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Laser Ablation & Passivation of Aluminum Alloys

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Outline

1. Overview
2. Laser Overlap Percentage & Processing Sequence
3. Sample Preparation/Focused Ion Beam Overview
4. Environment & Surface Preparation
5. Mechanical Testing
6. Summary
Background & Motivation

- Aluminum is used in a wide variety of applications because it is lightweight, ductile, and highly machinable, among other attractive properties.
- However, corrosion can significantly degrade the strength of aluminum over time.
- Hexavalent chromium (Cr⁶⁺) conversion coatings are one type of coating used to protect aluminum components while in service.

**Conversion Coating**

Applied to protect the surface of aluminum components, but are toxic, unstable at high temperatures, and degrade over time.

**Media Blasting**

Used to refurbish components, but can cause sub-surface damage/warpage/pin-holing and generates significant toxic waste.
Background & Motivation

The objective is to replace media blasting and conversion coatings with clean laser processing.

Fort Walton Machining, Inc.
Conversion Coating & Media Blasting

Adapt Laser Systems, LLC

Great Lakes Minerals, LLC
Laser Ablation & Passivation

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Laser Processing Overview

Pulsed laser processing involves two steps:

1. **Laser ablation** uses nanosecond-length pulses to vaporize existing coatings and contaminants on the surface.

2. **Laser passivation** uses a laser pulse for very short melting of the uppermost surface then immediate quenching to form a stable oxide layer.

### Nd:YAG Laser Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Ablation</th>
<th>Passivation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>40 kHz</td>
<td>15 kHz</td>
</tr>
<tr>
<td>Energy</td>
<td>7.4 mJ</td>
<td>15.6 mJ</td>
</tr>
<tr>
<td>Intensity</td>
<td>1.1E+07 W/cm²</td>
<td>5.3E+07 W/cm²</td>
</tr>
<tr>
<td>Fluence</td>
<td>2.01 J/cm²</td>
<td>4.23 J/cm²</td>
</tr>
</tbody>
</table>

Adapt Laser Systems, LLC
Laser Processing Overview

Laser passivation offers the following advantages over conversion coatings:

<table>
<thead>
<tr>
<th>Conversion Coating</th>
<th>Hyper-Passivation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thin, superficial layer</td>
<td>Thicker, stable oxide</td>
</tr>
<tr>
<td>Dehydrates &gt;120°F, impacting coating adhesion</td>
<td>Predicted stability &gt;2,000°F</td>
</tr>
<tr>
<td>Highly toxic during initial coating and overhauling</td>
<td>Non-toxic</td>
</tr>
</tbody>
</table>

## Conversion Coating

- Thin, superficial layer
- Dehydrates >120°F, impacting coating adhesion
- Highly toxic during initial coating and overhauling

## Hyper-Passivation

- Thicker, stable oxide
- Predicted stability >2,000°F
- Non-toxic

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Experimental Setup

• Laser processing parameters:
  – Laser overlap percentage
  – Processing sequence
  – Oxygen environment
  – Surface preparation

• Characterization techniques:
  – Materials Characterization: Optical microscopy (OM), scanning electron microscopy (SEM), energy dispersive spectroscopy (EDS), and optical profilometry
  – Environmental Testing: Corrosion/salt fog and paint adhesion testing
  – Mechanical Testing: Tensile, fatigue, and hardness testing

• Alloys: 5052-H32, 6061-TO, 6061-T6, and 6061-T651
Laser Overlap Percentage

- The laser overlap percentage is measured using the centerline distance between adjacent laser pulses within the raster pattern.
- The baseline process utilized a 50% laser overlap.
- The raster pattern is readily apparent in the surface topography post-treatment:

Pre-Treatment  Post-Treatment

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Corrosion Testing

- Corrosion testing was conducted in a salt fog chamber according to MIL-STD-810G.
- Samples were tested for 1,320 hours in 24 hour exposure cycles:

  - Based on visual pitting density, laser passivation offers similar corrosion protection compared to conversion coating.
  - Detailed corrosion and paint adhesion testing is in progress; initial results support this observation and suggest that passivated samples have superior paint adhesion.
Corrosion Testing

It was observed that minimally exposed regions between laser pulses were more prone to visual pitting than other areas:
Sample Preparation

- Focused ion beam (FIB) was used to prepare cross-sections for characterizing the oxide thickness and uniformity.
- FIB can be considered an “extension” of SEM in which material can be selectively deposited or removed while imaging.

**Sample Preparation**

- Deposit a carbon “cap” using an electron beam.
- Deposit the rest of the cap using an ion beam.
- Mill a triangular section using an ion beam.
- “Clean” the cross-section sidewall.

**Oxide Layer**

- 1 µm
Sample Preparation

Sample Surface

Carbon Deposited

Oxide Layer
Environment & Surface Preparation

- Two aluminum alloys were compared in this study: 5052-H32 & 6061-T6
- The following conditions were used to study the impact on the oxide profile thickness and uniformity:

<table>
<thead>
<tr>
<th>ID</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIR</td>
<td>Stagnant air environment</td>
</tr>
<tr>
<td>FAN</td>
<td>Continuous air flow across surface</td>
</tr>
<tr>
<td>OX</td>
<td>Surface flooded with 95% canned oxygen</td>
</tr>
<tr>
<td>OZO</td>
<td>Surface flooded with generated ozone</td>
</tr>
<tr>
<td>H2O</td>
<td>Wetted surface</td>
</tr>
<tr>
<td>Environment</td>
<td>Description</td>
</tr>
<tr>
<td>---------------</td>
<td>--------------------------------------</td>
</tr>
<tr>
<td>AIR</td>
<td>Stagnant air environment</td>
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<tr>
<td>FAN</td>
<td>Continuous air flow across surface</td>
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<tr>
<td>OZO</td>
<td>Surface flooded with generated ozone</td>
</tr>
<tr>
<td>H2O</td>
<td>Wetted surface</td>
</tr>
</tbody>
</table>

- **AIR**: AVG Thickness: 91.1 nm
- **FAN**: AVG Thickness: 167.9 nm
- **OX**: AVG Thickness: 152.9 nm
- **OZO**: AVG Thickness: 155.8 nm
- **H2O**: AVG Thickness: 173.3 nm

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Mechanical Testing

- Dogbone specimens were used for tensile testing according to ASTM B557M-15:
  - Successive treatments were used to simulate effects of a component being overhauled multiple times.
  - The average values were calculated from three samples of each type/configuration.
- Hardness testing was also conducted, but is not reported in this presentation.
- Fatigue testing is currently in progress.

A = Ablation Step, P = Passivation Step

Ex: A-P-A-P-A
<table>
<thead>
<tr>
<th>Alloy</th>
<th>Treatment</th>
<th>Elastic Modulus</th>
<th>Ult. Tensile Strength</th>
<th>Offset Yield Stress</th>
<th>Fracture Stress</th>
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</thead>
<tbody>
<tr>
<td>5052-H32</td>
<td>None</td>
<td>8465.8</td>
<td>22.0</td>
<td>0.0%</td>
<td>22.0</td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>8933.0</td>
<td>21.4</td>
<td>2.5%</td>
<td>21.8</td>
</tr>
<tr>
<td></td>
<td>A-P</td>
<td>8165.9</td>
<td>21.4</td>
<td>-2.9%</td>
<td>21.4</td>
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<tr>
<td></td>
<td>A-P-A</td>
<td>7982.4</td>
<td>22.2</td>
<td>1.1%</td>
<td>22.2</td>
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<tr>
<td></td>
<td>A-P-A-A</td>
<td>8439.9</td>
<td>21.8</td>
<td>0.0%</td>
<td>21.8</td>
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<tr>
<td></td>
<td>A-P-A-P</td>
<td>9082.8</td>
<td>21.8</td>
<td>-0.3%</td>
<td>21.8</td>
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<tr>
<td></td>
<td>Media Blasted</td>
<td>8230.4</td>
<td>18.5</td>
<td>-17.1%</td>
<td>18.6</td>
</tr>
<tr>
<td>6061-TO</td>
<td>None</td>
<td>8633.6</td>
<td>43.5</td>
<td>0.0%</td>
<td>38.6</td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>8746.6</td>
<td>45.1</td>
<td>3.6%</td>
<td>41.5</td>
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<tr>
<td></td>
<td>A-P</td>
<td>8741.5</td>
<td>44.5</td>
<td>2.1%</td>
<td>40.8</td>
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<td></td>
<td>A-P-A</td>
<td>8573.4</td>
<td>44.7</td>
<td>2.6%</td>
<td>41.6</td>
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<tr>
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<td>A-P-A-A</td>
<td>8687.9</td>
<td>44.9</td>
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<tr>
<td></td>
<td>A-P-A-P</td>
<td>8701.5</td>
<td>44.5</td>
<td>2.1%</td>
<td>40.6</td>
</tr>
<tr>
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<tr>
<td></td>
<td>A-P-A-P-A-A</td>
<td>8714.8</td>
<td>44.3</td>
<td>1.7%</td>
<td>40.8</td>
</tr>
<tr>
<td></td>
<td>A-P-A-P-A-P</td>
<td>8823.2</td>
<td>44.7</td>
<td>2.6%</td>
<td>40.9</td>
</tr>
<tr>
<td></td>
<td>Media Blasted</td>
<td>7455.5</td>
<td>38.3</td>
<td>-12.7%</td>
<td>35.2</td>
</tr>
</tbody>
</table>

Units in [kip/in²]
Summary

• Laser ablation and passivation is an attractive process for replacing media blasting and conversion coatings for aluminum alloys.
• The impact of several parameters have been evaluated, including:
  – Laser overlap percentage
  – Environment & surface preparation
  – Processing sequence
• This process did not degrade the mechanical properties compared to media blasting.
Thank You!

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