implement the NPF laser system in a full production robotic laser coating removal system for the RQ-4 and C-130 weapon systems at Warner Robins Air Logistics Complex (ALC).

15. SUBJECT TERMS
Environmentally Preferred, Improved (Rapid) Laser Coating Removal Process, Safe Removal, Coatings, Composite Substrates

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
UNCLASS	UNCLASS	UNCLASS	UNCLASS	44	Connor Eviston
					19b. TELEPHONE NUMBER *(Include area code)* 937-255-7730 (administrative POC)

Project Team

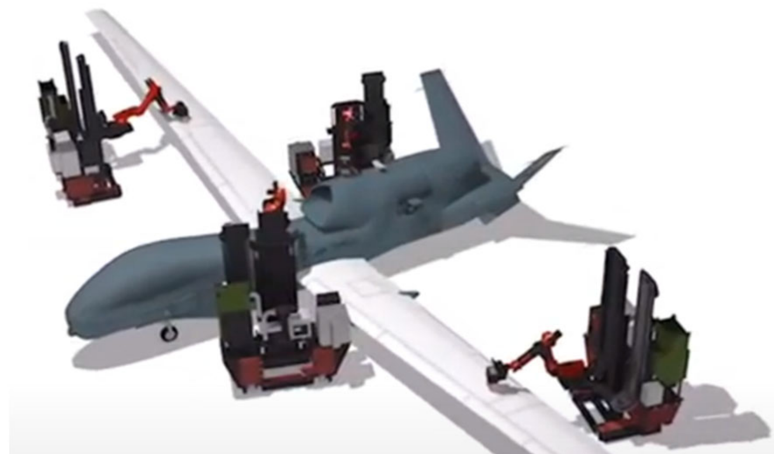
- Dwight Maness (AFLCMC/RO)
- Connor Eviston (AFLCMC/RO)
- Randall Straw (AFLCMC/EZPT)
- Jesse Holdaway* (AFLCMC/EZP)
- Bryan Pavlich (University of Dayton Research Institute)
- Marylee Dunphy (UDRI)
- Hannah Easton (UDRI)
- Natasha Voevodin (UDRI)
- Mike Rigney (Southwest Research Institute)
- Andy Strat (Titan Robotics)

* No longer with AFLCMC/EZP

Technical Objectives

- Validate and qualify 1 kW nano-pulsed fiber (NPF) laser for thin advanced composites coated with traditional and non-traditional military paint colors such as gloss white

- The outcome of the qualification will be to implement the NPF laser system in a full production robotic laser coating removal system for the RQ-4 and C-130 weapon systems at Warner Robins Air Logistics Complex (ALC) (concept shown right)



RQ-4 System Mock-Up

Technical Approach

- Conduct Optimization Testing on metallic substrates at Southwest Research Institute (SwRI) using 1kW NPF laser with polygon scanner
- Conduct Optimization Testing on composite panels (representative of RQ-4 and C-130 materials) at SwRI
- Conduct Screening Testing on metallic and composite substrates
  - Closed loop (automated) laser de-paint conducted at SwRI
  - Mechanical material evaluations conducted at University of Dayton Research Institute
- Obtain Airworthiness approval through AWB 1015 process
- Develop and install robotic laser coating removal system at Robins ALC

Note: there were personnel, contractor, and scope changes throughout the execution of this project

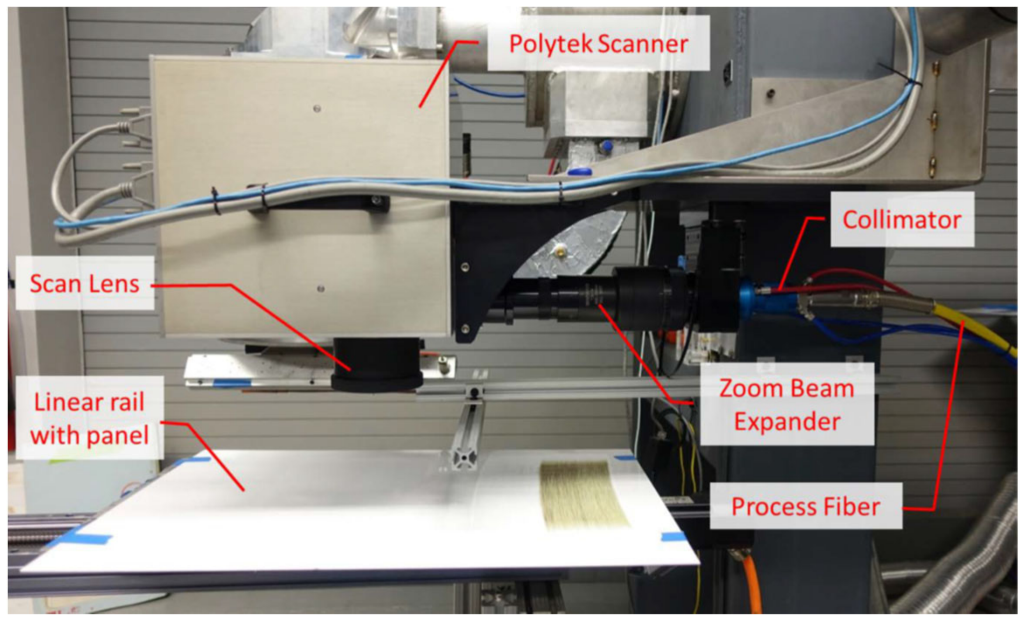
Project Execution

- May 2017 – Contract awarded to UDRI
- **Sep 2017 to Mar 2018 – Metallic Optimization Testing was conducted at SwRI using 1kW NPF laser with polygon scanner; lead to need for new scanner due to physical size**
- Mar to Jun 2018 – Equipment shipped through UDRI (Dayton, Oh) for repairs, then on to Titan Robotics (Pittsburgh, PA) and set up
- Jun to Oct 2018 – Scanner selection testing conducted at Titan Robotics; resulted in down-selection to galvanometer scanner to enable demonstration and integration into full-production system
- **Oct 2018 to Jun 2019 – Open-loop optimization testing was conducted at Titan Robotics on metallic panels, followed by on composite panels**
- **Jun 2019 to Jan 2020 – Evaluation (mechanical testing) of metallic and composite panels for laser damage was conducted at UDRI**
- **Jan to Mar 2020 – Deliberation and decision made to not proceed**

Project did not reach demonstration as results were not favorable for qualification / implementation

Summary of Work to Last IPR

- Southwest Research Institute conducted preliminary optimization testing on metallic substrates using polygon scanner
  - ♦ White coating was removed well
  - ♦ Good coating removal rates were acceptable
  - ♦ *However*, scanner was physically too large for envisaged robotic laser coating removal system use



Summary of Work to Last IPR (Cont.)

- Equipment shipped through UDRI, repairs made
- Equipment set up at Titan Robotics Laboratory style
- Selected scanner: ScanLab IntelliWELD galvanometer

Shipping damages

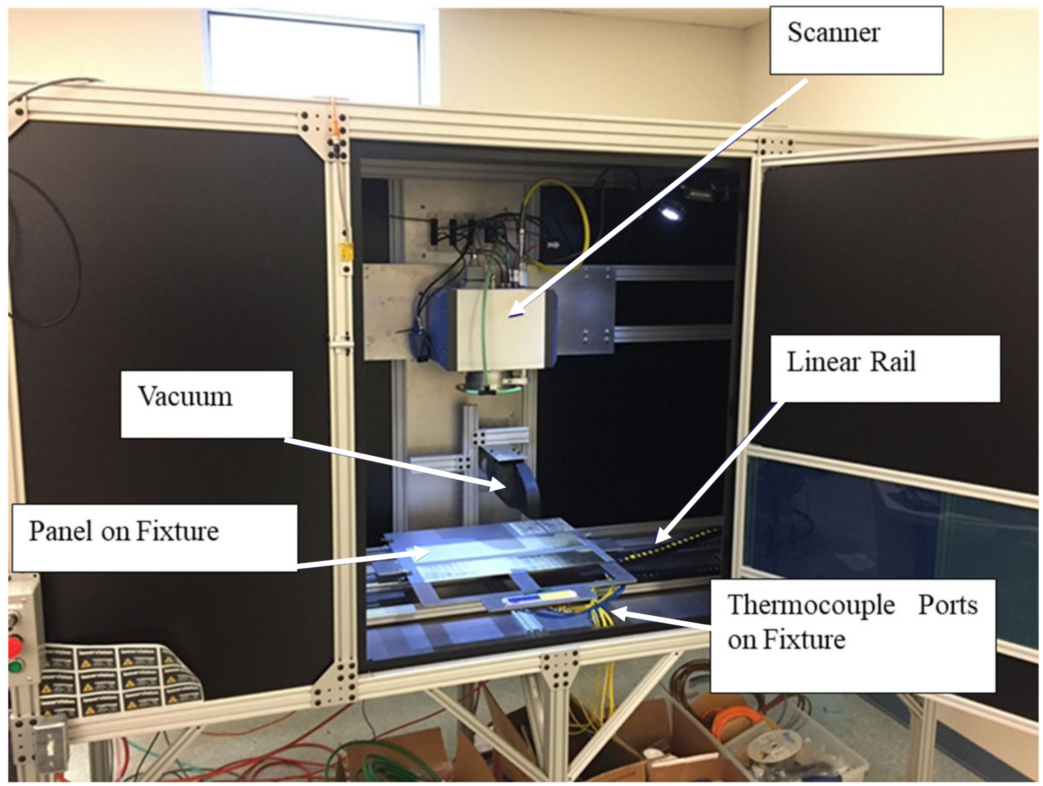
Selected scanner:
ScanLab IntelliWELD

OPTIMIZATION TESTING ON METALLIC SUBSTRATES

TITAN ROBOTICS

Optimization Testing on Metallic Substrates at Titan Robotics

- **Laser System (enclosed, laboratory scale)**
  - **1 kW NPF Laser: IPG Model YLPN-100-30X100-1000 with controls**
  - **Linear axis rail for sweep speed up to 200mm/s**
  - **Vacuum system for removal of ablated particles**
  - **ScanLab Intelliweld 30 Scanner used for optimization test**



Optimization Testing on Metallic Substrate Results

- 1 kW NPF Laser with the IntelliWELD galvanometer scanner
  - setting that produced the fastest removal rate (0.79 ft^2mils/min), while remaining under 300ºF limit, **does not exceed removal rate of 6 kW system at Hill AFB (8.71 ft^2mils/min)**
  - does not perform well on white coatings (high temperatures, low removal rates)

Parameter Set Name	Coating	Pulse Duration	Pulse Energy	Pulse Repetition Rate	Galvo Speed	Panel Speed	Ablation Width	Coverage Rate	Max Temp	Removal Rate	Removal Rate	Almen Strip Reading
		S	mJ	kHz	mps	mps	cm	ft^2/min	F	Mils/pass	ft^2mils/min	mils
T1	Gray	30	50	20	1	0.007	14	0.63	230	0.64	0.4	-0.354
T2	Gray	40	75	13.33	1	0.007	14	0.63	275	0.88	0.55	-0.551
T3	Gray	60	100	10	1	0.007	14	0.63	290	1.25	0.79	-0.669
T4	Gray	100	100	10	1	0.007	14	0.63		1.125	0.71	-0.748
T3-20kHz	Gray	60	50	20	1	0.007	14	0.63	421	1.6	1.01	-0.551
T3-20kHz-gap	Gray	60	50	20	2	0.007	14	0.63	263	0.6	0.38	-0.472
T3-2x	Gray	60	50	20	2	0.014	14	1.26	284	0.58	0.73	-0.394
T1	White	30	50	20	1	0.007	14	0.63	252	0.19	0.12	-0.276
T2	White	40	75	13.33	1	0.007	14	0.63	308	0.34	0.21	-0.472
T3	White	60	100	10	1	0.007	14	0.63	308	0.5	0.32	-0.630
T4	White	100	100	10	1	0.07	14	0.63	307	0.24	0.15	-0.748

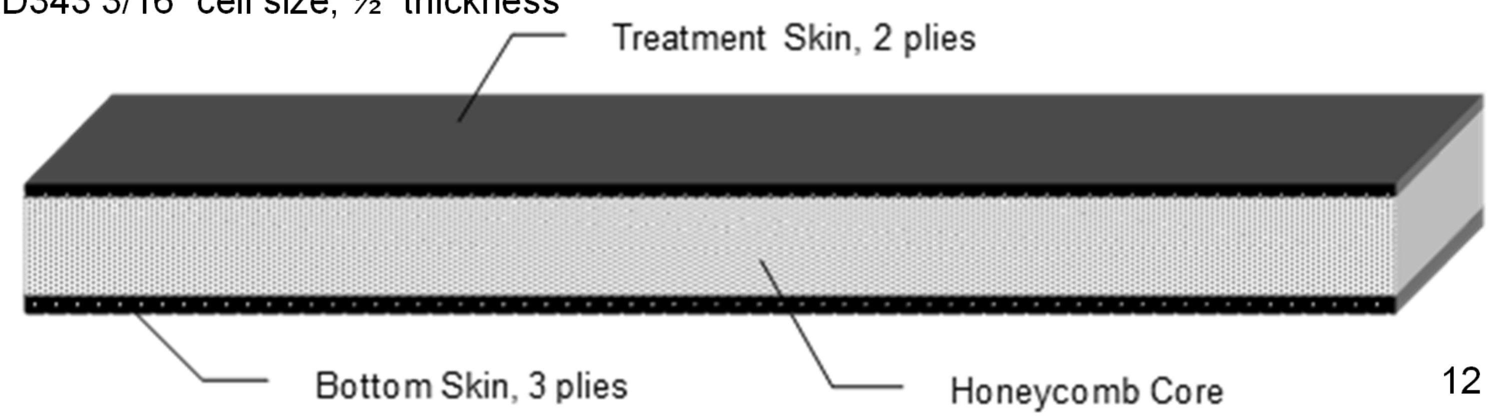
OPTIMIZATION TESTING ON COMPOSITES

TITAN ROBOTICS

Optimization Testing on Composites

Test Articles – Composite Panel Fabrication

- Panels were constructed at Aviation Equipment Processing, CA
- Six thermocouples (30 gauge, type T) embedded under topmost ply
- Sandwich panel with honeycomb core using materials found on C-130 and RQ-4 aircraft
    - Skin laminate materials:
        - M46J fiber with 7714A resin to ACS-MRS-5002
        - T650 fiber with F584 resin to STM22-817 Type 1 Class 2
        - 285K/120 fiberglass with 7714 resin to STM-22-912
    - Adhesive: Scotch-Weld AF 163-2M Film, red at 9.5mils
    - Core materials:
        - HD183 1/8” cell size, ½” thickness
        - HD343 3/16” cell size, ½” thickness



ESTCP

Optimization Testing on Composites

Test Articles – Composite Panel Coatings

- Coating application was performed at UDRI
  - Surface sealer (select panels): CA 8620 HS PU
  - Primer: MIL-PRF-23377 Type I Class C2
  - Top coats:
    - MIL-PRF-85285, Type IV Class H gray top coat (color 36173)
    - MIL-PRF-85285, Type IV Class H white top coat (color 27925)

	Panel ID	Surface Preparation	Coating
RQ-4 Representative	M46J_T_0_G_NPF_1,2	Light sand and alcohol wipe	Gray
	M46J_T_S_G_NPF_1,2	Light sand and alcohol wipe, Surface sealer	Gray
	M46J_T_0_GT_NPF_1,2	Light sand and alcohol wipe	Gray Thick
	M46J_T_0_W_NPF_1,2	Light sand and alcohol wipe	White
C-130 J Representative	285K_T_0_G_NPF_1,2	Light sand and alcohol wipe	Gray
	T650_T_0_G_NPF_1,2	Light sand and alcohol wipe	Gray

Indicates panel composite type

Thermocouples (T) or no thermocouples (0)

Surface sealer (S) or not (0)

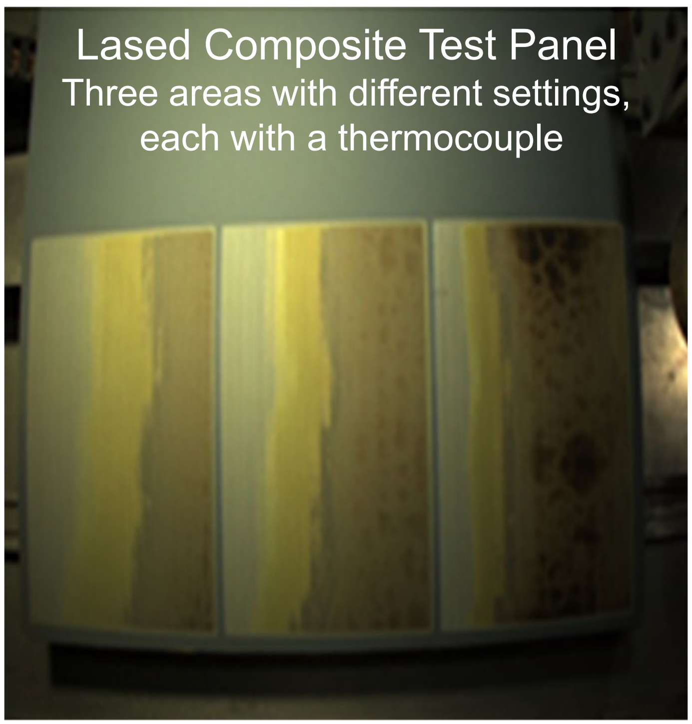
Coating:
G: primer + gray top coat
GT: “gray thick”
-four layers of [primer + gray top coat]
W: primer + white top coat

NPF: laser
CTL: control

Optimization Testing on Composites at Titan Robotics

Parameter Selection

- "Best" parameter selection criteria
  - ♦ Minimal temperature (required to be under 200ºF)
  - ♦ Visual inspection (no obvious burn marks)
  - ♦ Removal rate (estimated on minimum number of passes required to remove coating)



Recommended Parameters

Pulse Duration (ns)	Pulse Energy (mJ)	Pulse Rate (kHz)	Scan Speed (m/s)	Panel Speed (m/s)	Line Spacing (mm)
60	100	2.5	1.5	0.006	1.25

145° F was not exceeded using these parameters

SCREENING TESTING ON COMPOSITES

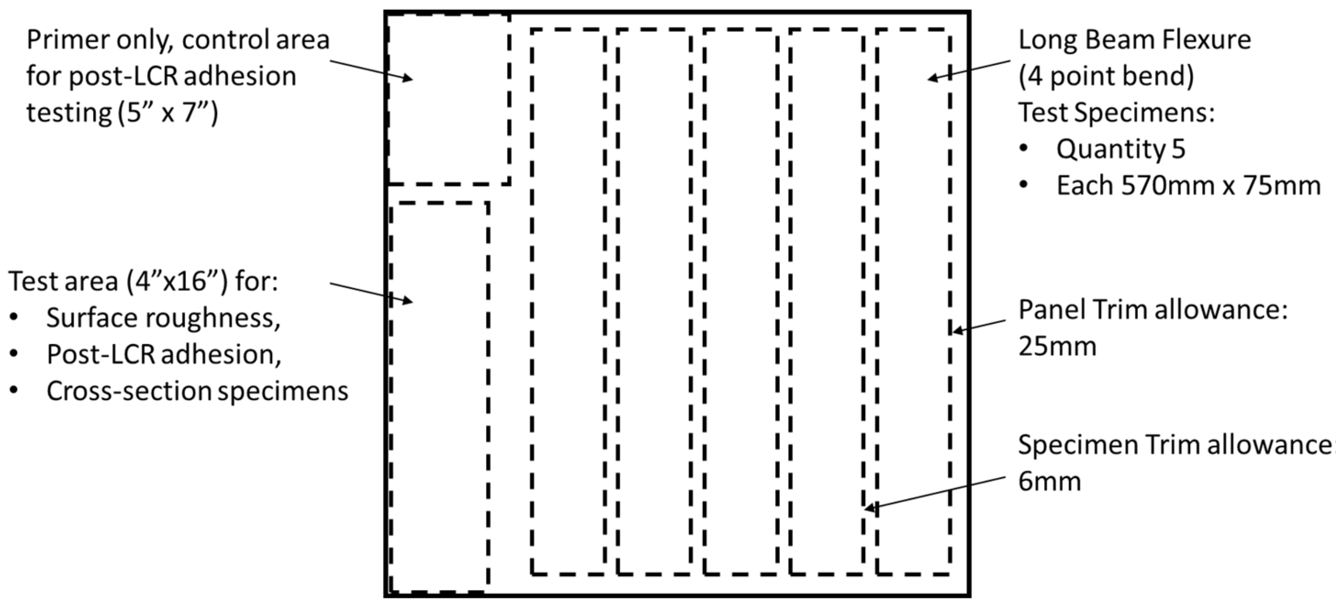
UNIVERSITY OF DAYTON RESEARCH INSTITUTE

Screening Testing on Composites

Test Articles – Composite Panels

- Composite sandwich panels identical to those used in optimization, but without thermocouples
- Samples were lased using selected coating removal parameters from composite optimization testing
- Test samples were cut from test panel after lase as shown:

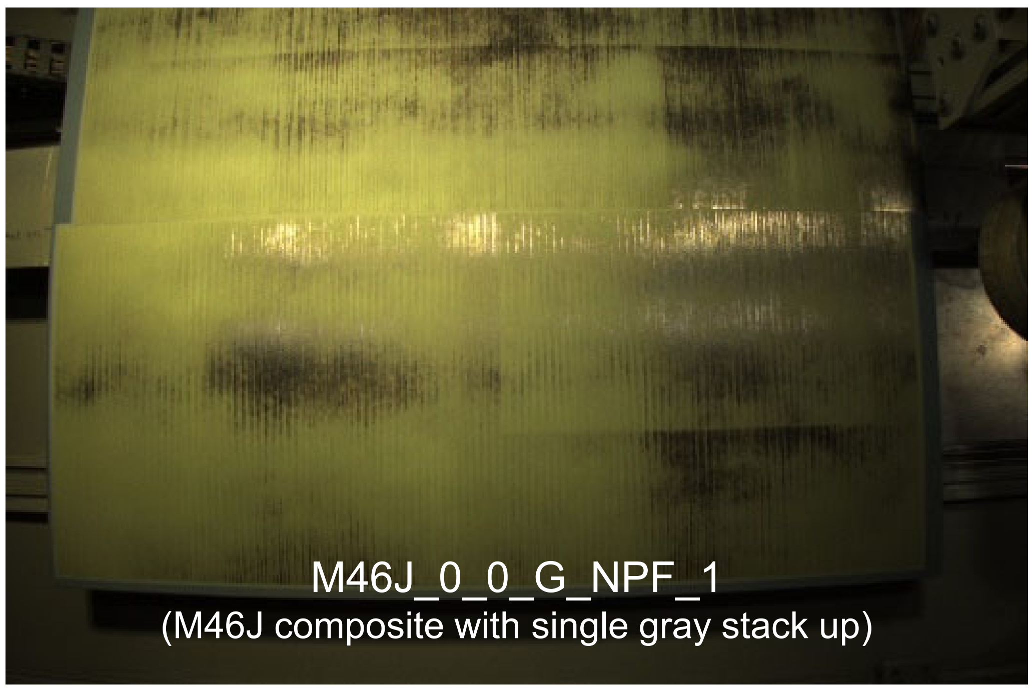
Screening Panels (no thermocouples) Test Specimen Cut Plan
(each panel 24” x 24”)



Screening Testing on Composites

Performance Assessment – Coating Removal Rate

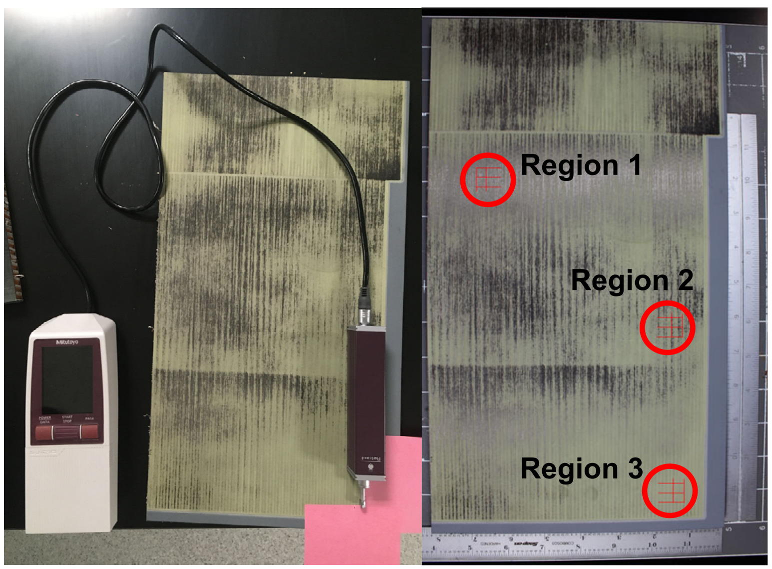
- The nominal strip rate while meeting the temperature limit of 145ºF was approximately 0.97 ft^2mil/min. (Removal rate of current system at Hill AFB is in order of 8.5 ft^2mil/min)

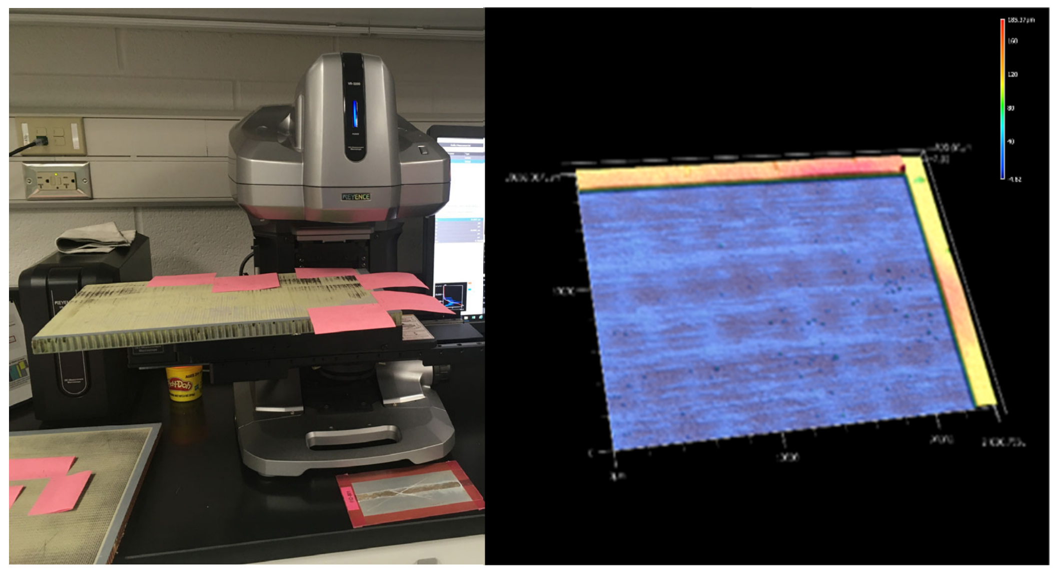


Screening Testing on Composites

Performance Assessment – Surface Roughness

- Minimal surface roughness is desired for coating re-application purposes
- Testing performed IAW Joint Test Protocol
- Roughness measured by two methods:
  - ♦ Using Mitutoyo SJ-210 Stylus, both parallel to and perpendicular to laser scan direction
  - ♦ Surface topography image taken by Keyence Microscope





Screening Testing on Composites

Performance Assess. – Surface Roughness (cont.)

- Averages taken and compared to controls

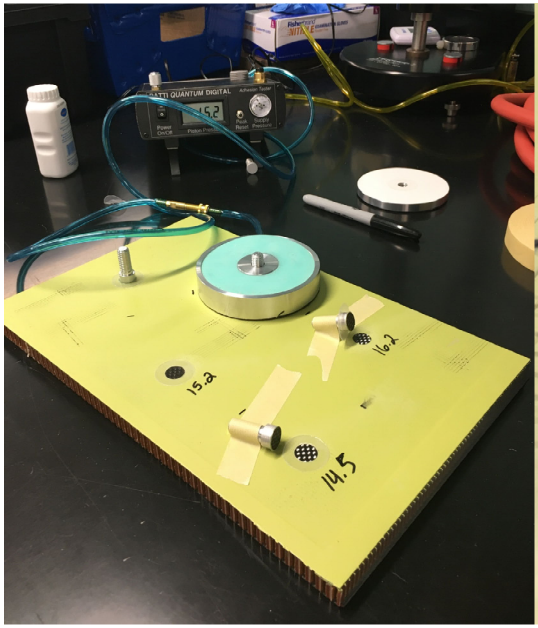
Aircraft Representative	Panel ID					Surface Roughness (Average)
	Composite	TCs	Surface Sealer?	Coating	Processed?	
RQ-4	M46J	None	None	Gray	Laser	2.852
	M46J	None	Surface Sealer	Gray	Laser	3.196
	M46J	None	None	Gray Thick	Laser	5.597
	M46J	None	None	None	Control	1.834
C-130	285K	None	None	Gray	Laser	2.368
	285K	None	None	None	Control	1.901
	T650	None	None	Gray	Laser	2.922
	T650	None	None	None	Control	0.829

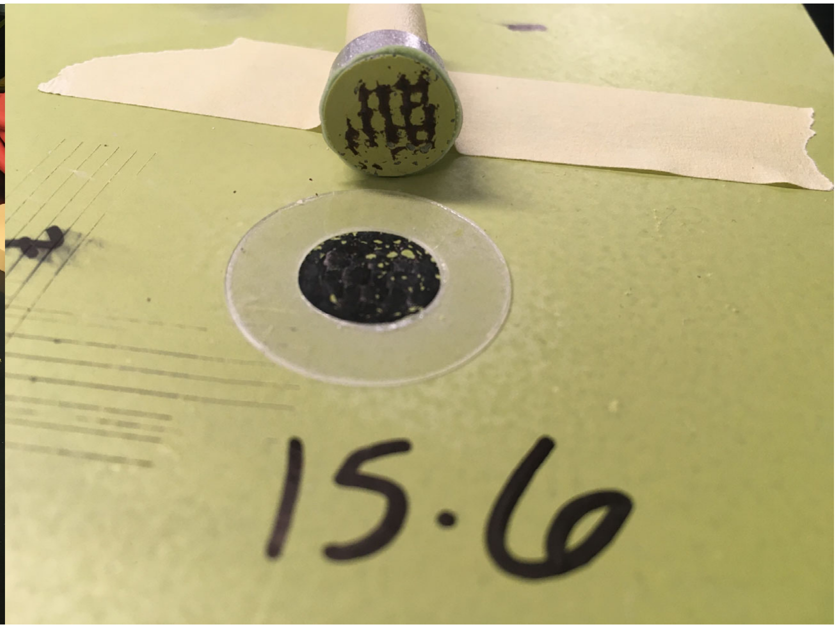
Surface Roughness of De-Painted samples greater than their control counterparts

Screening Testing on Composites

Performance Assessment – Adhesion Testing

- Good primer re-adhesion is desired to ensure coating removal method does not inhibit ability to recoat substrate
- Sample re-coated, then adhesion testing performed
  - ♦ Patti Adhesion test ASTM D4541 (3 tests per sample)
  - ♦ Cross Hatch Tape Adhesion test ASTM D3359 Method B (8 tests per sample)





Patti Adhesion Test Set Up

Screening Testing on Composites

Performance Assessment – Adhesion Testing (cont.)

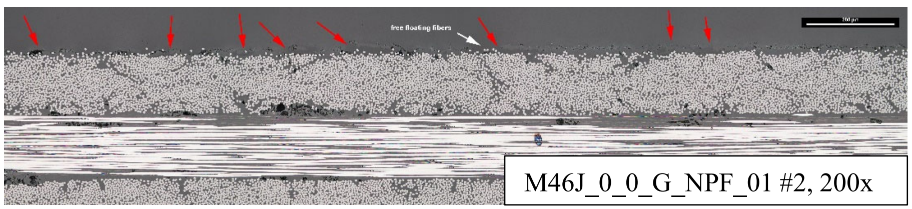
Aircraft Representative	Panel ID					Patti Adhesion (average pull off psig)	Crosshatch Tape Adhesion (Pass:Fail)
	Composite	TCs	Surface Sealer	Coating	Processed?		
RQ-4	M46J	None	None	Gray	NPF Laser	19.2	3:5
	M46J	None	Surface Sealer	Gray	NPF Laser	34.1	8:0
	M46J	None	None	Gray Thick	NPF Laser	20.7	7:1
	M46J	None	None	None	Control	19.0	0:8
C-130	285K	None	None	Gray	NPF Laser	22.6	8:0
	285K	None	None	None	Control	10.6	2:6
	T650	None	None	Gray	NPF Laser	16.3	8:0
	T650	None	None	None	Control	15.8	3:5

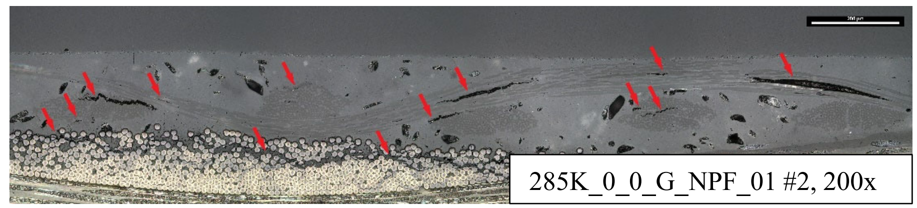
De-Painted samples passed more frequently that their control counterparts

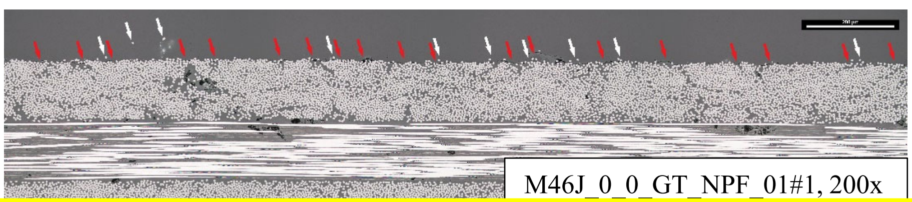
Screening Testing on Composites

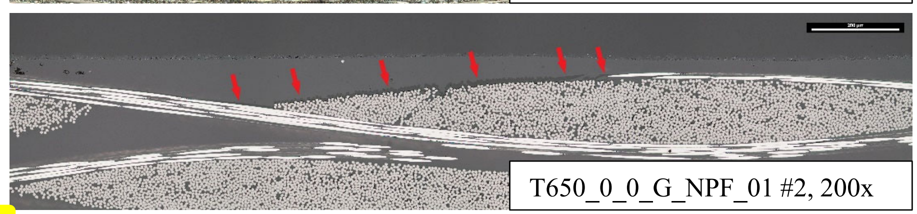
Performance Assessment – Damage to Substrate (Cross-section Analysis)

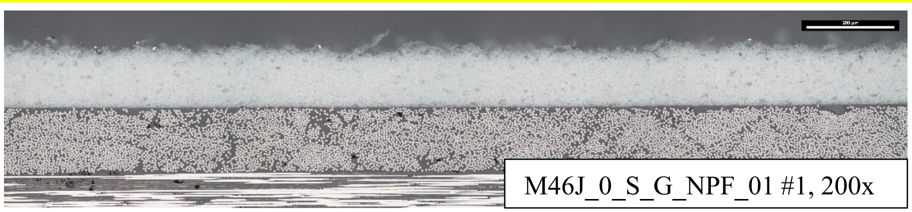
- 3 specimen cut from each sample panel using diamond blade band saw
- Specimens potted in Struers Epofix epoxy, polished, then analyzed by microscope
- Damages noticed are separation of epoxy resin from fibers (red arrows), and free floating fibers, i.e. resin ablated, (white arrows)


M46J_0_0_G_NPF_01 #2, 200x


285K_0_0_G_NPF_01 #2, 200x


M46J_0_0_GT_NPF_01#1, 200x


T650_0_0_G_NPF_01 #2, 200x


M46J_0_S_G_NPF_01 #1, 200x

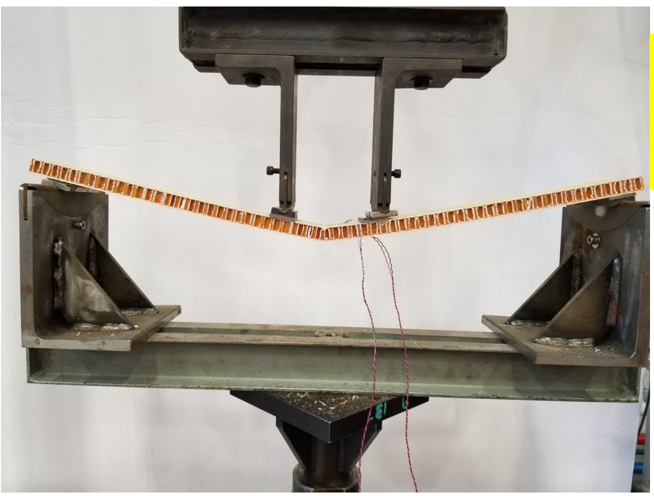
Surface sealer layer acted as barrier ensuring laser energy never contacted epoxy resin – ensuring resin remained undamaged

Damage found in all samples except that with Surface Sealer; Determined that temperature testing is not sufficient indicator of damage

Screening Testing on Composites

Performance Assessment – Long Beam Flexure Test

- Performed on 5 specimens cut from each sample panel
- Top Facesheet is the only side that is laser processed
- Results analyzed for ultimate stress, chord modulus and flexural stiffness



Panel IDs indicate composite material, (lack of) TCs, surface sealer, coating, processing/control

		Ultimate Stress	Effective Chord Modulus	Flexural Stiffness
M46J_0_0_GT_NPF_01	Top Facesheet	No Statistical Difference from Control	No Statistical Difference from Control	No Statistical Difference from Control
	Bottom Facesheet	No Statistical Difference from Control	No Statistical Difference from Control	
M46J_0_S_G_NPF_01	Top Facesheet	No Statistical Difference from Control	No Statistical Difference from Control	No Statistical Difference from Control
	Bottom Facesheet	No Statistical Difference from Control	Statistical Difference from Control	
M46J_0_0_G_NPF_01	Top Facesheet	No Statistical Difference from Control	No Statistical Difference from Control	Statistical Difference from Control
	Bottom Facesheet	No Statistical Difference from Control	No Statistical Difference from Control	
T650_0_0_G_NPF_01	Top Facesheet	Statistical Difference from Control	Statistical Difference from Control	No Statistical Difference from Control
	Bottom Facesheet	No Statistical Difference from Control	Statistical Difference from Control	
285K_0_0_G_NPF_01	Top Facesheet	No Statistical Difference from Control	No Statistical Difference from Control	No Statistical Difference from Control
	Bottom Facesheet	Statistical Difference from Control	No Statistical Difference from Control	

At least one statistical difference found in all samples except that with multiple (4) layers of coating

Screening Testing on Composites

Testing Summary

- De-painted panels were compared to un-painted control panels for a variety of materials properties tests

Panel ID	Number of de-paint passes	Surface Roughness (Average)	Patti Adhesion (average pull off psig)	Crosshatch Tape Adhesion (Pass: Fail)	Cross Section	Long Beam Flexure (stat. Diff. From control)
M46J_0_0_G_NPF_01	13	2.852	19.2	3:5	Minor surface damage	No statistical difference
M46J_0_S_G_NPF_01	15	3.196	34.1	8:0	No damage	bottom facesheet effective chord modulus only
M46J_0_0_GT_NPF_01	>40	5.597	20.7	7:1	damage	Flexural stiffness only
M46J_0_0_0_CTL_CTL	N/A	1.834	19.0	0:8	-	-
285K_0_0_G_NPF_01	7	2.368	22.6	8:0	damage	Multiple
285K_0_0_0_CTL_CTL	N/A	1.901	10.6	2:6	-	-
T650_0_0_G_NPF_01	12	2.922	16.3	8:0	damage	Bottom face sheet ultimate stress only
T650_0_0_0_CTL_CTL	N/A	0.829	15.8	3:5	-	-

Panel ID indicates composite material, presence of thermocouples, presence of surface sealer, coating, laser process, and panel number

Surface sealer appeared to protect underlying composite from damage by laser de-paint process, all other composites showed difference from control samples

Performance Assessment - Summary

- Removal of gloss white coating was successful on metallic substrate with polygon scanner (SwRI). An effective and efficient parameter set with selected IntelliWELD galvanometer scanner was not successful with Titan's efforts on removal of white paint

- Gray coating removal rates using the 1 kW NSP laser and the polygon scanner (SwRI metallic optimization testing) were equal or greater than the 6 kW continuous wave Robotic Laser Coating Removal System (RLCRS) currently employed at Hill Air Force Base. However, using the selected Intelliweld scanner (Titan optimization testing), coating removal rates were not adequate in comparison to the 6 kW RLCRS (removal rate criteria fair)

- Bulk temperature is not a sufficient indicator that damage to the composite material has or has not occurred

- Delamination and resin-fiber separation was found after laser de-paint in all composite samples inspected (lab test criteria not met) except that with surface sealer. Supports hypothesis that surface sealer or remaining coating can be used to protect composite from laser induced delaminations

Cost Assessment

- Cost assessment was not performed as project was terminated

Scale-up

- Scale Up from Laboratory to Air Force Implementation was not performed
  - ♦ Lab scale coating removal rates did not out perform those attainable by the 6 kW CW laser currently in operation at Hill AFB, UT
  - ♦ Material properties test showed damage to resin when de-painting down to substrate material; requires similar process limit as current 6 kW laser operating procedures to leave some coating remaining

Next Steps

- Investigation into the 1 kW NSP laser has been closed as expected benefits were not realized

Technology Transfer

- 1 kW NSP laser is not recommended for technology transfer for aircraft outer mold line de-paint processes as current technology does not allow for faster coating removal rates that the 6 kW continuous wave fiber laser

Key Points

- The 1 kW Nano second pulse fiber laser does not provided a realizable advantage over currently used 6 kW continuous wave fiber laser (Hill AFB)
  - ♦ All laser parameters tested lead to damage of the composite resin when all coating was removed, except sample with surface sealer
  - ♦ Coating removal rates did not exceed those attainable with the current 6 kW CW system

BACKUP SLIDES

Publications

- No Publications

ESTCP

XX-201709: Environmentally-Preferred and Improved (Rapid) Laser Coating Removal Process for the Safe Removal of Coatings from Composite Substrates

Performers

- *Air Force Life Cycle Management Center, Product Support Engineering*
- *University of Dayton Research Institute (UDRI)*
- *Southwest Research Institute (SwRI)*
- *Titan Robotics Inc.*

Technology Focus

- *1kW (avg.) nanosecond pulsed fiber laser (1070nm wavelength) for coating removal over C-130 and RQ-4 composite materials*

Demonstration Sites

- *Laser setting tests were conducted at Titan Robotics, Pittsburgh, PA.*
- *Material Properties tests were conducted at UDRI, Dayton, OH.*

Demonstration Objectives

- *Outperform current robotic laser de-paint system (Hill AFB) in removal rate, proximity to composite substrate, and coating variety*

Project Progress and Results

- *Complete coating removal (to substrate) is not possible without damaging composite epoxy resins or fiber*

Implementation

- *Implementation is not recommended as continuous wave fiber lasers can perform at an equal or better efficiency*

AIR FORCE LCMC

University of Dayton Research Institute

SOUTHWEST RESEARCH INSTITUTE

TITAN ROBOTICS

OPTIMIZATION TESTING

SOUTHWEST RESEARCH INSTITUTE (SwRI)

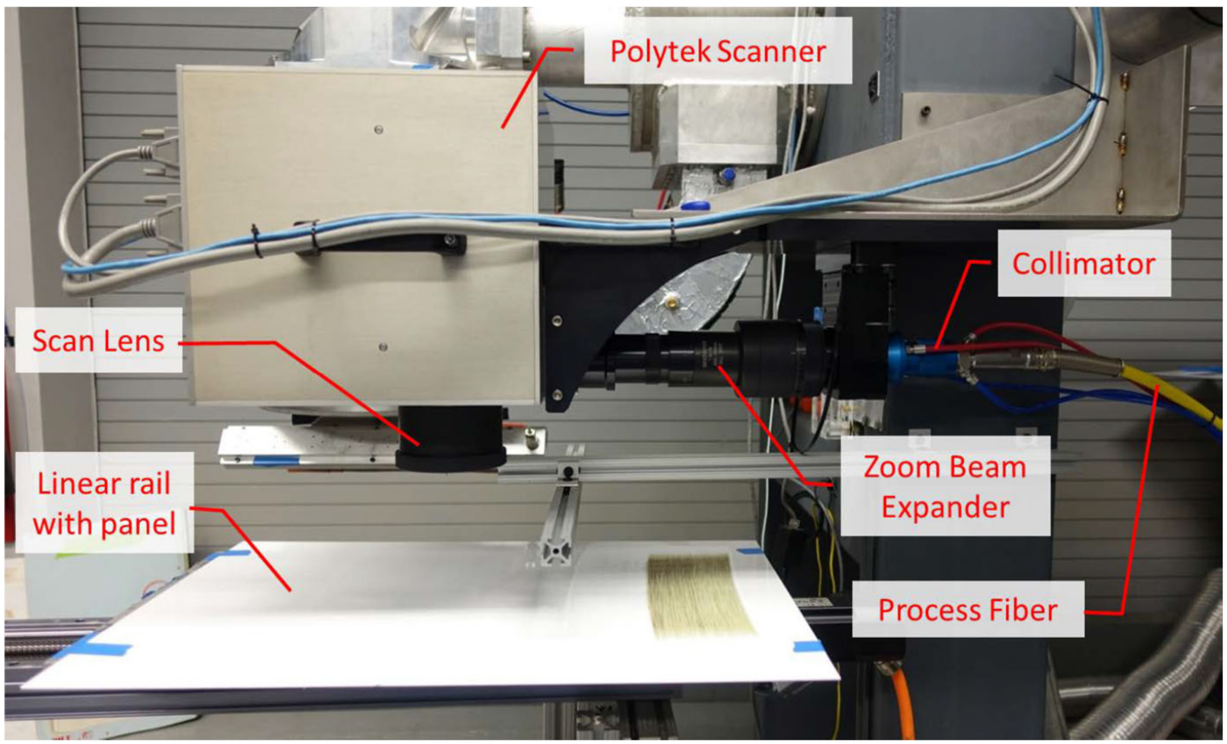
Optimization Testing at SwRI

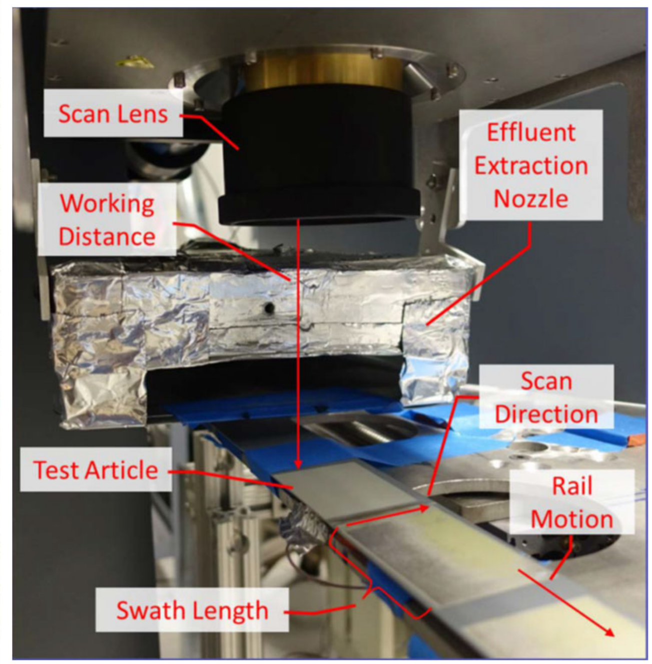
- 1 kW NPF Laser: IPG Model YLPN-100-30X100-1000
- 60 mm square process fiber

Nominal Laser Operating Modes		
Pulse Width	Pulse Rate	Pulse Energy
ns	kHz	mJ
30	20	50
40	13.3	75
60	10	100
100	10	100

Optimization Testing at SwRI

- Polygon Laser Scanner: Lincoln Laser Polytek model
- Effluent extracted to HEPA filter
- Working Distance of 130 mm,
- Scan Width of 49 mm, Swath Length of 75 mm





Optimization Testing at SwRI

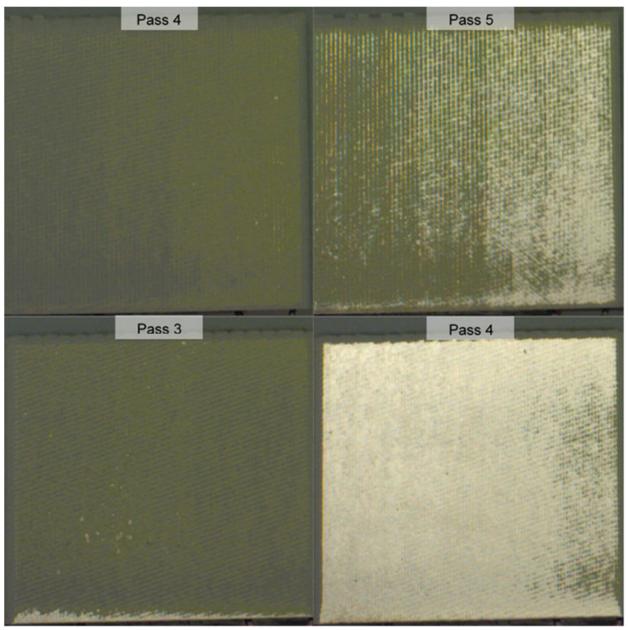
Performance Objectives

Performance Objective	Data Requirement	Success Criteria	Success Criteria Achieved?
Quantitative Performance Objectives			
Low Impact on Substrate	Temperature	Backside < 300°F	Yes
Qualitative Performance Objectives			
Low Impact on Substrate	Visual Inspection	No visual damage to metal substrate	Yes

Optimization Testing at SwRI

Performance Assessment

- Recommended process parameters were found resulting in 0.9mil/pass removal rate of gray military coating and adequate temperature
- Removal of white topcoat was also reasonably efficient



NPF Laser Process Parameters					
Laser Attributes					
Wavelength	1.06	um	Pulse Rate	10	kHz
Output Power (max)	1	kW	Pulse Energy	100	mJ
Pulse Duration	60	ns			
Beam Attributes			**Derived Beam Attributes**		
Beam Shape	-	Square	Beam Area	cm^2	0.026
Beam Profile	-	Flat top	Pulse Power	kW	1667
Spot Size	mm	1.6	Pulse Intensity	kW/cm^2	65104
Scanner Attributes			**Derived Scan Attributes**		
Scan Duty Cycle (max)	%	40%	Scan Velocity	mm/s	8000
Scan Width (max)	mm	49.5	Scan Frequency	Hz	64.6
Working Distance	mm	130	Sweep Velocity	mm/s	51.7
Spot Step	%	50%	Scan Fluence	kJ/m2	78
Scan Step	%	50%	Pass Fluence	kJ/m2	156
Time Between Passes	sec	60			

Although performance parameters were met, Polytek scanner was determined to be too bulky for envisaged robotic laser system concept; equipment returned to UDRI

EQUIPMENT DAMAGES

UNIVERSITY OF DAYTON RESEARCH INSTITUTE REPAIRS

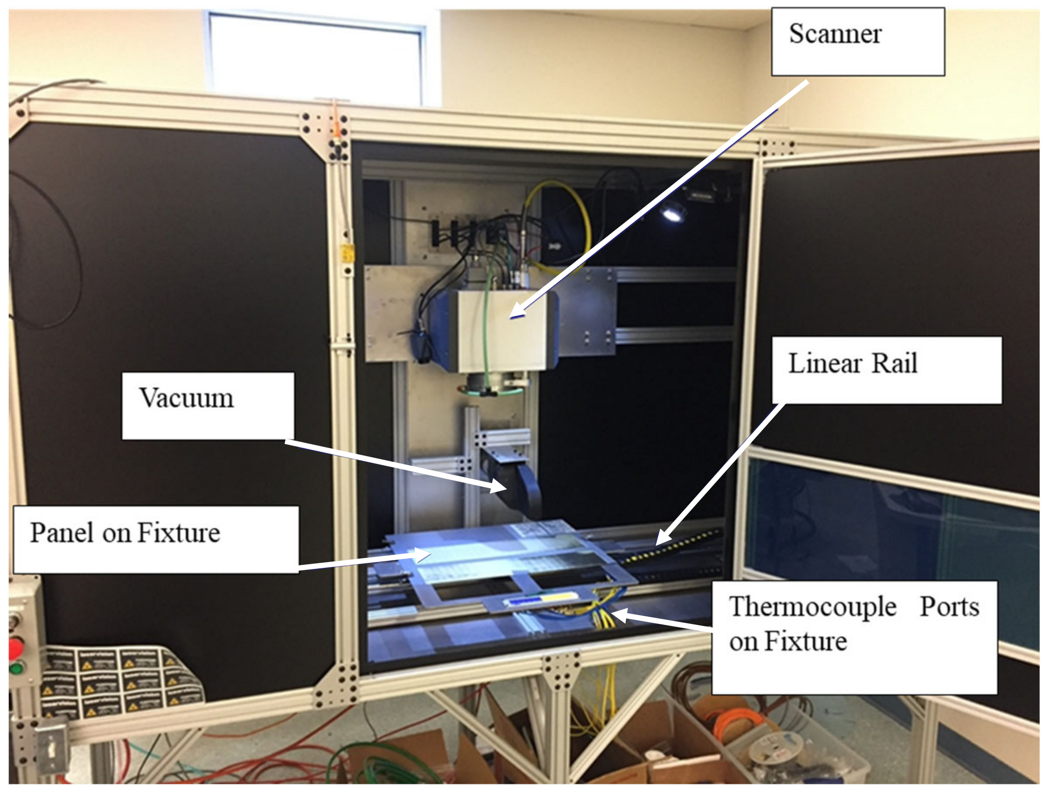
Damages to Equipment

- Laser was shipped from SwRI to UDRI (Spring 2018)
  - ♦ Cosmetic damage to laser housing
  - ♦ Corrosion was found inside chiller line fittings
- Repairs were conducted at UDRI

SCANNER SELECTION TESTING
TITAN ROBOTICS

Scanner Selection Testing at Titan Robotics

- **Laser System (enclosed, laboratory scale)**
  - **1 kW NPF Laser: IPG Model YLPN-100-30X100-1000 with controls**
  - **Linear axis rail for sweep speed up to 200mm/s**
  - **3D scanner with intrinsic functions for focus, scan speed, scan width**
  - **Vacuum system for removal of ablated particles**



Scanner Selection Testing at Titan Robotics

- **Four scanner set ups tested:**
  - **ScanLab IntelliWeld with beam shapping optic**
  - **Scan Lab IntelliWeld with the beam shapping optic removed**
  - **IPG Mid Power Scanner**
  - **IPG Mid Power Scanner with replacement f-theta lens**

Scanner:	IntelliWeld with optic	IntelliWeld without optic	IPG Mid Power	IPG Mid Power with new lens
Focal Length (mm)	460	460	254	163
Field Width (cm)	30	30	19	8
Max Spot Speed (m/s)	9	9	2.5	1.25
Focus Range (mm)	+/- 70	+/- 70	N/A	N/A
Spot Width (mm)	2.49*	2.49	3.03	1.94
Spot Area (cm^2)	*	0.062	0.0915	0.0377
Beam clipped (%)	8.9	8.9	22.2	22.2

* Beam shaping optic makes an ellipse with one of the axes larger, while maintaining short axis length

Scanner Selection Testing at Titan Robotics

Performance Assessment

	IntelliWeld		IPG Mid Power		IPG Mid Power with new lens	
Parameter Set	Irradiance (MW/cm^2)	Fluence (J/cm^2)	Irradiance (MW/cm^2)	Fluence (J/cm^2)	Irradiance (MW/cm^2)	Fluence (J/cm^2)
T1	24.49	0.74	14.17	0.43	34.39	1.03
T2	27.54	1.10	15.94	0.64	38.68	1.55
T3	24.49	1.47	14.17	0.85	34.39	2.06
T4	14.69	1.47	8.5	0.85	20.63	2.06

	IntelliWeld	IPG Mid Power	IPG Mid Power with new lens
Maximum Coverage Rate (ft^2/min) (no row overlap)	14.473	4.892	1.566

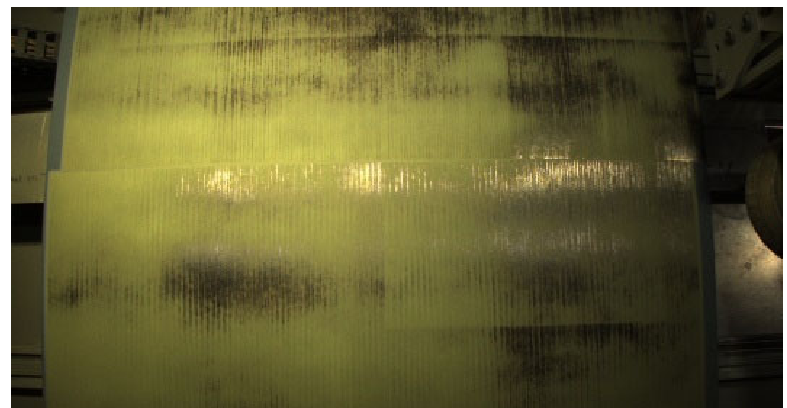
ScanLab Intelliweld Scanner allowed for fluence and irradiance values while also being capable of a fast coverage rate

Screening Testing on Composites

Performance Assessment – Coating Removal Rate

- The nominal strip rate while meeting the temperature limit of 145° F was approximately 0.97 ft^2mil/min. (Removal rate of current system at Hill AFB is in order of 8.5 ft^2mil/min)

	Panel ID	Number of Passes
RQ-4 Representative	M46J_0_0_G_NPF_1	13
	M46J_0_S_G_NPF_1	15
	M46J_0_0_GT_NPF_1	> 40
C-130 J Representative	285K_0_0_G_NPF_1	7
	T650_0_0_G_NPF_1	12


M46J_0_0_G_NPF_1
(M46J composite with single gray stack up)

Coating removal rate is not greater than current capability at Hill AFB, UT, using a 6 kW continuous wave robotic laser coating removal system