CONTAMINATION AND SURFACE PREPARATION EFFECTS ON COMPOSITE BONDING

Eileen O. Kutscha¹, Paul G. Vahey¹, Marcus A. Belcher¹, Peter J. VanVoast¹, William B. Grace¹, Kay Y. Blohowiak¹, Frank L. Palmieri², John W. Connell²

¹Boeing Research and Technology
Seattle, WA 98124 USA

²National Aeronautics and Space Administration
Langley Research Center
Hampton, VA 23681 USA

ABSTRACT

Results presented here demonstrate the effect of several prebond surface contaminants (hydrocarbon, machining fluid, latex, silicone, peel ply residue, release film) on bond quality, as measured by fracture toughness and failure modes of carbon fiber reinforced epoxy substrates bonded in secondary and co-bond configurations with paste and film adhesives. Additionally, the capability of various prebond surface property measurement tools to detect contaminants and potentially predict subsequent bond performance of three different adhesives is also shown. Surface measurement methods included water contact angle, Dyne solution wettability, optically stimulated electron emission spectroscopy, surface free energy, inverse gas chromatography, and Fourier transform infrared spectroscopy with chemometrics analysis. Information will also be provided on the effectiveness of mechanical and energetic surface treatments to recover a bondable surface after contamination. The benefits and drawbacks of the various surface analysis tools to detect contaminants and evaluate prebond surfaces after surface treatment were assessed as well as their ability to correlate to bond performance. Surface analysis tools were also evaluated for their potential use as in-line quality control of adhesive bonding parameters in the manufacturing environment.

INTRODUCTION

This work was performed as part of NASA’s Advanced Composites Program. Benefits of the project are outlined below.

Bonding System Assessment – Contamination and Surface Preparation Effects

A bonding system is comprised of the substrate(s), surface treatment(s), adhesive, and process to form the adhesive bond. Changing any one of these can affect bond performance. Substrate, surface preparation, adhesive, and contaminant effects on bond performance reported here provides initial direction to the industry in selecting a bonding system. Results presented here identified certain parameters that have more of an impact on bond performance than others. This work provides a better understanding of the effects of different types of contaminants and surface preparations on bond performance with select adhesives.
Bonding System Evaluation Methods for Pre-Certification Testing
The number of reworks in the development process and the timeline to certification can be reduced by early identification of bonding systems with good performance. This effort evaluates the effect of surface preparations, adhesives, bonding processes, and contaminants on bond performance utilizing the double cantilever beam (DCB) test. The DCB coupon configuration stresses the substrate-adhesive interface and is sensitive to detecting the effects of prebond surface conditions on adhesion. Utilization of the various test methods investigated herein can identify threats at the substrate-adhesive interface for a specific bonded system under consideration.

Surface Analysis Tool Capabilities for In-Line Bond Process Monitoring and Control
Guaranteed bond reliability and robustness will enable higher usage of bonded joints in service which can potentially result in subsequent cost savings. Strict process control can provide verification of surface treatment, surface consistency and cleanliness, and subsequently bond reliability in alignment with recommendations in Federal Aviation Administration (FAA) Advisory Circular AC 20-107B. This work identified limits and thresholds for bonding process control based on output of analytical tools used to measure the prebond surface. Understanding the limits and capabilities of the analytical methods is critical to whether they can be used in bond process monitoring. Work here demonstrated that surface analysis methods must be tailored to the specific bonding system in order to capture the benefits.

Targeting resources in areas of value - Savings of Time and Money
Better understanding the threat level of various contaminants can be utilized to better direct resources to areas of greatest need. Knowing the impact of various contaminants on bond performance can assist in defining realistic requirements for process environment controls. Contaminants requiring the highest level of controls can be identified or eliminated from the production environment entirely. Cost savings can be captured in avoiding attempts to control every material and thereby avoiding implementation of unnecessary requirements. Thus, resources can be focused on targeting the highest risk contaminants that are known to impact bond performance.

EXPERIMENTATION

Composite panel fabrication
DCB adherends were constructed using 10 plies of 177 ºC (350ºF) 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]. Witness panels for surface analysis were fabricated using only two plies of the fabric prepreg. Panels were cured against a tool treated with Frekote 710NC mold release agent (control), against a 1-3 mil thick, non-perforated, fluorinated ethylene propylene (FEP) film on a tool, or with one of two different peel plies: Precision Fabrics Group 60001/049/0009 polyester peel ply (PP) or Style 52006 nylon peel ply (NY). Panels without peel ply were solvent wiped with Eastman™ methyl propyl ketone (MPK) prior to any surface treatment using cleaning cloths meeting the requirements of AMS3819B Class 2 Grade A.
Contaminant application

After peel ply removal and before surface treatment, contaminants were applied to the prebond surfaces using an airbrush or high-volume, low-pressure (HVLP) spray gun (Figure 1) at coat weights shown in Table 1. Coat weights were determined by weight using a 102 x 152 x 0.51 mm (4 x 6 x 0.02 in) clad aluminum witness panel.

Figure 1. Spray application of diluted contaminants onto panels with HVLP spray gun

Table 1. Contaminant target and actual coat weights

<table>
<thead>
<tr>
<th>Contaminant</th>
<th>Target</th>
<th>Actual Witness</th>
<th>Actual DCB</th>
<th>Avg</th>
<th>St Dev</th>
<th>Avg</th>
<th>St Dev</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mg/ft²</td>
<td>μg/cm²</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frekote 710NC (silicone) (FK)</td>
<td>Low</td>
<td>2</td>
<td>1.9</td>
<td>1.1</td>
<td>0.8</td>
<td>0.5</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>8</td>
<td>9</td>
<td>11</td>
<td>2.8</td>
<td>5</td>
<td>0.0</td>
</tr>
<tr>
<td>Chain Lube (hydrocarbon) (HC)</td>
<td>Low</td>
<td>10</td>
<td>14</td>
<td>3</td>
<td>12</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>50</td>
<td>54</td>
<td>43</td>
<td>12</td>
<td>57</td>
<td>4</td>
</tr>
<tr>
<td>Syntilo9828 (machining fluid) (MF)</td>
<td>Low</td>
<td>10</td>
<td>11</td>
<td>6.5</td>
<td>0.91</td>
<td>8.3</td>
<td>0.91</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>50</td>
<td>54</td>
<td>51</td>
<td>2.3</td>
<td>64</td>
<td>8.7</td>
</tr>
<tr>
<td>latex glove extract (LG)</td>
<td>Low</td>
<td>2</td>
<td>2</td>
<td>1.9</td>
<td>0</td>
<td>1.6</td>
<td>0.46</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>8</td>
<td>9</td>
<td>*29</td>
<td>8.2</td>
<td>7</td>
<td>0.0</td>
</tr>
</tbody>
</table>

* inadvertently high application of contaminant

Contaminants were diluted in hexanes (FK, HC), isopropyl alcohol (MF) or analytical grade methyl propyl ketone (LG) prior to application. Latex glove extract was generated by soaking gloves in MPK for approximately 30 days. It should be noted that contaminants were applied at levels beyond what is normally seen in production except in the case of Frekote which can be found on tool surfaces in this range and bond failures are known to occur at these levels.

Surface treatments

After contamination, panels were surface treated by grit blasting (GB) using 180 grit aluminum oxide, random orbital sanding (ROS) using 180 grit aluminum oxide Merit sand paper, or energetic surface treatment with laser ablation (LR) or plasma (PL). Laser ablation was performed at NASA Langley Research Center using a PhotoMachining, Inc. system with a Coherent®, Avia®, frequency tripled, Nd:YAG laser (7 W nominal pulsed output at 355 nm and 10 ns pulse duration).
with a speed of 25.4 cm/s (10 in/s) and an average fluence of 19.4 mJ/mm². Atmospheric pressure plasma treatment was performed at Boeing using a Plasmatreat system consisting of five RD1004 heads each with a 17° nozzle tip at one operating parameter set.

**DCB coupon bonding and test**

DCB assemblies were secondarily bonded using Henkel™ EA9696 0.06 psf 121°C (250°F) cure film adhesive cured in an autoclave or Henkel™ EA9394 paste adhesive cured at 82°C (180°F) in a press or co-bonded using 3M™ Scotch-Weld™ AF 555M 0.05 psf 177°C (350°F) cure film adhesive. Bonded coupon configuration is shown in Figure 2.

![Figure 2. DCB coupon bonding configuration using EA9696 film](image)

Coupons were tested in accordance with ASTM D 5528 at a loading rate of 1 inch (25mm) per min after the specimen was precracked by hand. The propagated strain energy release rate \( G_{IP} \), or fracture toughness, was calculated using the area under the load displacement curve in accordance with Equation 1.

\[
G_{IP} = \frac{E}{(A \times B)} \quad \text{Eq 1}
\]

- \( E \) – 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

**Surface Analysis**

Prebond surfaces before and after surface treatment were characterized using the following: 1) ballistic drop deposition water contact angle (WCA) measured with a Surface Analyst Model SA1001 from BTG, 2) *Dyne* solution wettability based on methods in ASTM D 2578 using solutions between 30 and 70 dyne/cm from Accu Dyne Test™, 3) optically stimulated electron emission (OSEE) using an ultraviolet light prototype instrument at NASA Langley Research Center, 4) surface free energy (SFE) calculated using sessile drop contact angles of deionized water, diiodomethane, and ethylene glycol measured using a Krüss DSA100 Drop Shape Analysis system, and 5) inverse gas chromatography (IGC) using an SMS-IGC from Surface Measurement Systems, London, UK with a thin film cell clamp attachment. Chemical signature information was gathered using Fourier transform infrared (FTIR) spectroscopy measured using an Agilent model 4100 "Exoscan" spectrometer with a spherical diamond attenuated total reflectance (D-ATR) attachment. Spectra were collected from panels by placing the D-ATR directly on the surface and
also using a residue method. The residue method eliminates the effect of the composite background by lifting the D-ATR off the surface prior to data collection. Chemometrics on FTIR spectra was performed with Unscrambler® X Version 10.3 software from Camo Software and principal component analysis (PCA).

RESULTS

Bonding Results

The effects of contaminants and surface preparation on fracture toughness and failure mode of DCB coupons are shown below in Figure 3 and

Figure 4 for EA9696 121°C (250°F) cure film adhesive, Figure 5 and Figure 6 for EA9394 180°F cure, paste adhesive, and

Figure 8 and Figure 9 for AF 555M 350°F cure film adhesive. Baseline fracture toughness values are shown for comparison and were selected based on test data generated here or supplier values for the adhesive found in their technical data sheets. Contaminants were applied at levels beyond what is normally seen in production except in the case of Frekote. Frekote at levels applied here can be found in production at these coat weights on tools surfaces and bond failures are known to occur in these ranges.

Figure 3. DCB results for EA9696 250°F film adhesive after contamination or surface preparation, as-tooled surfaces (left) and peel ply surfaces (right)
Figure 4. DCB results for EA9696 121°C (250°F) film adhesive after contamination followed by surface preparation, as-tooled surfaces (left) and peel ply surfaces (right). Reduced bond performance was observed consistently with nylon peel ply, FEP, Frekote, and latex residue with all adhesives. In this testing, EA9696 was more sensitive to all contaminants except Frekote while AF 555M was highly sensitive to Frekote but less so to the other contaminants. This further demonstrates that each bonding system needs to be fully characterized prior to implementation, including assessing sensitivities to contaminants known to be in the manufacturing environment.

Nylon peel ply is known to be incompatible with the composite prepreg tested here but was tested as a known “worst case scenario” [1]. As expected, NY did not have good bond performance with any adhesive tested.

An overall reduced bond performance was observed with laser treated panels bonded with paste adhesive. The lower bond performance was not likely due to contamination but the laser treatment itself. Magnification of the bonded surface revealed that the failure mode was a combination of light fiber tear and up to 40% adhesion failure mode. Laser trough imprints were observed in the paste adhesive confirming this (Figure 7 c.). This adhesion failure mode was not observed on laser treated surfaces with film adhesives cured in the autoclave. This supports the observation that the surface treatment process needs to be optimized for each bonding system. In this work, only one set of laser surface treatment conditions was evaluated.
Figure 5. DCB results for EA9394 paste adhesive after contamination or surface preparation, as-tooled surfaces (left) and peel ply surfaces (right).

Figure 6. DCB results for EA9394 paste adhesive after contamination followed by surface preparation, as-tooled surfaces (left) and peel ply surfaces (right).

Figure 7. EA9394 paste bonded panels with visible troughs indicating “adhesion” failure mode between adhesive and substrate on laser treated substrates.
Pre-bond composite surfaces cured against a tool with FEP did not have good subsequent bond performance either. The FTIR residue method identified that some FEP material was left behind on the cured composite surface (Figure 10).
Previous work using X-ray photoelectron spectroscopy (XPS) confirmed FTIR results and showed fluorine does transfer to the surface of a composite panels from FEP [2]. All bonded panels were compacted with red perforated FEP with no observable impact to bond performance. Heat during cure may play a role in residue transfer of the FEP residue.

A summary of the bond performance results are shown in Table 2.

Table 2. Summary of bond performance results of three adhesives

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Contaminant</th>
<th>Surface Preparation</th>
<th>AF555 Bond Performance</th>
<th>EA096 Bond Performance</th>
<th>EA094 Bond Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Before Surface Treatment</td>
<td>After Surface Treatment</td>
<td>Before Surface Treatment</td>
</tr>
<tr>
<td>NA</td>
<td>Laser</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>NA</td>
<td>SDS</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>NA</td>
<td>GB</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>NA</td>
<td>Plasma</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Poor</td>
</tr>
<tr>
<td>Polyester PP</td>
<td>Laser</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Polyester PP</td>
<td>GB</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Polyester PP</td>
<td>Plasma</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Nylon PP</td>
<td>Laser</td>
<td>Poor</td>
<td>Poor</td>
<td>Poor</td>
<td>Poor</td>
</tr>
<tr>
<td>Nylon PP</td>
<td>GB</td>
<td>Poor</td>
<td>Poor</td>
<td>Poor</td>
<td>Poor</td>
</tr>
<tr>
<td>Nylon PP</td>
<td>Plasma</td>
<td>Poor</td>
<td>Poor</td>
<td>Poor</td>
<td>Poor</td>
</tr>
</tbody>
</table>

In general, as-tooled surfaces were more sensitive to contaminants than peel ply treated surfaces prior to surface treatment. Surface preparation prior to bonding enabled good bond performance with the tested film adhesives, regardless of type or level of contamination. AF 555M cured at 177°C (350°F) with a low viscosity during cure in particular was more able to accommodate the presence of all contaminants after surface treatments. The paste adhesive tested here, however, had more difficulty overcoming the knockdown from the presence of contaminants in the bondline even after surface treatment. Because it is not clear whether adhesive cure temperature, bonding process (press versus autoclave), adhesive chemistry, or surface treatment affected the bond performance, testing of the specific bonding system to optimize performance is required early on in the development phase.

**Surface Analysis**

*Ballistic drop deposition water contact angle (WCA) measurements*

WCA measurements are shown in Figure 11 for as-tooled and peel ply surfaces. Results demonstrated that ballistic WCA was capable of differentiating between uncontaminated and contaminated surfaces. The one exception was that ballistic WCA was not able to differentiate...
between polyester and nylon peel ply surfaces. Ballistic WCA was also able to differentiate between surfaces with and without surface treatment with the exception of as-tooled surfaces as shown in Figure 12.

![Figure 11. Ballistic WCA - Effect of contaminants – as-tooled (left) and peel ply surfaces (right)](image1)

**Figure 11. Ballistic WCA - Effect of contaminants – as-tooled (left) and peel ply surfaces (right)**

![Figure 12. Ballistic WCA - Effect of surface preparations](image2)

**Figure 12. Ballistic WCA - Effect of surface preparations**

*Dyne solution wettability*

Effect of surface preparation and contamination is shown in Figure 13 for as-tooled and peel ply surfaces. In some cases, Dyne solution wettability was able to detect the presence of contaminants. For example, the surface energy decreased significantly with FEP and silicone on as-tooled surfaces, which also correlated to poor bond performance. In other cases, the contaminants were detected but the surface wettability increased contrary to the expected result.

Dyne solutions were able to easily detect laser, ROS, and GB surface treatments on as-tooled and peel ply surfaces as dyne solutions will completely wet out on abraded surfaces (Figure 14). Dyne solutions were not able to detect plasma treatment of as-tooled surfaces or the difference between as-tooled and NY or PP surface which all had a dyne solution reading of 42 dyne/cm.
Optically stimulated electron emission spectroscopy (OSEE)

OSEE spectroscopy results from panels treated with various contaminants demonstrated that the technique could distinguish between a clean baseline panel and contaminated panels except for machining fluid (Figure 15). Additionally, results showed that ROS, GB, and laser treated panels were “cleaner” than the baseline clean and contaminated panels. However, there were some incongruous results with the contaminated panels that received subsequent abrasion. The contaminated and surface treated panels appeared cleaner than the baseline panel. These incongruous results may be due to the fact that this technique is more sensitive at lower concentrations. Additionally, the OSEE technique is sensitive to the amount of exposed fiber and epoxy resin on the surface. A surface preparation that removes epoxy resin as it removes contamination may result in a stronger OSEE signal that could easily exceed the signal measured from the baseline material.
Surface free energy (SFE)

Surface free energy (SFE) values for contaminated surfaces are shown in Figure 16. For peel ply surfaces, limited data were available due to the irregular droplet shapes, particularly on highly contaminated, peel ply surfaces. On as-tooled surfaces, SFE was reduced with FEP and FK (silicone) as would be expected. There was an expected inverse correlation with machining fluid based on previous ballistic WCA measurements. Inconclusive results were obtained with the other contaminants.

SFE was a good indicator of all surface treatments as shown in Figure 17. There is some indication that the dispersive component may provide more information than the polar component, except in the case of machining fluid. Overall, SFE was not a good indicator of bond performance.
Inverse gas chromatography

Only selected panels were evaluated with IGC due to the 12 hour measurement time required. Error of the IGC method has been demonstrated to be quite low [3] so these differences can be considered to be statistically significant. IGC was not successful at distinguishing machining fluid from non-contaminated panels (data not shown). However, the IGC dispersive component and the acetone polar component did differentiate between no, low, and high FK on as-tooled surfaces (Figure 18). Additionally some expected differences were observed on peel ply panels with low Frekote and plasma treatment (Figure 19). On all other surface energy measurement methods (Dyne, WCA, SFE), the plasma treated samples had extremely high surface energy or low contact angle values. This same trend was not observed with IGC. However, these panels were not measured immediately after plasma treatment.

Figure 18. IGC detection of Frekote levels – Dispersive Surface Energy (left) and Acetone polar component (right)
FTIR and Chemometrics

Chemometrics analyses of FTIR data presented here focused on the as-tooled surfaces as those were the most affected by applied contaminants. Principal components analysis (PCA) of the FTIR residue data showed clustering of surface contamination data in Figure 20 (left). The PC-2 versus PC-1 scores plot shows no contamination at the center "bullseye" cluster and more highly contaminated samples farther away from the center. Such clustering of data can be used to sort degree of contamination.

A PCA scores plot showing the effect of different surface treatments within the FTIR data is shown in Figure 20 (right). There is an apparent difference between the untreated composite surface (NA) and all of the other surface treatments. It is thought that these differences reflect the amount and state of the resin remaining on the surface after treatment. With more "training" these models can be used with the handheld FTIR Exoscan instrument to identify the presence of contaminants or surface treatments.
Overall, chemometrics was able to differentiate between high and low contaminant levels and was able to detect contaminants known to be a threat to bond performance on as-tooled surfaces including FEP and Frekote and latex residues. Chemometrics analysis was also able to detect and differentiate between different surface treatments.

**Summary of Surface Analysis Methods**

A summary of the surface analysis tools is shown below in Table 3 along with capabilities, benefits, and limitations.

<table>
<thead>
<tr>
<th>Table 3. Surface analysis tool assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Surface Energy – Goniometer</strong></td>
</tr>
<tr>
<td>Detection of Contaminants</td>
</tr>
<tr>
<td>Selected contaminants as-tooled surface only</td>
</tr>
<tr>
<td><strong>IGC</strong></td>
</tr>
<tr>
<td>Detected (limited panels measured)</td>
</tr>
<tr>
<td><strong>FTIR residue – chemometrics</strong></td>
</tr>
<tr>
<td>Yes</td>
</tr>
<tr>
<td><strong>FTIR direct – chemometrics</strong></td>
</tr>
<tr>
<td>Identified higher concentration contaminants that were detrimental to bond performance.</td>
</tr>
<tr>
<td><strong>Brighton Water Contact Angle</strong></td>
</tr>
<tr>
<td>Yes except Nylon PP</td>
</tr>
<tr>
<td><strong>Dyne Solutions</strong></td>
</tr>
<tr>
<td>Generally</td>
</tr>
<tr>
<td><strong>OSEE</strong></td>
</tr>
<tr>
<td>Yes except machining fluid</td>
</tr>
</tbody>
</table>
## Detection of Contaminants

<table>
<thead>
<tr>
<th>Detection of Contaminants</th>
<th>Detection of Surface Preparation</th>
<th>Correlate to bond performance</th>
<th>Benefits</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>FTIR (no chemometrics)</td>
<td>Yes</td>
<td>Would require detailed peak area or height analysis</td>
<td>Larger detection area contaminant must be photo emitter</td>
<td></td>
</tr>
</tbody>
</table>

The suite of analytical tools tested here are capable of evaluating pre-bond surfaces but must be tailored to the specific bonded system being evaluated.

### CONCLUSIONS

- As-toolled surfaces were more sensitive to contamination than peel ply treated surfaces.
- Reduced bond performance was observed consistently with nylon peel ply, FEP, Frekote, and latex residue with all adhesives.
- The paste adhesive tested here was not able to accommodate the presence of contaminants as well as the film adhesive.
- Surface analysis tools, including wettability, contact angle methods and chemical fingerprint FTIR methods with chemometrics, were successful at distinguishing between contaminants and surface treatments in selected cases.
- Inverse gas chromatography surface energy methods were not as successful at detecting surface differences.
- Surface texture played a role in the ability to collect reliable and consistent wettability measurements (Dyne, WCA, SFE).
- The ballistic water drop contact angle method was more consistent and reliable at collecting information than the sessile drop goniometer method.
- Surface analysis methods tested here did not provide good bond performance, fracture toughness and failure mode, prediction information.

Overall, results demonstrated that compatibility of the entire bonding system (substrate, surface preparation, adhesive, and bonding process) was critical for good bond performance.

The material is based upon work supported by NASA under Award No. NNL09AA00A, Agreement No: C15-2A38-Boeing.

Acknowledgements to Diane LaRiviere for her insight on FTIR spectra collection and analysis, Ryan Wilson for inverse gas chromatography and goniometer investigations, Ashley Tracey for consulting on surface energy, Dan Perey and Josh Brown, and John Hopkins from NASA for the OSEE results and laser surface treatment processing, respectively.
REFERENCES

