OPTICALLY ENHANCED BONDING WORKSTATION FOR ROBUST BONDING

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ABSTRACT

Process control is one of the methods recommended by the FAA to reduce risk in fabrication of structurally bonded composite joints for aircraft structure based on guidance provided in circular AC-107B [1] for certification of structurally bonded joints. An Optically Enhanced Bonding Workstation is presented here that reduces the risk in bonded joint fabrication. Results will be presented demonstrating the benefits of process monitoring and its ability to reduce risk in performing pre-bond composite surface preparation steps. This supports reduction in the timeline to certification of bonded composite structures through development of a robust bonding process upstream of any part certification steps.

Sanding surface preparation has been identified as a high risk process step that is known to impact bond performance. Control of sanding during surface preparation can be performed using portable surface analysis tools previously identified including included gloss, color, Fourier Transform Infrared spectroscopy (FTIR) and optically stimulated electron emissions (OSEE). Threshold limits for the surface analysis tool measurements were determined based on an example objective bonding system utilizing a common EA9394 paste adhesive measured using standard double cantilever beam fracture toughness testing. The patented Optically Enhanced Bonding Workstation (OEBW) [2], was tailored to monitor and control the epoxy composite surface preparation step. Surface analysis tool threshold limits were incorporated into the OEBW to demonstrate improved composite bond performance through process control. The surface analysis tools investigated here can easily be incorporated into an automated system due to their applicability to rapidly quantify the composite sanded surface treatment and their portability.

1. INTRODUCTION

2.1 Process Control of Composite Bonding

Process control is a key component of the FAA's guidance document on certification of bonded joints [1,3]. In the aerospace industry process control is recommended to ensure quality of a manufactured part including fabrication of a bonded joint [4]. This work supports the overall objective of the NASA Advanced Composite Project (ACP) to reduce the timeline to certify bonded composite structure through verifying a robust bonding system upstream, prior to any subsequent certification testing. This work demonstrates how process control results directly in a more reliable bond based on composite bond performance results.

Steps in executing process control for the bonded joint fabrication are outlined below:

1) Fully document the bonding system
2) Assess bonded system risks and identify parameters with highest risk
3) Evaluate and identify tools that can quantify high risk process steps
4) Measure and assign threshold values for analysis tool outputs
5) Verify bonded joint is affected by high risk property through bonding tests
6) Incorporated threshold values into bond process monitoring system and quality control

Steps 1-4 were conducted previously for the bonded system selected here [5]. A risk analysis was performed and identified that defects from sanded surface preparation were highly likely to occur and had a high consequence of causing a bad bond. Work here demonstrates the correlation between the high risk, sanding surface preparation step and bond performance. Additionally, surface analysis tools that detect the threshold levels of sanded surface preparation were identified and utilized for superior process control based (Step 6).

2.2 Bonded System

Bonded joint fabrication is a multiple input system that includes numerous materials (substrate, adhesive, surface preparation materials) and processes (substrate and/or bonding cure time and temperature, out time and storage life of materials, surface preparation parameters) variables [6].

The bonded system investigated here was selected, not because it is considered a best practice, but because paste bonding is utilized throughout the industry. Sanding surface preparation of composites is highly variable, difficult to control and can be performed in several different ways. Random orbital sanding (ROS) was selected as a representative of those composite sanding operations. Henkel EA9394 adhesive was selected because this adhesive was identified to be more sensitive to contaminants and surface preparations [7] as compared to other film adhesives. Paste adhesive bonding is utilized frequently in low risk, general aviation applications. The bond process control optimization demonstrated here can be transferred to any bonded joint fabrication system.

2.3 Digital Engineering

In the age of digital engineering, new technologies are now available to assist with composite bonded joint fabrication and support reliable and robust bond performance and monitor to control these multiple variables.

One component of digital engineering, as described in a recently released DoD Digital Engineering Strategy document, [8] is the importance of a digital model of the system to verify sustainable and reliable production and delivery of an end item. The OEBW provides this model through documentation of reference images, storing key inputs and tracking targeted process flow times. This tracks the manufacturing bonding process to a known set of reference standards.

In addition it recommends creating an “authoritative source of truth” and making decisions based on data. The OEBW records and stores critical bond process data in graphical and photographic format, creating a digital thread for potential future access. This creates a single source of information on production and fabrication processes in a digital format.

2.4 Optically Enhanced Bonding Workstation (OEBW)

The concept of using video cameras to document and monitor bonding operations for process control was described in work performed as part of the Composites Affordability Initiative [9] in 2000. Significant improvements in data recording, storage and recall has enabled process monitoring to be a viable option for bonded joint fabrication. The modern OEBW system [2] has camera monitoring, image documentation capabilities as well as time stamp verification. In addition, the capability to have a robust graphical user interface (GUI) is now possible. A LabVIEW software based GUI has been incorporated into the system. The GUI enables surface analysis tool outputs to be referenced in the system. Other benefits include incorporating surface characterization tools into the system that have been correlated to end-product performance.

The OEBW system itself is digital twin or model of the existing bonding process. An operator can reference and ideally duplicate the digitally stored virtual bonding operation at any time or place. The documented images could be utilized for standardization and training at multiple sites for offloading of parts to new fabrication facilities without adversely impacting costs. This supports FAA work force development goals to enable better training of repair and fabrication technicians in remote locations potentially using virtual training tools [10].

2.5 Surface Analysis Tool Background

Surface analysis tools typically been used to investigate the presence of contamination on pre-bond surfaces was done with the Air Force funded Composite Affordability Initiative (CAI) program [11, 12, 13, 14] with X-ray photoelectron spectroscopy (XPS), surface energy and surface roughness measured using non-contact laser reflectometry. The DARPA Transition Reliable Unitized STructure (TRUST) project investigated the use of ballistic water contact angle (B-WCA) and XPS [15]. More recently the NASA ACP utilized goniometer water contact angle (WCA), FTIR, XPS [16,17], B-WCA, Dyne surface energy, FTIR, OSEE, IGC, surface energy [7] as well as scanning electron microscopy (SEM), WCA, micro laser induced breakdown spectroscopy (µLIBS), and electron spin resonance (ESR) [18] to evaluate surfaces primarily for contaminants. Some of these tools are very good at detecting level of contaminates such as silicone but may not be suitable as bond process control tools. Previous work did identify that some of these tools did have the capability to in some cases detect presence and level of laser, plasma, peel ply, grit blast and/or sanding surface preparation [7]. These tools were main investigated for detection of surface contamination. In other cases the tools were not portable or easily implemented as an in-line quality control check.

More recent work investigated a wider range of surface analysis tools to specifically evaluate their ability to be used as process control of ROS treated composite surfaces [5]. It was demonstrated that color, gloss, FTIR and OSEE surface analysis tools were successful at measuring the level of ROS surface preparation. This paper builds on that work correlating surface preparation to bond performance. This work demonstrates that quantitative surface analysis measurements in combination with a bond process check system can be utilized to produce robust, reliable composite bonds in the field.

Process control can be executed using machine output information such as geometric positioning data or power usage but in some cases it is better to rely on actual end item property. Surface analysis tools presented here perform exactly that function in that they verify surface preparation has been performed on the part, not inferred from equipment output data.

2. EXPERIMENTATION

2.1 Composite Panel Fabrication

Composite substrates were fabricated by laying up 10 plies of 177 ºC (350 ºF) cure carbon fiber epoxy prepreg. The eight inner plies were unidirectional tape (Torayca P2352W-19 T800S/3900-2B UD) and two outer plies were fabric (Torayca FM6673G-37K T830H-6K-PW/3900-2D). Plies were layed up on an invar tool treated with Frekote 710NC mold release agent and the panels cured in an autoclave for 120 min at 177ºC (350 ºF).

Composite substrates were fabricated using 10 plies of 177 ºC (350 ºF) cure carbon fiber epoxy prepreg. The eight inner plies were unidirectional tape (Torayca P2352W-19 T800S/3900-2B UD) and the two outer plies were fabric (Torayca FM6673G-37K T830H-6K-PW/3900-2D).

2.2 Surface Treatment

Panels were surface treated by manually sanding with a random orbital sander (ROS) using180 grit aluminum oxide Merit sand paper disks (Figure 1). For the purposes of this study, time was used as the processing variable. The same operator was used for all part sanding to reduce the influence of pressure on the sanding process. Prior to and after surface preparation, panels were solvent wiped with Eastman™ methyl propyl ketone (MIBK) - methyl isobutyl ketone (MPK) mixture [19] using cleaning cloths, meeting the requirements of AMS3819B Class 2 Grade A [20].

Figure 1. Manual ROS sanding process and materials for surface preparation of epoxy composite panels

2.3 Surface Analysis

Surfaces analysis was performed before and after surface treatment using color, gloss, FTIR and OSEE. Color was measured with a BYK Gardner spectro-guide 45/0 gloss Model CC-6801 using a Commission Internationale de l'Elcairage (CIE) Lab color scale. Gloss measurements taken at 85 degree illumination angle geometry were also collected using a BYK Gardner micro-TRI-gloss micro Model 4435 instrument. Chemical information was gathered using FTIR spectroscopy with an Agilent Model 4100 "Exoscan" spectrometer, gain of 243, 64 scan, 8 cm^{-1} wavenumber resolution between 650 and 4000 wavenumbers and a diffuse reflectance attachment. Peak area analysis was performed in the region between 3016-2785 cm^{-1} representing the C-H bonding region of the epoxy polymer). OSEE was performed at Boeing with an instrument developed by NASA [21] using an ultraviolet (UV) lamp set point of 3041, grid offset of -41 and peak to peak amplitude of 3.7.

2.4 Bonded Coupon Fabrication

Composite-composite assemblies were bonded using Henkel™ EA 9394 paste adhesive cured at 82 ºC (180 ºF) in a press. Bonded assembly with Teflon tape crack starter configuration is shown in below in Figure *2*. Metal shims were used to control bondline thickness.

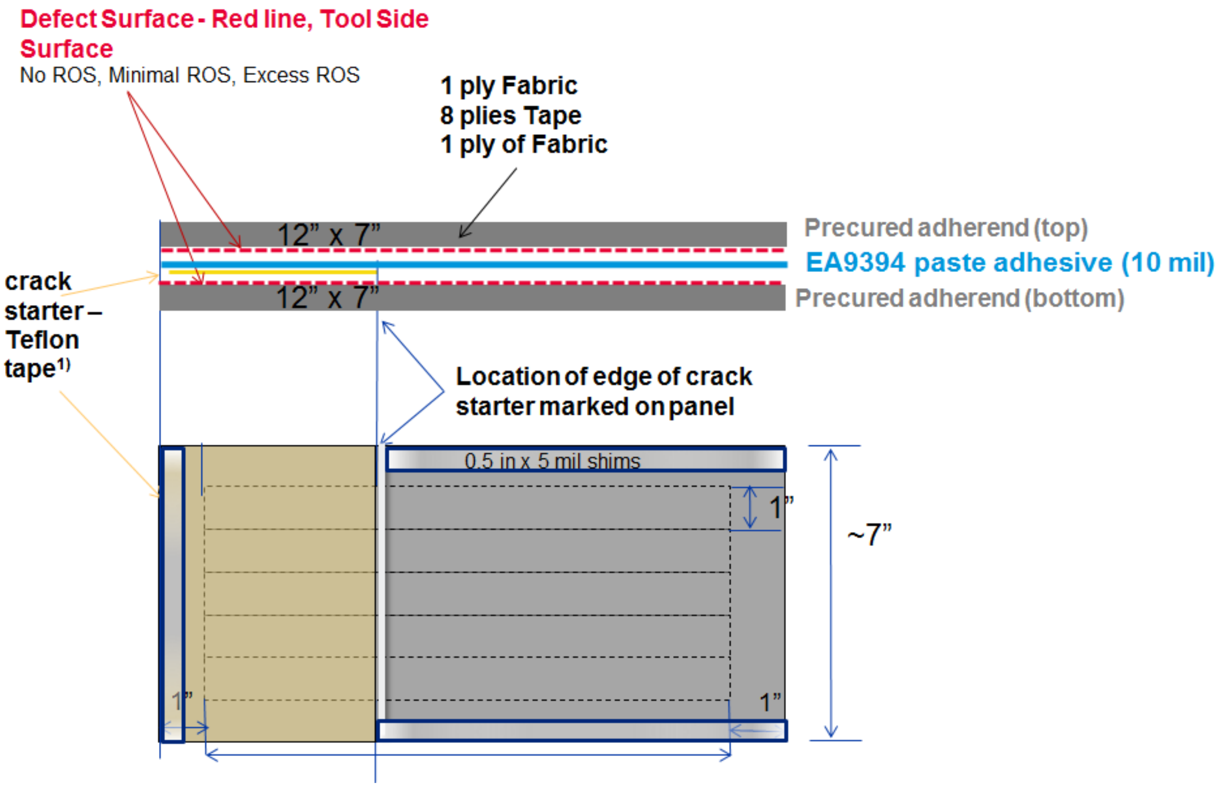


Figure 2. Bonded assembly configuration using EA9394 paste

Coupons were trimmed to dimensions 2.5 x 25 cm dimensions (1” x 10”) in accordance with ASTM D5528 [Ref J].

2.5 Fracture Toughness and Failure Mode Analysis

Double cantilever beam (DCB) coupons were tested in accordance with ASTM D5528 [22] with a loading rate of 1 inch (25mm) per min after the specimen was precracked by hand. A 2.50 mm (0.098 in) hole was drilled through the centerline of the coupons and a pin and clevis tool (Figure 3) used to apply the load.

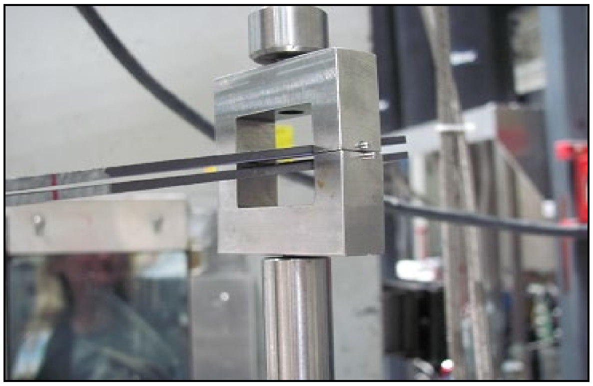


Figure 3. DCB coupon loading using a pin and clevis tool

The propagated strain energy release rate G_{1P}, or fracture toughness, was calculated using the area under the load displacement curve in accordance with Equation 1.

$$G_{1P} = E / (A \times B) \qquad \text{Eq 1}$$

E – area of the load deflection curve between the initial and final crack positions
A – crack length extension corresponding to E, initial crack tip to final crack tip
B – specimen width

Failure modes were quantified visually in accordance with methods and terminology used in ASTM D5573-99 [23] and ASTM D5573-ADJ [24].

3. RESULTS

3.1 Bond Performance

Fracture toughness of the bonded DCB coupons with various levels of sanding is shown in Figure 4. A baseline GIP value of 0.26 kJ/m^2 for EA9394 is based on a standard peel ply composite surface with no additional surface treatment is shown in the charts for comparison. The bond performance results are all similar to known values for this same composite substrate with a polyester peel ply surface preparation. The failure modes are also shown in Figure 4 as indicated by color coding. All green failure modes (inter and intralaminar as well as cohesive in the adhesive) are considered acceptable. The red failure mode (adhesion failure between the substrate and the adhesive) are considered to be bad. The bonded surfaces of the fractured DCB coupons showing their failure modes are shown in detail in Figure 5. Results showed that a sanding time of 1 minute was needed to achieve good bonding and no poor failure modes.

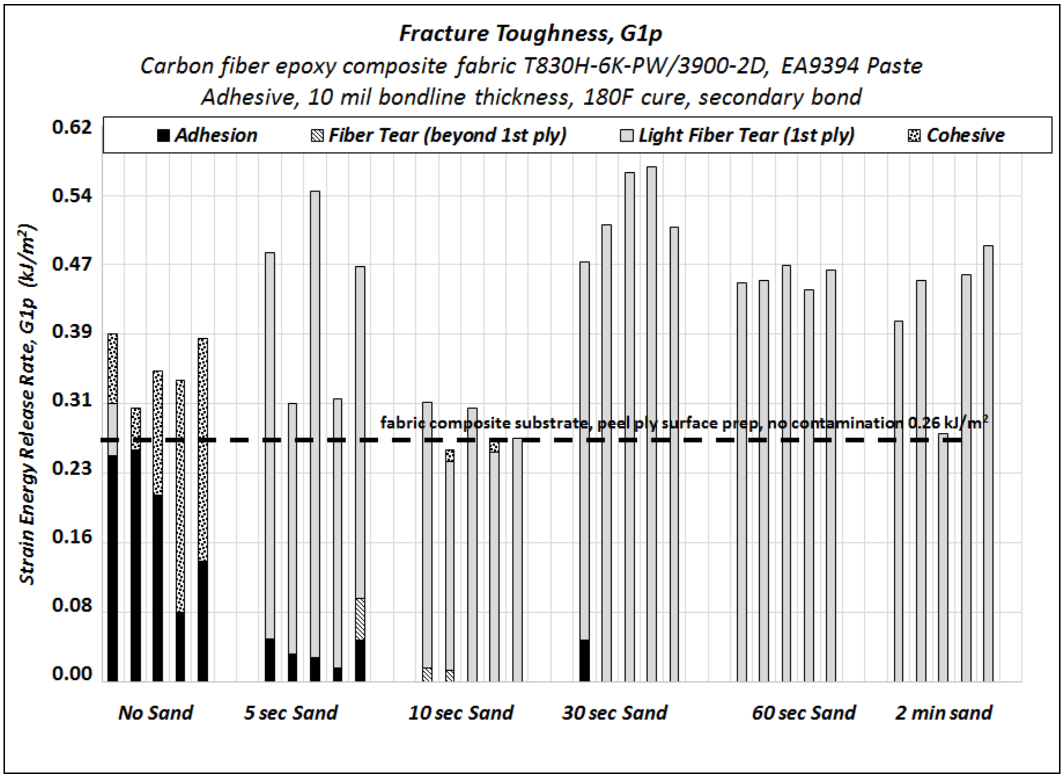


Figure 4. DCB coupon facture toughness values and failure modes

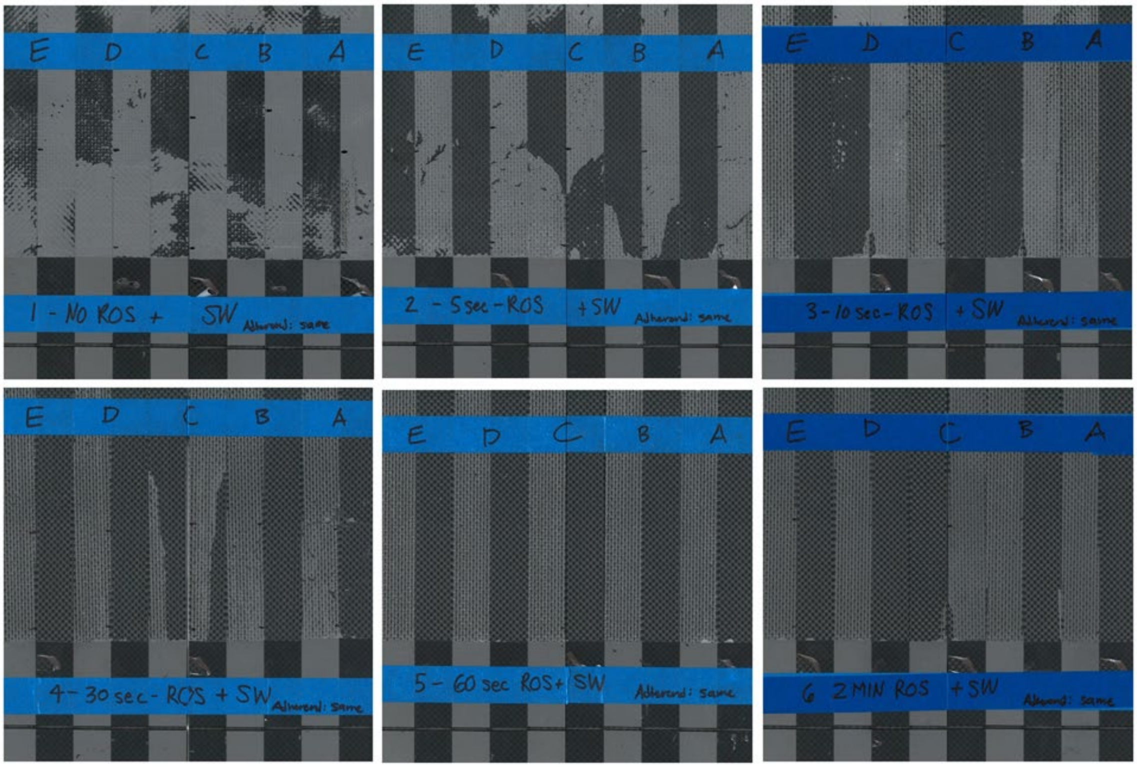


Figure 5. DCB coupon fracture surface failure modes

3.1 Surface Analysis Tools

An array of surface analysis tools were investigated previously and several were identified with the capability to detect level of sanding surface preparation of the epoxy composite surfaces tested here [Ref **F** 2018 Kutscha Sampe]. Color (delta E*, individual max) (Figure 6), Gloss (85 deg, indiv max) (Figure 7), FTIR (Figure 8) and OSEE (Figure 9) all demonstrated had the ability to detect the presences and level of random sanding on the prebond composite surfaces again here in this study.

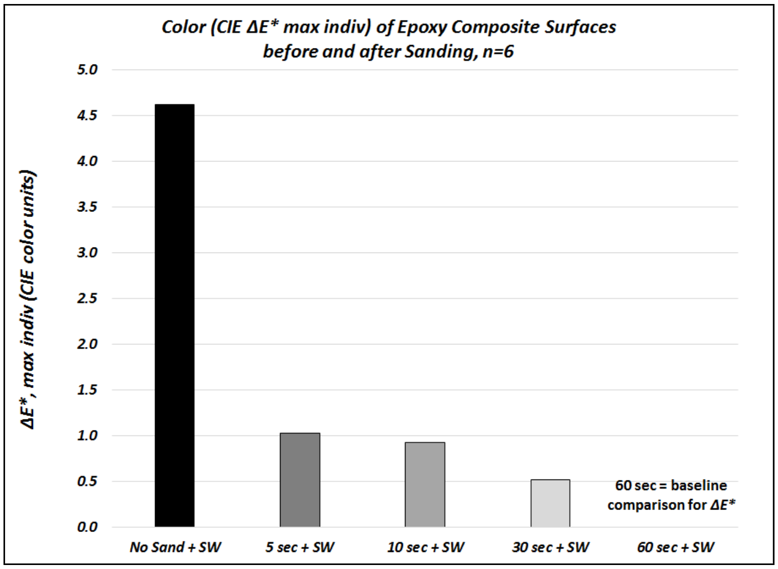


Figure 6. Color of sanded epoxy surfaces before and after sanding

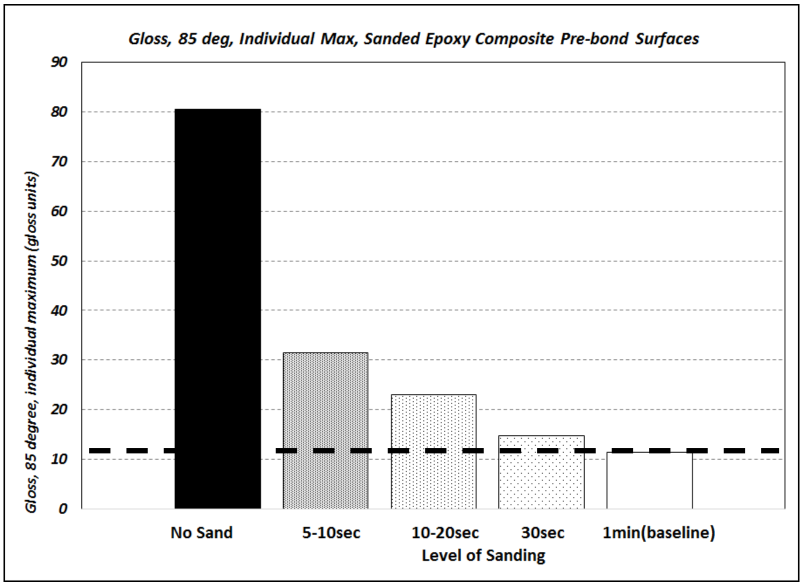


Figure 7. Gloss (85 deg, indiv max) of epoxy composite surfaces before and after sanding

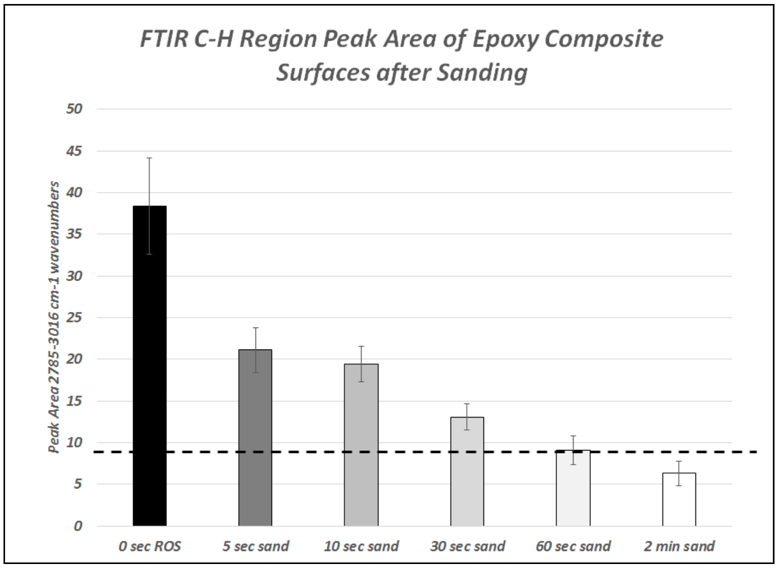


Figure 8. FTIR (C-H epoxy bonding peak area) of epoxy composite surfaces before and after sanding

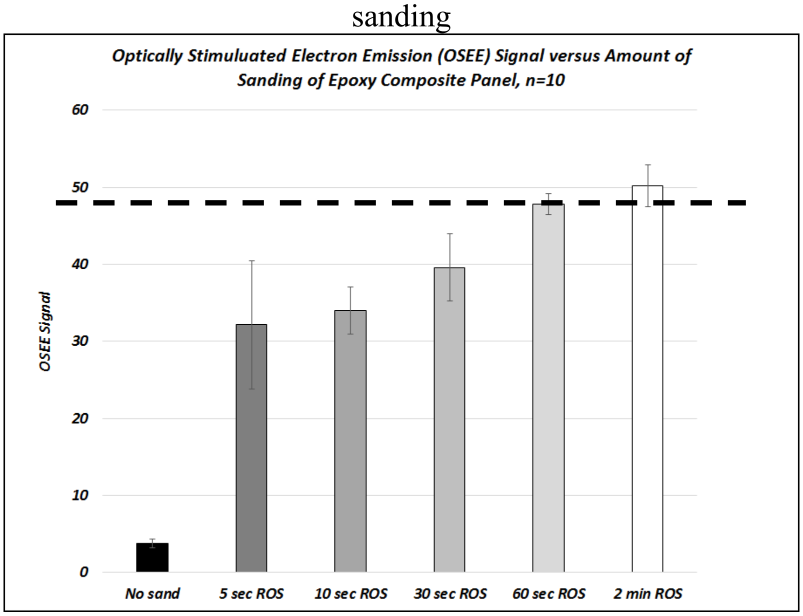


Figure 9. OSEE signal of epoxy composite surfaces before and after sanding

Threshold limits were defined for the minimum sanding target of one minute, based on bond performance results (Figure 4), which can subsequently be utilized for quantitative process control of the sanding operation.

It should be noted that ballistic water contact angle and surface roughness using a stylus method were not good indictors of sanded surface preparation and thus were not presented here.

3.2 Optically Enhanced Bonding Workstation (OEBW)

An Optically Enhanced Bonding Workstation (OEBW) was developed to improve robust bonding through process control [Ref PAT Wu Patent]. The system has a graphic user interface (GUI) based on LabVIEW software. The system verifies the bonding process steps through 1) time-stamps, 2) reference images and 3) verification of the surface preparation with surface analysis tool measurements.

To implement the system, reference images were generated for each step in the bonding operation (Figure 10). The reference images were incorporated into the graphical user interface (GUI) representation as shown in the lower right of Figure 11 for the Materials Check Step and Figure 12 for the Sanding Step. The reference image (lower right) can be compared to the actual operation (center) and should also be the same as the operator documented image (upper right) which is stored digitally. Note that the Materials Check step has a checklist to verify all materials are available prior to proceeding.

After the bonding operation is complete the Optically Enhanced Bonding Workstation creates an output documentation file containing the process time stamp information (Figure 13) as well as any deviations for the expected flow times (Figure 14). Documented images are also stored in a file for potential future reference.

Work here demonstrates how process control and the OEBW is able to reduce the risk in the bonded joint fabrication of a selected system through verification of process steps. The technology was further advanced during this work by demonstrating how in-line process control tools could be incorporated into the system. This technology is transferable to any substrate and bonded system with some calibration of the surface analysis tools.

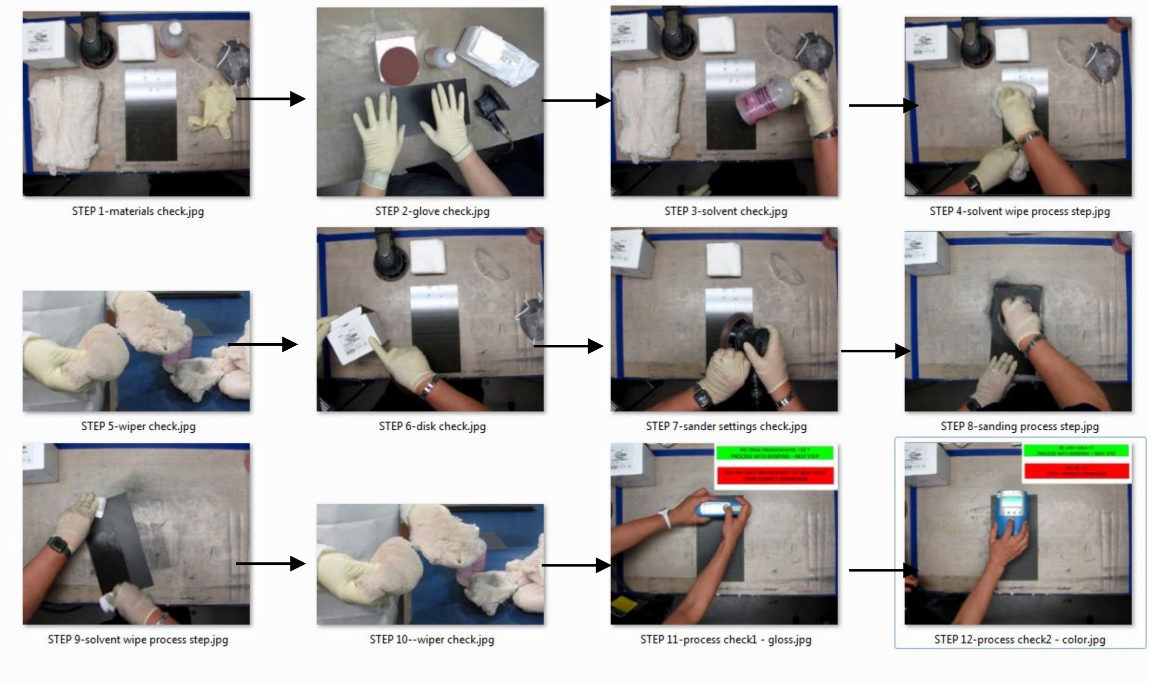
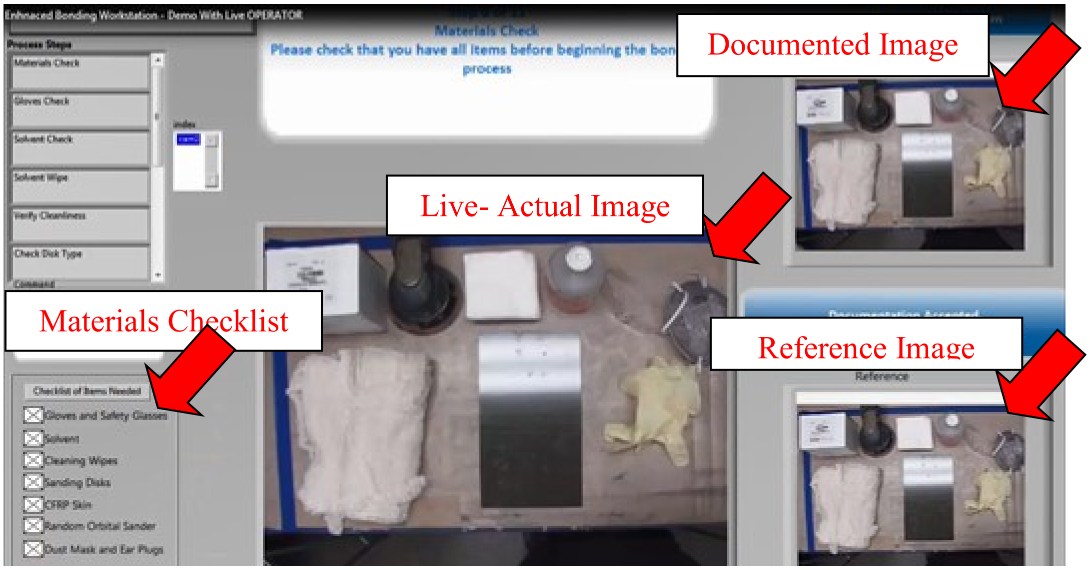


Figure 10. Optically Enhanced Bonding Workstation Reference Images



Materials Check

Please check that you have all items before beginning the bon
process

Checklist of Items Needed
☒ Gloves and Safety Glasses
☒ Solvent
☒ Cleaning Wipes
☒ Sanding Disks
☒ CFRP Skin
☒ Random Orbital Sander
☒ Dust Mask and Ear Plugs

Figure 11. Optically Enhanced Bonding Workstation - Materials Check Step

Step 7 of 11
Perform Random Orbital Sanding
Perform Random Orbital Sanding of Part for approximately 1 minute
until gloss reduced
"DOCUMENT" when complete

"NEXT STEP" to Proceed

Documentation Accepted.
Click here or say 'Next Step' to Proceed

Figure 12. Bond Optimization Workstation - Sanding Process Step

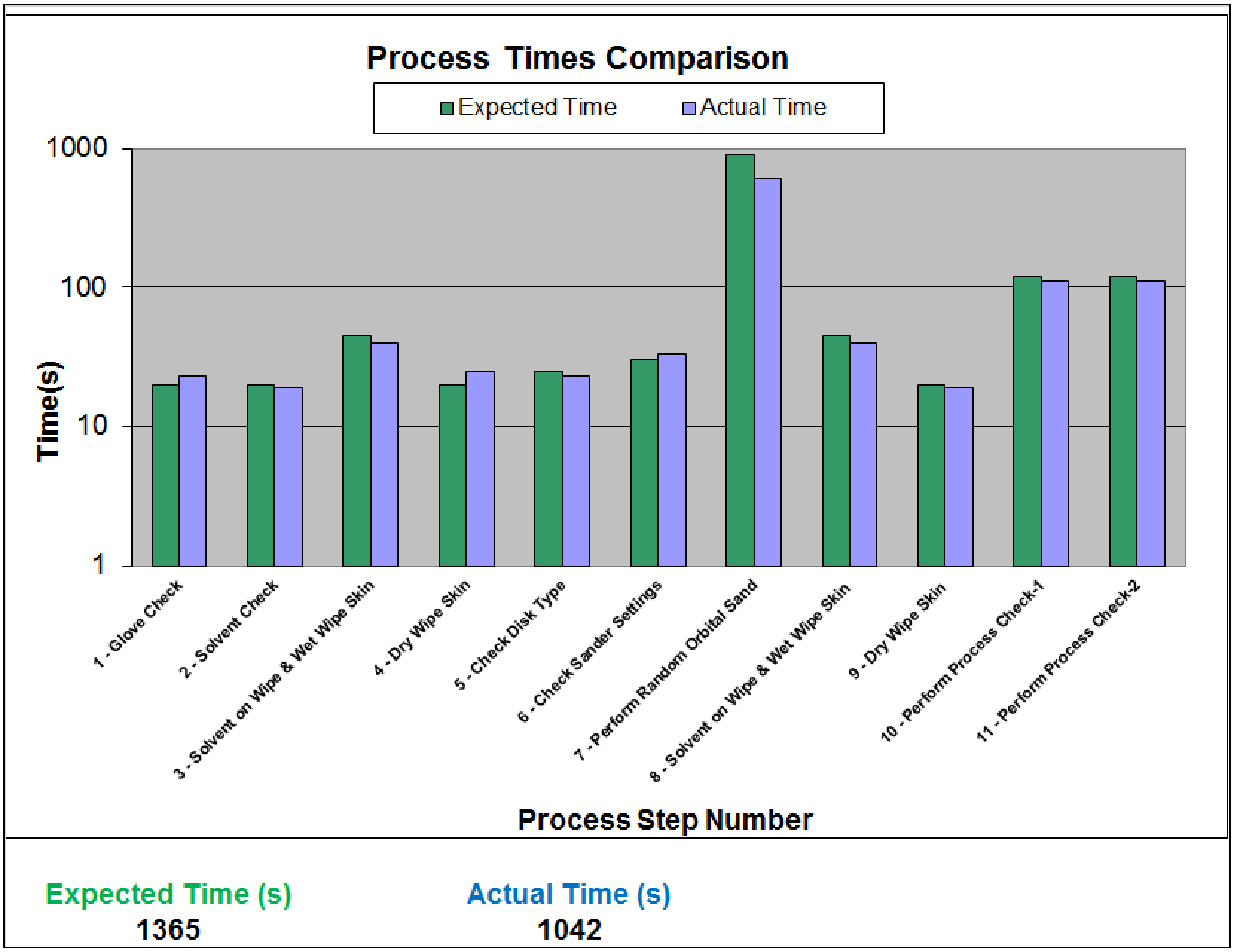
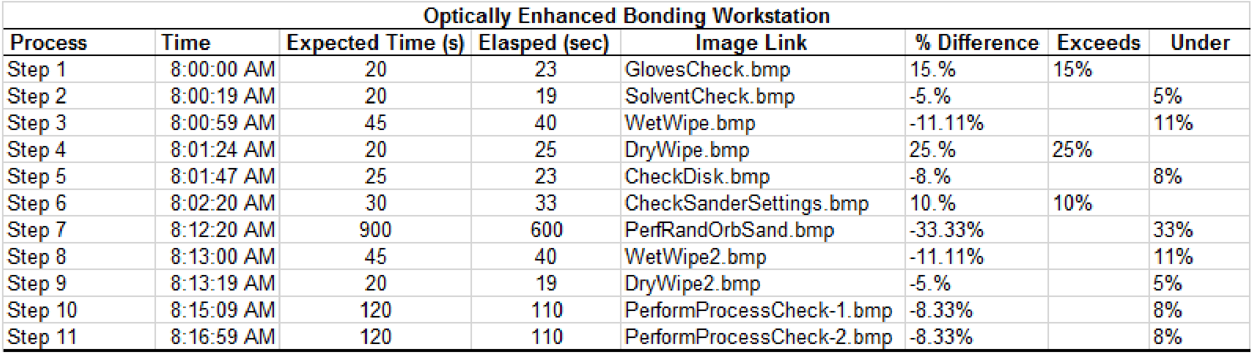


Figure 13. Optically Enhanced Bonding Workstation Timestamp Output Documentation



Optically Enhanced Bonding Workstation

Process	Time	Expected Time (s)	Elasped (sec)	Image Link	% Difference	Exceeds	Under
Step 1	8:00:00 AM	20	23	GlovesCheck.bmp	15.%	15%	
Step 2	8:00:19 AM	20	19	SolventCheck.bmp	-5.%		5%
Step 3	8:00:59 AM	45	40	WetWipe.bmp	-11.11%		11%
Step 4	8:01:24 AM	20	25	DryWipe.bmp	25.%	25%	
Step 5	8:01:47 AM	25	23	CheckDisk.bmp	-8.%		8%
Step 6	8:02:20 AM	30	33	CheckSanderSettings.bmp	10.%	10%	
Step 7	8:12:20 AM	900	600	PerfRandOrbSand.bmp	-33.33%		33%
Step 8	8:13:00 AM	45	40	WetWipe2.bmp	-11.11%		11%
Step 9	8:13:19 AM	20	19	DryWipe2.bmp	-5.%		5%
Step 10	8:15:09 AM	120	110	PerformProcessCheck-1.bmp	-8.33%		8%
Step 11	8:16:59 AM	120	110	PerformProcessCheck-2.bmp	-8.33%		8%

Figure 14. Bond Optimization Workstation Timestamp Output Documentation and Deviations

4. CONCLUSIONS

- Bonding results confirmed that sanded surface preparation of composite surfaces is a high risk parameter as demonstrated in the failure mode of the adhesive
- Analytical surface analysis tools selected previously were able to consistently detect presence and level of sanding surface preparation
- Threshold limits were easily determined based on the analytical tool measurements
- The threshold limits were easily incorporated into the OEBW and utilized as in-line bond process controls
- Surface analysis tools identified here can be easily incorporated into an automated system because of their portability and ability to rapidly provided quantitative results.

Note that results presented here are applicable to the selected objective bonding system. This step-wise system to implement process control can be applied to nearly any bonding system.

Benefits of the Optically Enhanced Bonding Workstation include the following:

1) Digital Thread – Recording and storage of bonded joint fabrication results for potential future trouble shooting if needed
2) Digital Twin or Model - Documentation of a standardized bonding process electronically for reference at any time or location for either standard part manufacturing or training purposes
3) Human-Machine Interface – A GUI system is available to receive and input data throughout the process real time
4) Data Visualization – Output data clearly identifies discrepancies between target and actual performed bond process steps

The work presented here demonstrates the correlation between process control and improved bond performance. It demonstrates quantitatively that FAA recommendations to perform process control, as outlined in their certification guidance document [1], do result in more robust bond performance. This work also provides guidance to the industry on a stepwise process to reduce risk of defects in the process development prior to full certification testing. This achieves NASA ACP goals to reduce timeline to certify bonded structure through establishing a robust bonded system in advance.

5. ACKNOWLEDGEMENTS

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