Investigation of Damage Evolution, and Modeling of Residual Stress and Fracture Toughness in the Ti-Al<sub>3</sub>Ti Metal Intermetallic Laminate (MIL) Composites

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Outline

• Introduction
• Research Objective
• Experimental Results
• Theoretical Modeling
• Preliminary Conclusions
Introduction
Intermetallics - Applications

- Aerospace structure
- Protective shields
- Automobile industry
- Coatings
- Armor
Intermetallics

• Advantages:
  □ Good high-temperature strength
  □ High stiffness
  □ Good creep resistance
  □ High oxidation resistance

• Disadvantages:
  □ Low tensile ductility at low temperature
  □ Poor fracture resistance
Toughening Intermetallics – Ductile Reinforcement

(a) Particle
(b) Short fiber/Whisker
(c) Continuous fiber
(d) Layer
Challenges in Producing Ductile Reinforced Intermetallic Composites I

• Chemical compatibility
  – To avoid undesirable microstructure and properties

• Environmental resistance
  – Subject to dynamic environment at low/intermediate temperature

• Consolidation and processing
  – Complete densification
Challenges in Producing Ductile Reinforced Intermetallic Composites II

• Mismatch of thermal expansion coefficients
  – Introduce residual stress during processing and service

Courtesy to Miracle
Ductile Reinforced Laminate Composites
Ti-Al\textsubscript{3}Ti MIL Composites I

[Diagram showing material properties and phase boundaries]

Courtesy to Ashishy
Ti-$\text{Al}_3\text{Ti}$ MIL Composites II

Courtesy to Ashishy
Research Objective

- Investigation of damage evolution in Ti-Al$_3$Ti metal intermetallic laminate (MIL) composites

- Modeling of residual stress and fracture toughness in Ti-Al$_3$Ti metal intermetallic laminate (MIL) composites
Experiments
Optical Microscopy Observation on Untested Ti-Al$_3$Ti

Typical untested sample
Cracks in Untested Ti-Al$_3$Ti

Parallel cracks

Perpendicular cracks

45$^\circ$ angled cracks
Optical Microscopy Observation on Untested Ti-Al₃Ti
Micro-defects in Untested Ti-Al$_3$Ti

Micro-defects along the interface
Micro-defects in Untested Ti-Al$_3$Ti

Micro-defects along the interface
Micro-defects in Untested Ti-Al₃Ti

Middle line in Al₃Ti layer
Crack Morphology in Untested Ti-Al₃Ti I

- parallel crack
- 45 angled crack
- perpendicular crack

- Crack length (micrometer)
- Crack angle to the interface (°)
Crack Morphology in Untested Ti-Al₃Ti II
Crack Morphology in Untested Ti-$\text{Al}_3\text{Ti}$ III

$\rho_{\text{crack}} = \frac{\ell}{\Theta} = 1.6/cm$

- 45 angle crack: 47%
- Perpendicular crack: 36%
- Parallel crack: 17%
## Compression Tests on Pure Al$_3$Ti I

<table>
<thead>
<tr>
<th></th>
<th>Maximum compressive stress of pure Al$_3$Ti (MPa)</th>
<th>Maximum compressive stress of Ti-Al$_3$Ti (35% Ti, perpendicular loading) (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dynamic (1000/s)</td>
<td>1285</td>
<td>1300</td>
</tr>
<tr>
<td>Quasistatic (0.01/s)</td>
<td>921</td>
<td>1100</td>
</tr>
<tr>
<td>Quasistatic (0.0001/s)</td>
<td>890</td>
<td>1000</td>
</tr>
</tbody>
</table>
Compression Tests on Pure Al₃Ti II

Strain rate has little influences on crack modes.

Intergranular crack

Transgranular crack
## Compression Tests on Ti-Al₃Ti I

<table>
<thead>
<tr>
<th>Volume Fraction of Ti-6-4</th>
<th>Loading Direction to the Laminate Plane</th>
<th>Strain Rate (/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>14%</td>
<td>Perpendicular</td>
<td>0.0001</td>
</tr>
<tr>
<td>14%</td>
<td>Perpendicular</td>
<td>2800</td>
</tr>
<tr>
<td>14%</td>
<td>Parallel</td>
<td>0.0001</td>
</tr>
<tr>
<td>14%</td>
<td>Parallel</td>
<td>0.01</td>
</tr>
<tr>
<td>14%</td>
<td>Parallel</td>
<td>2100</td>
</tr>
<tr>
<td>50%</td>
<td>Perpendicular</td>
<td>0.0001</td>
</tr>
<tr>
<td>50%</td>
<td>Perpendicular</td>
<td>1300</td>
</tr>
<tr>
<td>50%</td>
<td>Perpendicular</td>
<td>2500</td>
</tr>
<tr>
<td>50%</td>
<td>Parallel</td>
<td>0.0001</td>
</tr>
</tbody>
</table>
Compression Tests on Ti-$\text{Al}_3\text{Ti}$ II

effect of *volume fraction* of titanium

14% Ti

50% Ti

![Images of microstructures showing Ti-$\text{Al}_3\text{Ti}$ and Ti phases with different volume fractions.](image)
Compression Tests on Ti-Al₃Ti III

effect of the strain rate

\[ \dot{\varepsilon} = 2800 / s \]

\[ \dot{\varepsilon} = 0.0001 / s \]
Compression Tests on Ti$_3$Al IV

\[ \dot{\varepsilon} = 2100 \text{ } / \text{s} \]

\[ \dot{\varepsilon} = 0.0001 \text{ } / \text{s} \]
Physical Modeling: Damage Evolution I
Physical Modeling: Damage Evolution II
Physical Modeling: Damage Evolution III

Without Confinement

With Confinement

Ti

Al₃Ti

Ti

crack

Ti

Al₃Ti

Ti

crack

buckling

Without Confinement
Physical Modeling: Damage Evolution IV
Theoretical Modeling
Elastic Properties of Ti-Al$_3$Ti

- Volume Fraction
- Orientation
Residual Stress in Ti-\text{Al}_3\text{Ti}
## Residual Stress in Ti-Al₃Ti

Calculated residual stress

\[ \sigma_c = \frac{E_1(1-c) \cdot \left[ \left( \alpha_2 - \alpha_1 \right) \cdot \Delta T \right]}{1 + \left( \frac{1-\gamma_2}{1-\gamma_1} \cdot \frac{E_1}{E_2} - 1 \right) \cdot c} \cdot (1-\gamma_1) \]

<table>
<thead>
<tr>
<th></th>
<th>14%Ti</th>
<th>20%Ti</th>
<th>35%Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Calculated residual stress (MPa)</strong></td>
<td>345</td>
<td>327</td>
<td>282</td>
</tr>
<tr>
<td><strong>Measured residual stress (MPa)</strong></td>
<td>65.01</td>
<td>32.38</td>
<td>8.29</td>
</tr>
<tr>
<td><strong>Measured residual stress (slow cooling) (MPa)</strong></td>
<td>30.79</td>
<td>25.24</td>
<td>10.59</td>
</tr>
</tbody>
</table>
Residual Stress Release Mechanism I: Creep

Creep, known as time-dependent deformation, is characterized by the Doner-Conrad equation:

\[
\dot{\varepsilon}_s \frac{kT}{D \mu b} = A \left( \frac{\sigma}{\mu} \right)^n
\]

- \(\dot{\varepsilon}_s\) is the steady-state strain rate.
- \(\mu\) is the shear modulus.
- D: the diffusion coefficient.
- b: the Burgers vector.
- T: the temperature.
- k: the Boltzmann's constant.
Residual Stress Release Mechanism I: Creep

- Residual stress due to mismatch of thermal expansion coefficients of Ti and AlTi: \( \sigma_{n,i} = f(\Delta T) \)
- Initial residual stress: \( \sigma_{i,i} = \sigma_{r,i-1} + \Delta \sigma_{n,i} \)
- Dorn-Cornel equation to obtain strain rate: \( \varepsilon_{2,i} = A \left( \frac{\sigma_{2,i}}{\mu} \right) \frac{D_i}{kT} \)
- Obtain strain: \( \varepsilon_{2,i}^* = \varepsilon_{2,i} \cdot (t - t_i) \)
- The reduction of stress due to creep in Ti: \( \Delta \sigma_i = E_i \cdot \varepsilon_{2,i} \)
- The residual stress after creep in Ti: \( \sigma_{r,i} = \sigma_{r,i} - \Delta \sigma_i \)

Flowchart:
- \( t = t_i \)
- \( \sigma_{r,i} = \sigma_{r,i} - \Delta \sigma_i \)
- \( t = t_n \)
- End
Residual Stress Release Mechanism I: Creep in Ti

![Graph showing residual stress release mechanism in Ti]

- Stress with creep in Ti only for 14% Ti
- Stress with creep in Ti only for 20% Ti
- Residual Stress w/o creep for 14% Ti
- Stress with creep in Ti only for 35% Ti
- Measured residual stress for 14% Ti
- Measured residual stress for 20% Ti
- Measured residual stress for 35% Ti
- Residual Stress w/o creep for 20% Ti
- Residual Stress w/o creep for 35% Ti
Residual Stress Release Mechanism I: Creep in Both Ti and Al$_3$Ti

Residual stress vs temperature

- Stress with creep in Ti only for 14% Ti
- Stress with creep in Ti only for 20% Ti
- Stress with creep in Ti only for 35% Ti
- Measured residual stress for 14% Ti
- Measured residual stress for 20% Ti
- Measured residual stress for 35% Ti
- Residual Stress w/o creep for 14% Ti
- Residual Stress w/o creep for 20% Ti
- Residual Stress w/o creep for 35% Ti
- Stress with creep in both Ti and Al$_3$Ti for 20% Ti
- Stress with creep in both Ti and Al$_3$Ti for 14% Ti
- Stress with creep in both Ti and Al$_3$Ti for 35% Ti
Residual Stress Release Mechanism II: Crack Propagation
Residual Stress Release Mechanism II: Crack Propagation

\[ \sigma_c = \frac{E_1 (1 - c) \cdot \left( (\alpha_2 - \alpha_1) \cdot \Delta T \right)}{1 + \left( 1 - \frac{E_1}{E_2} \right) \cdot c (1 - \gamma_1)} \]

\[ E_2^e = E_2 \left( a, \frac{s}{a} \right) \]

Spring model

\[ E_2^e = E_2 \cdot \left( 1 - \frac{4a}{s} \right) \]

(Griffith criterion)
**Residual Stress Release Mechanism II: Crack Propagation**

\[
\sigma_c = \frac{E_1 (1 - c) \cdot [\alpha_2 - \alpha_1] \cdot \Delta T}{1 + \left(\frac{1 - \gamma_2}{1 - \gamma_1} \cdot \frac{E_1}{E_2^e} - 1\right) \cdot c} (1 - \gamma_1)
\]

\[
E_2^e = E_2 \left(a, \frac{s}{a}\right)
\]

**Salganik model**

\[
E_2^e = \frac{E_2}{\left(1 + \frac{16 \cdot (10 - 3\nu_2) \cdot (1 - \nu_2^2)}{45 \cdot (2 - \nu_2)} \cdot N \left(a, \frac{s}{a}\right) \cdot a^3\right)}
\]
Residual Stress Release Mechanism II: Crack Propagation
Residual Stress Release Mechanism: Combining Creep and Crack Propagation

\[ \sigma_{\text{residual}} = \sigma \left( a, \frac{s}{a}, T \right) \]

\[ \sigma^*_{\text{critical}} = \frac{K}{2} \frac{e}{\sqrt{\pi a}} \]
Residual Stress Release Mechanism

\[ \sigma = \sigma \left( a, \frac{s}{a}, T \right) \]

\[ \sigma^* = \frac{K e}{\sqrt{\pi a}} \]
Residual Stress Release Mechanism (cont’d)

\[ \sigma = \sigma \left( a, \frac{s}{a}, T \right) \]

\[ \sigma^* = \frac{K_s^e}{Y \sqrt{\pi a}} \]

\[ Y = 1 + 0.256 \left( \frac{a}{W} \right) - 1.152 \left( \frac{a}{W} \right)^2 + 12.2 \left( \frac{a}{W} \right)^3 \]
Apparent fracture toughness of Ti-Al$_3$Ti MIL composite can be calculated from

$$K_{c, app} = K_T + K_0$$

where $K_T$ is the stress intensity due to the designed residual stresses, $K_0$ is the crack-initiation toughness of MIL, and $K_c$ is the fracture toughness.

Stress intensity was evaluated as a function of volume fraction of Ti:

![Graph showing the relationship between toughness and volume fraction](image_url)

- **TOUGHNESS DUE TO RESIDUAL STRESSES [MPa m$^{1/2}$]**
- **VOLUME FRACTION OF Ti-Al$_6$V$_4$**
Preliminary Conclusions
Preliminary Conclusions (Experiments)

- Optical microscopy observations have showed the crack morphology of untested Ti-Al₃Ti MIL composites.
- Quasi-static and dynamic compression tests were conducted on pure Al₃Ti. Transgranular and intergranular cracks were found under SEM. The experiments show the strain rate has little effects on the formation of the two different crack morphologies.
- Compression tests were conducted on the Ti-Al₃Ti MIL composites, and the effects of different loading directions, different strain rates and different volume fraction of titanium on the damage evolution have been assessed.
- Four different damage evolution mechanisms have been identified, including axial splitting, shear localization in Ti layers, crack propagation along the central plane of weakness in Al₃Ti, and delamination at Al₃Ti-Ti interface.
Preliminary Conclusions (Theoretical Modeling)

- The effect of orientation and volume fraction of Ti on the elastic properties of Ti-Al\(_3\)Ti has been investigated.
- Residual stress in Ti-Al\(_3\)Ti has been evaluated by elastic analysis and two stress relaxation mechanisms.
- The apparent fracture toughness of Ti-Al\(_3\)Ti has been evaluated using a weight function method.
Thank you.
Calculations (Lines) and Data from RUS-Measurements (Dots)
Elastic Constants for MIL