Fracture Testing of a Layered Functionally Graded Material

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Outline

- Material
  - Ti/TiB functionally graded material
- $K_I - R$ fracture testing
- Effect of precracking
  - Three methods attempted
- Residual stress measurement
- Correction of $K_I - R$ results for residual stress
  - Weight function
  - Superposition
Material

- Manufactured by Cercom (Vista, CA)
  - Ti and TiB₂ powders
  - Six Ti/TiB₂ mixtures on CP Ti plate
- Processing
  - Hot press (1578K, 13.8 MPa)
  - Ti + TiB₂ → TiB (little residual TiB₂)
- Ceramic/Metallic
  - Modulus range: 107 (Ti) to 313 (15Ti/85TiB) GPa
  - Toughness range: 134 (Ti) to 6.5 (Pure TiB) MPa·m¹/²
R-curve Fracture Testing

- Standard SE(B) tests (E1820-96)
  - Nearly full thickness samples
  - $W = 13.6$ to $14.7$ mm
  - $S \approx 4 \ W$
  - $a_0 \approx 0.36$ to $0.4 \ W$
  - $B \approx 0.5 \ W$

- Crack driving from TiB-rich side
- Optical crack length measurement
- Data reduction based on monolithic material
- Results for three precrack conditions
  - No precrack, compression, reverse bending
Fracture Testing - Precracking

- Precracking methods
  - Crack-tip in tension (metals)
    - Uncontrollable crack growth (pop-in)
  - Uniform compression (ceramics)
    - High loads required to initiate crack
    - Global modulus changed 33%
    - Damage: Yielding of Ti, Debonding of TiB in Ti matrix, Microcracking of TiB
  - Reverse bending
    - Controllable crack growth, no modulus change

- Effect on toughness?
Fracture Testing - Results

- **Rising R-curve**

- **Precracking affects toughness**
  - Uniform compression → 40% lower
  - Early failure of sample without precrack
Toughening Mechanisms

- Intrinsic (crack-tip) toughening
- Crack branching and bridging

(Layer 6, TiB in Ti matrix)
Residual Stress

- FGM contains residual stress (RS)
- Remove RS effect from $K_I - R$ measurement
  - Measure residual stress through thickness
  - Use weight function to find $K_{RS}$
  - Use superposition to find material toughness
    \[ K_{material} \approx K_{measured} + K_{RS} \]
- Measure RS using the compliance method
  - Slot incrementally
  - Measure strain release
  - Back-calculate to find RS
Compliance Method

- Assumes elastic stress release
  - Released strain a function of residual stress
- Express unknown RS in Legendre basis
  - \( \sigma_{RS}(x) = \sum_{i=2,m} A_i P_i(x) \)
  - Strain can be found for known stress (FEM)
  - Find strain for basis functions using FEM
  - Include property variation for FGM
- Find basis amplitudes from measured strain
  - \( \mathbf{\varepsilon} = \mathbf{C} \mathbf{A} \quad \mathbf{A} = (\mathbf{C}^T \mathbf{C})^{-1} \mathbf{C}^T \mathbf{\varepsilon} \)
Measured Residual Stress

- Measured Strain
- Strain Fit
- Residual Stress

[Diagram showing measured residual stress and strain fit with data points and fitted curves.]
Residual Stress Corrected R-curve

- $K_{RS} < 0$ (toughness overestimated)

- Initial *material* toughness 35% lower
Conclusions

- Precracking method affects toughness
  - Tension fatigue uncontrollable
  - Uniform compression damaging
  - Reverse bending produced desired results

- FGM exhibits rising R-curve behavior
  - Intrinsic toughness
  - Crack branching
  - Crack bridging

- R-curve corrected for residual stress
  - Residual stress measured, $K_{RS}$ computed
  - Superposition of $K_{RS}$ and $K_{measured}$
  - 34% change in brittle region