INVESTIGATORS: Yaomin Lin, Teh-Hwa Wong, Kan Ni and Mool Gupta

**ABSTRACT/DESCRIPTION:**
The objective of the project “Laser Micromachining of Titanium Alloys” is to develop the laser micro-machining process to create initial cracks on Ti alloys for the fatigue life cycle studies. This allows the evaluation of the damage limits for Ti tubing used in aircrafts and its comparison with finite element modeling. The objective of the project “Laser Cleaning & Welding of Ti-3Al-2.5V Tubes” is to develop the methods of laser cleaning on Ti tubes to remove the oxidized layer and the welding of the tubes to fitting assemblies. Laser is also applied in the processing of aluminum alloys and carbon-fiber composites materials.

**PROGRESS TO DATE:**
- Pre-crack formation on straight 1/4”, 1/2”, 5/8” and 3/4” outer diameter Ti alloy tubing. (completed)
- Optical and electron microscopy characterization of laser micro-machining samples. (completed)
- Demonstration laser cleaning and welding of Ti-tube to fitting. (completed)
- Preparation of 1/2” and 3/8” outer diameter samples (tube-to-fitting welding) for testing. (completed)

**BENEFITS TO MEMBERS (Achieved and Anticipated):**
- A new method for crack initiation studies in fracture mechanics.
- Comparison of experimental life cycles to theoretical predictions.
- A new method of laser cleaning of tubes and weld them to fittings.

**MILESTONES**
- Laser micro-machining of precracks on Ti alloy tubes of 1/4” – 3/4” diameter.
- Characterization of laser micro-machining precracks by optical and SEM.
- Fatigue life evaluation of Ti alloy tubes.
- Outer and inner surfaces laser cleaning of different size tubing.
- Welding of laser cleaned tube to fittings.
Laser Micromachining of Titanium Alloy

Yaomin Lin, The-Hwa Wong and Mool C. Gupta

University of Virginia

May 4, 2007

Sponsor: NAVAIR

Photo courtesy U.S. Navy
Objectives

- Establishment of damage limits for the tubes of various sizes
- Preparation of test samples for fatigue life study using laser micromachining of Ti-3Al-2.5V tubes
  - 1/4”OD × 0.022”TWT;
  - 3/8”OD × 0.032”TWT;
  - 1/2”OD × 0.043”TWT;
  - 5/8”OD × 0.054”TWT;
  - 3/4”OD × 0.065”TWT.

Notes: OD – outer diameter;
TWT – tube wall thickness.
Impact of Laser Micromachining

• New tool for fracture mechanics applications
• Smaller HAZ
• Generating sharper notches
• Controlling of dimensions of notch
• Reproducible process
Experiment Setup

- Nd:YAG laser
- Focusing lens
- Sample & fixtures, cooling gas nozzle
- Motion stage
- Motion control software
- Ti -tube
- Focusing lens
Results
Crack Profiling – Fracture Analysis

Short crack
Initial notch length: 50 mils

1/2” OD × 0.043” TWT

5/8” OD × 0.054” TWT

3/4” OD × 0.065” TWT
Results

Long Crack Profile

1/4" OD×0.022” TWT  Initial notch length: 0.5 inch

3/4" OD×0.065” TWT  Initial notch length: 0.5 inch

5/8” OD×0.054” TWT  Initial notch length: 1 inch
Results

Summary of Crack Profiling

- Tubes with a short notch (length less than or equal to 0.050”), cracks initiate at notch roots, grow along both radial and axial directions in almost the same rate.

- Tubes with a long notch (length equals to 0.5” or 1”), cracks initiate along whole notch root, grow much faster around the notch center; no sideway growth was observed.
**Fatigue Life Test Results**

Example: 1/4” OD tube

<table>
<thead>
<tr>
<th>Tube size</th>
<th>Crack depth $a_0$ (inch)</th>
<th>Crack length $2c_0$ (inch)</th>
<th>Experimental life to failure (cycles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/4” OD</td>
<td>0.002</td>
<td>0.020</td>
<td>&gt; 200,000</td>
</tr>
<tr>
<td>1/4” OD</td>
<td>0.002</td>
<td>0.020</td>
<td>&gt; 200,000</td>
</tr>
<tr>
<td>1/4” OD</td>
<td>0.002</td>
<td>0.050</td>
<td>&gt; 200,000</td>
</tr>
<tr>
<td>1/4” OD</td>
<td>0.002</td>
<td>0.050</td>
<td>&gt; 200,000</td>
</tr>
<tr>
<td>1/4” OD</td>
<td>0.004</td>
<td>0.020</td>
<td>&gt; 200,000</td>
</tr>
<tr>
<td>1/4” OD</td>
<td>0.004</td>
<td>0.020</td>
<td>&gt; 200,000</td>
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<tr>
<td>1/4” OD</td>
<td>0.004</td>
<td>0.050</td>
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<tr>
<td>1/4” OD</td>
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<td>&gt; 200,000</td>
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<tr>
<td>1/4” OD</td>
<td>0.006</td>
<td>0.020</td>
<td>&gt; 200,000</td>
</tr>
<tr>
<td>1/4” OD</td>
<td>0.006</td>
<td>0.050</td>
<td>63,768</td>
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<tr>
<td>1/4” OD</td>
<td>0.006</td>
<td>0.050</td>
<td>72,340</td>
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</table>

Short crack
### Fatigue Life Test Results

**1/4” OD tube**

**Long crack**

<table>
<thead>
<tr>
<th>Tube size</th>
<th>Crack depth $a_0$ (inch)</th>
<th>Crack length $2c_0$ (inch)</th>
<th>Experimental life to failure (cycles)</th>
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<td>1/4” OD</td>
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<td>0.5</td>
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<td>1/4” OD</td>
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<td>1</td>
<td>77,527</td>
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<tr>
<td>1/4” OD</td>
<td>0.002</td>
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<td>1</td>
<td>3,164</td>
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</tbody>
</table>
Results

Fatigue Life Trend (Short Crack)

Fatigue life (cycles)

Crack depth (mils)

SAFE

UNSAFE

1/4" OD
1/2" OD
5/8" OD
3/4" OD

Crack length: 50 mils

63,768
Results

Fatigue Life Trend (Long Crack)

- **SAFE**
- **UNSAFE**

Fatigue Life (cycles)

Crack length: 0.5 inch

- 1/4" OD
- 1/2" OD
- 5/8" OD
- 3/4" OD

Crack depth (mils)

Results

9,203
Finite Element and Fracture Mechanics Analysis of Damage Limit of Ti Tubes of V22 Aircraft (Navair)
Conclusions

- Pre-notches have been generated on straight Ti-alloy tubes (ODs equal to 1/4”, 3/8”, 1/2”, 5/8” and 3/4” respectively) for fatigue life testing using method of LMM.
- Tubes can withstand over 200,000 impulse pressure cycles (nominal internal impulse pressure: 5,000 psi, maximum pressure: 7,500 psi) if the notch length is less than or equal to 0.020” (notch depth up to 0.006”)
- Tubes can withstand over 200,000 impulse pressure cycles if the notch depth is no more than 0.002” and notch length is less than or equal to 0.050”
- Tubes with a longer and deeper notch have shorter fatigue life
- Crack growth behaves differently for tubes with a short notch and a long notch
Publications


Laser Cleaning & Welding of Ti-3Al-2.5V Tubes

Teh-Hwa Wong, Yaomin Lin and Mool C. Gupta

University of Virginia

Sponsor: NAVAIR
Objectives

- Laser cleaning to remove the oxidized layer of titanium tube before welding.
- Welding of tube-to-fitting right after laser cleaning of titanium tube

Impact

- Dry cleaning process for oxide removal
- Potential to integrate the laser cleaning and welding processes in one single step

Current Method

- Chemical cleaning
Laser Cleaning Advantages

- very low operating cost
- residue free
- safe
- high dependability
- low maintenance
- no damage to the substrate
- environmentally friendly
Experimental Setup

Translation Stage

Rotational Stage

Ti Tube

Ar Gas Line

HeNe Laser Beam

1064 nm
Laser Parameters & Tube Welder

Tornado Laser  
(Spectra Physics)  
1064 nm  
10 KHz  
250 ns  
2.25W  

Other parameters  
Translation Stage  
  Speed: 10 mm/sec  
Rotation Stage  
  Speed: 4 degree/sec  
Ar gas  
  5 psi  

PTW-160 Tube Welder
## Results

### SEM/EDS

<table>
<thead>
<tr>
<th>Element</th>
<th>Line</th>
<th>keV</th>
<th>K Ratio</th>
<th>Wt%</th>
<th>At%</th>
<th>Chi Square</th>
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</thead>
<tbody>
<tr>
<td>Ti</td>
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<td></td>
<td></td>
<td>100.00</td>
<td>100.00</td>
<td>23.44</td>
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</tbody>
</table>
## Results

### SEM/EDS

<table>
<thead>
<tr>
<th>Element</th>
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<tr>
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<td>1.487</td>
<td>0.014</td>
<td>100.0</td>
<td>100.0</td>
<td>8.44</td>
</tr>
</tbody>
</table>
Results

1/2"

3/8"

1/4"
Conclusions

• Initial laser cleaning on the titanium straight tube surface has been demonstrated

• 3/8” OD and 1/2” OD tube laser cleaning and tube-to-fitting welding has been performed
Future Work

• Further characterization of initial & laser treated surface: (1) surface roughness (2) oxide layer thickness
• Refine the cleaning parameters based on the welding result
• Develop a cleaning & welding combined chamber
• Simplify the setup & make it portable
• Supply the weld sample (to NAVAIR) for burst, fatigue life and impulse pressure tests
• Examine failed samples
• Improve welding procedures
• Demonstrate laser cleaning & welding in a single step
Laser Processing of Aluminum Alloy and Composite Materials

Yaomin Lin\textsuperscript{a}, David Dawicke\textsuperscript{b}, Phil Bogert\textsuperscript{b}, Andy Newman\textsuperscript{b} and Mool C. Gupta\textsuperscript{a}

\textsuperscript{a}University of Virginia
\textsuperscript{b}NASA-Langley Research Center

May 4, 2007
Experiment Setup

Sample

YAG laser

Cooling gas supply

Motorized stages

Al 2024

Al 6061

Carbon-fiber composites
Results

Al-alloy sample cross-section

Carbon-fiber composites (High magnification)

Laser micromachining generated notch

Laser-machined line
Conclusions

- Samples of aluminum alloy and carbon fiber composites with specified notch dimensions have been prepared for fracture mechanics study.

- Laser micromachining of aluminum alloys and carbon fiber composites has been successfully demonstrated. The results are better than those from electric discharge machining.