Non-destructive and Non-contact Stress-Strain Characterization of Aerospace Alloys and Coatings using Laser Infrared Photo-Thermo-Mechanical Radiometry (PTMR)

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Outline

1. Background: Mechanical strength evaluation for aerospace materials
2. Methodology: Laser Infrared Photo-Thermo-Mechanical Radiometry (PTMR)
3. Experiment: Non-contacting stress-strain relation characterized by the PTR signal
4. Theory and analysis: Quantification of experimental results through a 1-D thermo-mechanical-wave model
5. Results and Outlook: The present work gives rise to Photo-Thermo-Mechanical Radiometry (PTMR) as a non-destructive, non-contact strain gauge for the evaluation of mechanical strength of materials
Background

• Hidden fatigue underlies threat to safety in aerospace components

Overloading or cyclic loading

Intact material $\rightarrow$ Stress residue/ fatigue $\rightarrow$ Cracks and failure

It will be of great value if the strength condition of the material can be evaluated before fatigue actually occurs!
Material Property

- Strength evaluation by FEM

- The sample is made of aluminum 6061-T6, a general material in aerospace industry.
- Use linear elastic stress-strain constitutive equation and balance of force:
  \[
  \tau = C : \varepsilon \\
  \nabla \cdot \tau = -F
  \]
- \( \tau \) – stress tensor, \( \varepsilon \) – strain tensor, \( C = C_{ijkl} \) – modulus tensor of rank four (\( i,j,k,l = 1,2,3,4 \)), \( F \) – external force.
- According to ASTM 308, the elastic limit of this material is at least 240 MPa, which yields:
  \[
  \varepsilon \leq 0.0035(3500 \ \mu m/m)
  \]
  in terms of strain representation.

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Methodology

Main advantages:

- Non-destructive when operated below the elastic ceiling.
- Totally non-contact and localized detection.

PTR signal:  \[ S = A \exp[i(\omega t + \Phi)] \]

Signal amplitude:  \[ A = \| S \| \]

Signal phase:  \[ \Phi = \arg(S) \]
Experimental

Frequency-scan signal: 1-30 Hz (low frequency)  \[ \mu(f) = \sqrt{\frac{\alpha}{\pi f}} \gg \Delta L \]

Stress condition: Within elastic regime.
Stress procedure: Loading and relaxing.

Good reproducibility and reversibility of the PTR signal within the elastic regime!
**Experimental Results**

- Strain-scan result: stress free to ~1400 μm/m, within the elastic regime
- Set frequency at 2.5 Hz. Involving multiple loading and unloading process

The elastic loading and unloading test shows a good repeatable and reversible pattern. This indicates that the sample recovers its thermal properties after removal of tension within the elastic regime.
In the necking regime, the sample undergoes large deformation and thus the surface is deformed significantly, which drastically changes the PTR amplitude. Phase is less sensitive to this change and is more reliable as it is less affected by extraneous factors like surface curvature and shape change.
Theory and Analysis

• Frequency dependence of PTR signal

\[
T(0, \omega) = \frac{\beta I(\omega)(1 + e^{-2\sigma_1 L})}{k_1 \sigma_1 (1 - e^{-2\sigma_1 L})} \tag{1}
\]

Amplitude: \[A(\omega) \sim \|Y(\omega)\|I(\omega)\frac{1 + e^{-2\sigma_1 L}}{k_1 \sigma_1 (1 - e^{-2\sigma_1 L})} \tag{2}\]

Phase: \[\Phi(\omega) = \arg \left( \frac{1 + e^{-2\sigma_1 L}}{1 - e^{-2\sigma_1 L}} \right) - \frac{\pi}{4} + \Phi_0(\omega) \tag{3}\]

\[\Phi_0(\omega) = \arg[Y(\omega)]\]

Normalized to:

\[A(f) \sim \|Y(f)\|I_0(f)\left(\frac{1}{e_1 \sqrt{f}}\right)\left[\frac{(1 - e^{-2\gamma})^2 + 4e^{-2\gamma} \sin^2 \gamma}{(1 - e^{-\gamma} \cos \gamma)^2 + e^{-2\gamma} \sin^2 \gamma}\right]^{1/2}, \Phi(f) = \arctan \left( \frac{-2e^{-\gamma} \sin \gamma}{1 - e^{-2\gamma}} \right) - \frac{\pi}{4}, \gamma \equiv 2\sqrt{\pi f} \kappa(\tau), \kappa(\tau) \equiv L/\sqrt{\alpha(\tau)} \tag{4}\]

\(\kappa\) is the only parameter that affects the phase signal Eq. (4) while amplitude relies on both \(\kappa\) and \(e_1\). Fitting the phase curve can extract \(\kappa\); subsequent fitting the amplitude can yield \(e_1\).
Quantification Results

- Applying 1-D single layer thermal-wave model to the tensile test results, we can obtain diffusivity and effusivity as functions of strain within the elastic regime:

  \[ \alpha(\varepsilon) = \frac{k}{\rho C} = 5.536 \times 10^{-3} \times \text{strain} + 6.434 \times 10^{-5} \quad \text{m}^2/\text{s} \]

  \[ e_1(\varepsilon) = \sqrt{k \rho C} = 8.17 \times 10^5 \times \text{strain} + 19389.25 \quad \text{J/(m}^2\text{Ks}^{1/2}) \]

- Diffusivity increases with stress/strain:
- Effusivity increases with stress/strain:

\( \text{FS} : \) Frequency scan
\( \text{SS} : \) Strain scan
Results (cont’d)

• Comparison between effusivity- and diffusivity-derived thermal conductivity:

  ➢ Conductivity values obtained from two approaches show very good agreement.

  ➢ Conductivity shows linear dependence on strain within the elastic regime.

  ➢ Thermal conductivity dependence on stress is the primary effect within the elastic regime.

Analysis of Results

- Analogy: PTR phase-measured diffusivity-strain vs. stress-strain relation\(^2\):

![Graph showing stress-strain relationship with various labels and notes](http://www.leonghuat.com/articles/civil%20engineering.htm)
Tests on Coated Samples

• The coated samples are:

  Sample 1: Substrate: intact dog-bone
  Coating thickness: 0.005”

  Sample 2: defective substrate with coating (one hole at center, diameter: 1 mm, depth: ~1 mm)
  Coating thickness: 0.005”

• Experiments:
  Frequency scan
  Strain scan

• Analysis:
  Single layer model
  Three-layer model

Intact coated sample

Defect: hole on the substrate
Coated Samples (cont’d)

Sample 1 (intact substrate)

Sample 2 (defective substrate)

Bare aluminum
Coated Samples (cont’d)

• Quantification: single layer model (results)

Because the coated sample is not a single layer, the frequency range used for quantification should be low enough (0.5 Hz-5Hz). The results yield averaged overall thermal parameters for both coating and substrate.

- As the coated samples have different materials for substrate and coating, this single-layer model can only derive a nominal diffusivity which represents an approximate average diffusivity of the samples. The diffusivity of the aluminum substrate is chosen to be the nominal diffusivity for all three samples.

- Due to the existence of defects on the substrate of sample 2, best fits from FS and SS show larger differences than the other samples.
Coated Samples (cont’d)

- Quantification: three-solid-layer model (results)

Frequency was scanned from 0.5 Hz to 15 Hz, and was fixed at 2.3 Hz for the intact sample and at 1.07 Hz for the defective substrate sample. For the coating layer and substrate:

- Compared with the single-layer results, the three layer model indicates diffusivity changes of both coating and substrate. For both, the changes are larger for the defective substrate.

Coating diffusivity of the two coated samples

Substrate diffusivity of the two coated samples
Coated Samples (cont’d)

Discussion:

• Compared with the single-layer model, the three-layer model reveals more detailed information on the thermal conductivity strain dependencies of both coating and substrate materials

• The coated samples perform much better at the same strain than the bare aluminum sample: A comparison between coated and uncoated sample at fixed strain is shown below:

<table>
<thead>
<tr>
<th>Sample</th>
<th>Effective Diffusivity Change</th>
<th>NiCo coating Diffusivity Change</th>
<th>Aluminum Substrate Diffusivity Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare Aluminum Alloy</td>
<td>11%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Sample 1 (intact and coated)</td>
<td>1.6%</td>
<td>3.4%</td>
<td>0.55%</td>
</tr>
<tr>
<td>Sample 2 (Defective substrate coated)</td>
<td>6.1%</td>
<td>17%</td>
<td>2.3% (Effective)</td>
</tr>
</tbody>
</table>

It is hypothesized that for the defective aluminum substrate, the stretch is larger for both substrate and coating at the same strain, so the coating undergoes more deformation and thus larger thermal conductivity / diffusivity change. At the same level of strain, the defective substrate sample undergoes larger tensile loading because its “waist” is more “yielding” than the intact substrate. Thus, it elongates more and so does the coating.

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Conclusions: Significance and Outlook

A) PTMR analysis proved to be able to quantify mechanical property relations of aerospace-relevant metallic components under stress.

B) PTMR emerges as a non-contacting, non-destructive, quantitative “strain gauge” with a much expanded strain range compared to conventional contacting mechanical strain gauges. It works instantaneously and does not require long adhesive curing times (usually overnight).

C) PTMR can quantify the mechanical performance of multilayer (coated) samples:
   1) It can assess the mechanical strength of NiCo coatings toward the protection of coated substrates through measurements of PTMR signals at fixed strain.
   2) It can assess the mechanical strength or improvement of defective substrates through coating and can quantify thermophysical changes of both coating and substrate upon mechanical stress application using stress scans and frequency scans.
   3) The elastic limits of solids can be identified and studied as functions of geometric shape, material and coating.

D) PTMR can map the entire stress-strain cycle for uncoated and coated samples from the unstressed state through the elastic, plastic and fracture stages. This is not possible for attached mechanical strain gauges.
Future work

Having proven the feasibility of non-contact evaluation of mechanical property relations by the PTMR approach, further work for this methodology will include:

• Apply PTMR test with the application of mid-infrared camera to quantify the three conductivity components under multi-directional loading.

• Develop more complex, applicable 3-D quantitative thermal-wave theory and inverse algorithms to reconstruct the internal thermal conductivity tensor distribution from fitting the contours at various surfaces of the sample.

• Testing samples with known (or unknown) residual stresses
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