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*Title:* Interface Bond Strength of HIP-Clad Depleted Uranium and 6061-Aluminum

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# Interface Bond Strength of HIP-Clad Depleted Uranium and 6061-Aluminum

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**Abstract**

Compact tension (CT) experiments were conducted with fixtures that allowed mode-I (tensile opening mode), mode-II (shearing mode), and mixed-mode loading to measure the interfacial strength between HIP-clad Al and Al, and Al and Zr/DU-10wt%Mo. Specimens were made with the same HIP process used for making thin composite foils, but instead used 25 mm thick Al-6061 cladding that allowed specimens to be gripped without adhesives. Three configurations of specimens were tested: (1) Al/Al specimens with a pre-crack along the seam; (2) specimens containing both a Zr/DU-10wt%Mo layer and an Al/Al seam along part of the interface; and (3) specimens containing only a Zr/DU-10wt%Mo layer at the interface, but with a pre-notch along part of the interface. Digital image correlation (DIC) was used to measure full-field deformations during the test. The results show that mode-I loaded interfaces exhibit the weakest strength and the widest scatter. The strength increases when more shearing component is introduced.



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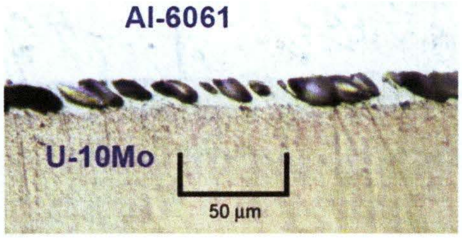
# Motivation

- Reduced Enrichment for Research and Test Reactors (RERTR) program provides the fuel technology and analytical support required to convert research and test reactors from nuclear fuels that utilize highly enriched uranium (HEU) to fuels based on low enriched uranium (LEU) (defined as <20% U-235).
- The new design chosen was a very high density plate-type nuclear fuel, using a U-Mo alloy fuel foil sealed in aluminum cladding, refer to as "monolithic" fuel as oppose to the traditional dispersion design. Thus, interfacial strength and toughness become the key factors in performance and Q&A assessment.



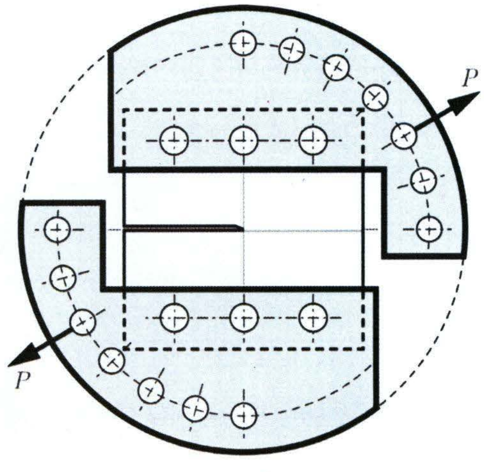

Bubble formation in the interaction layer between a U-10Mo foil and Al-6061

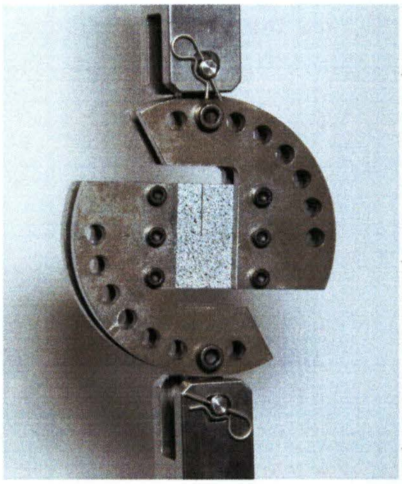
- **We are tasked to develop technology to quantitatively measure interfacial strength and toughness of both fresh as well as spent fuel plates for the down-selection process.**
- One of the test series using compact tension (CT) specimen combined with Arcan loading fixture and DIC will be presented in this talk.

# Outline

- Experimental method:
  - Compact tension (CT) specimen & Arcan loading fixture;
  - Different sample configurations;
  - Application of digital image correlation (DIC) for determining deformation field.
- Mechanical response of samples with different configurations:
  - Strength measurement;
  - Failure patterns associated with different configurations and different strength levels.
- Some DIC results of the deformation field CT specimen surface.
- Summary.

## Compact Tension Sample & Arcan Loading Fixture



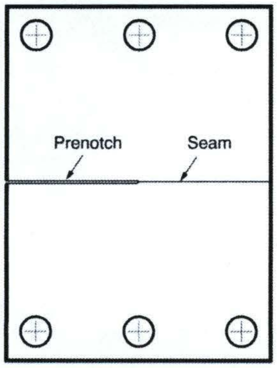
- By selecting different pair of pin holes, different loading modes can be applied to the testing sample.
- Three loading angles are considered: 0° (mode-I), 45° (mixed-mode), and 90° (mode-II).

## Compact Tension Sample Configurations

- In using the modified compact tension (CT) specimen with the Arcan loading fixture to measure fracture toughness, additional configurations and information will be obtained for assessing mechanical performance of fuel foil and the bonding process.

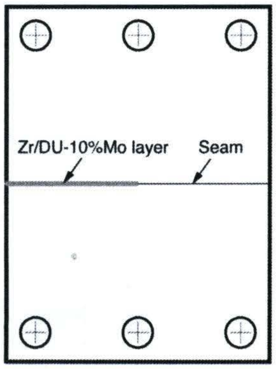
### Configurations to be considered:

Measuring the fracture toughness along the seam between Al blocks



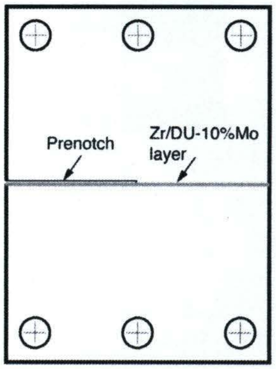

Al-Al-Notch

Measuring deformation around the corner of Al/Zr/DU-10%Mo layer subject to different stress states



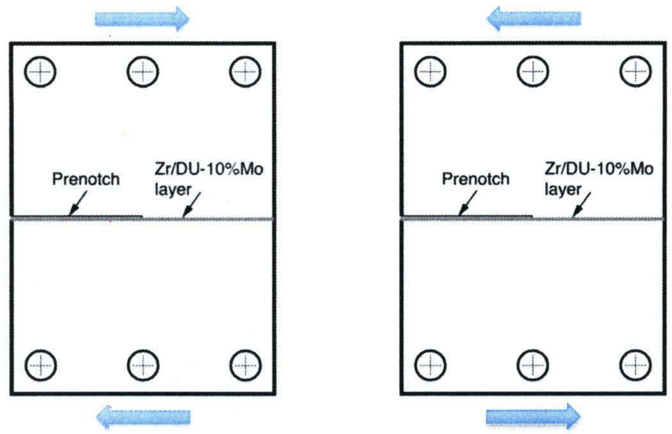

Al-DU-Corner

Measuring the interfacial fracture toughness of Al/Zr/DU-10%Mo




Al-DU-Notch

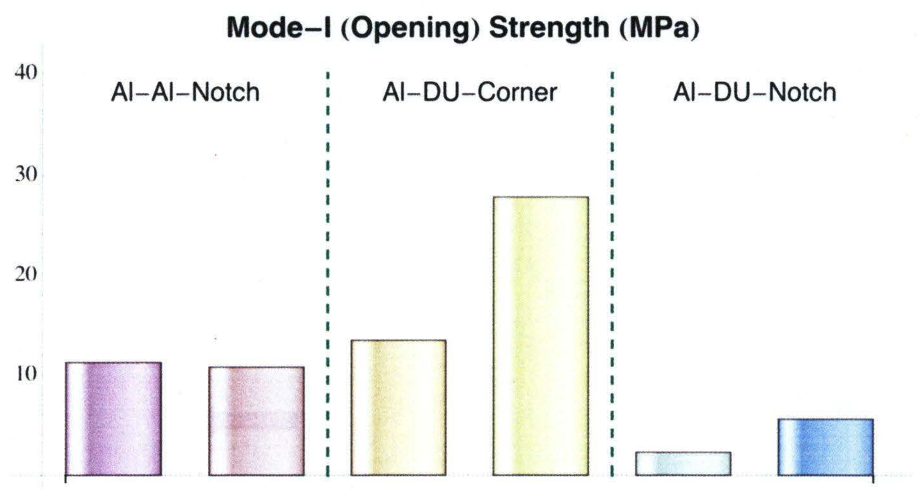
## More Categories of Al-DU-Notch Samples




Positive shear    Negative shear

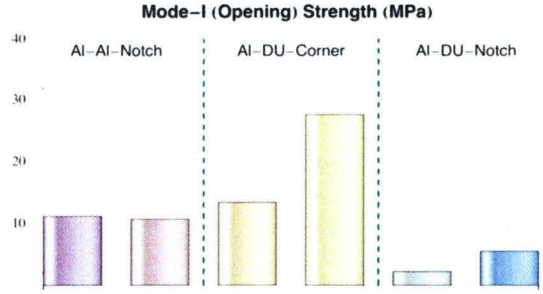
- Due to the asymmetry about the interfacial crack, shearing deformation can be divided into positive shear and negative shear for the Al-DU-notch specimens.

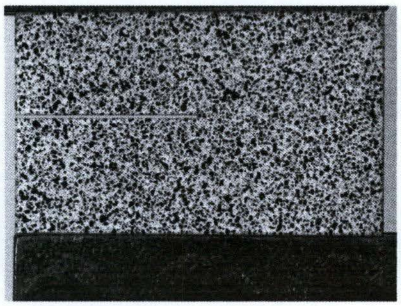
## Mode-I (Opening) Strength



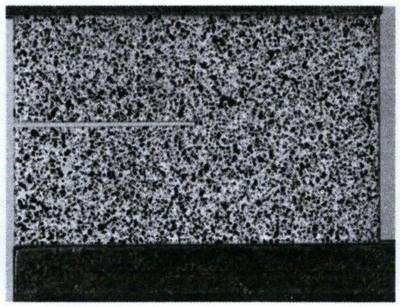

- Al-Al-Notch: Very small (but visible) amount of crack growth followed by brittle failure;
- Al-DU-Corner: Stronger sample failed in a complete brittle fashion, the weak failed in an interesting pattern;
- Al-DU-Notch: Stronger sample failed in a complete brittle fashion, the weak failed in an interesting pattern.

# Al-Al Mode-I (Opening) Failure Patterns

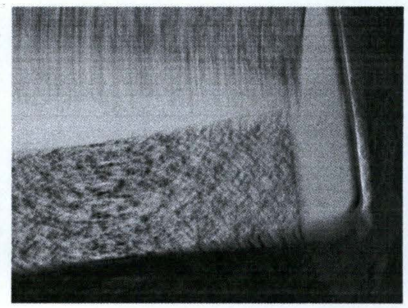


Initial image

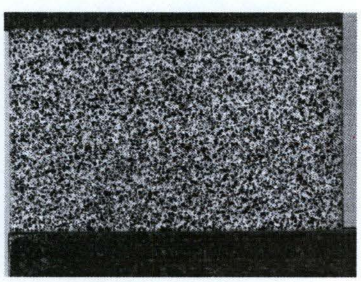


Moment before failure

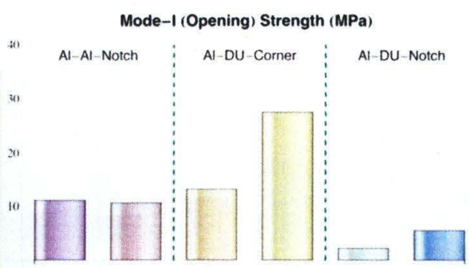


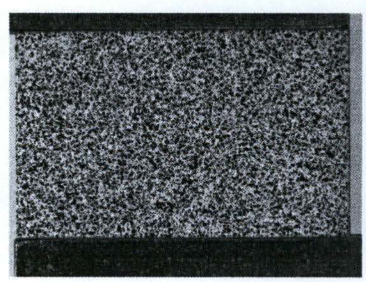
Instant of failure

# Al-DU-Corner Mode-I (Opening) Failure Patterns

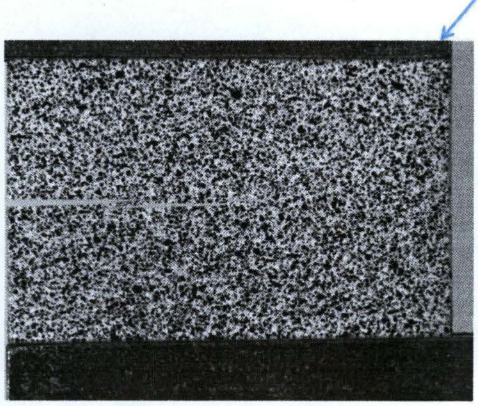


Moment before failure

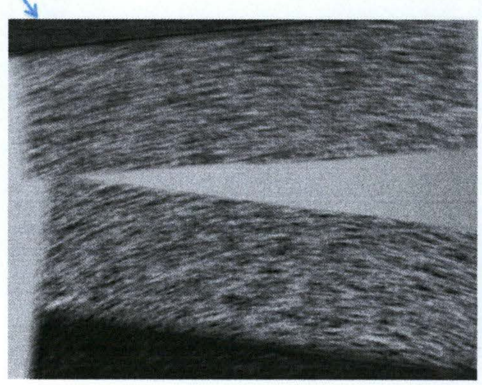


Moment before failure

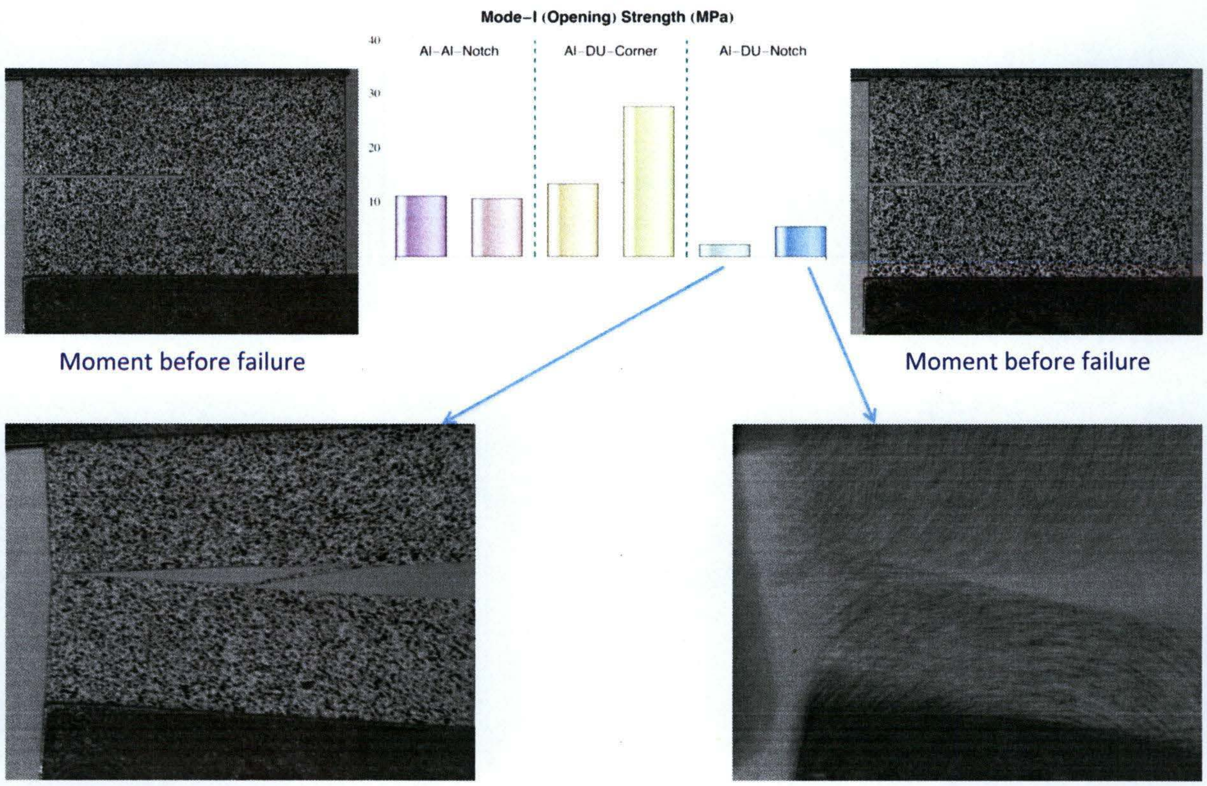


Instant of failure



Instant of failure

# Al-DU-Notch Mode-I (Opening) Failure Patterns



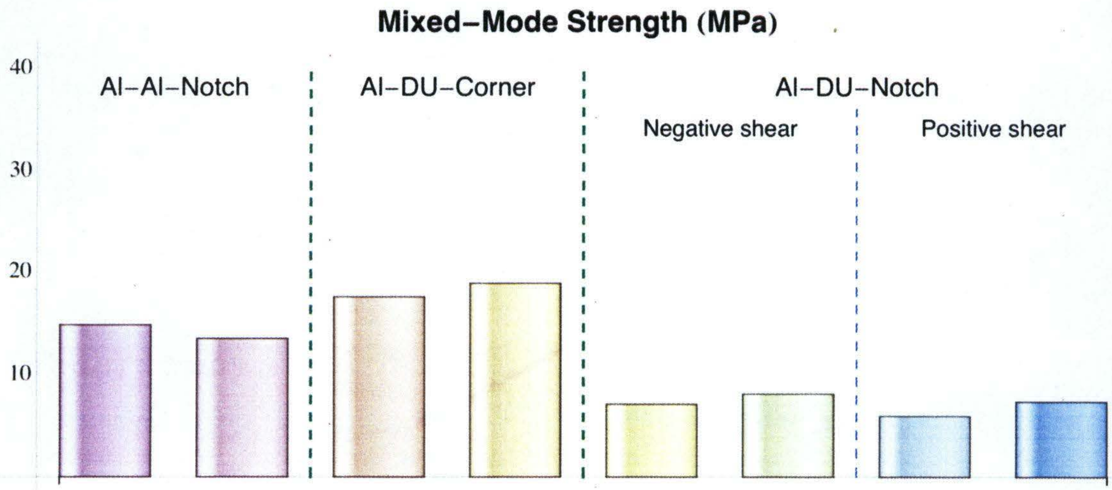

Moment before failure

Moment before failure

Instant of failure

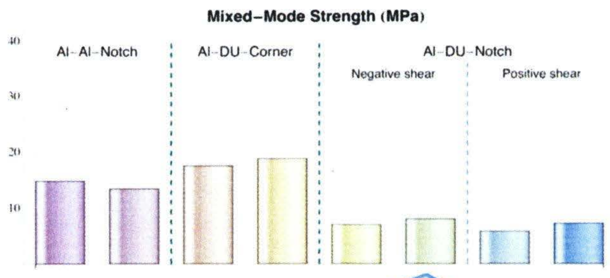
Instant of failure

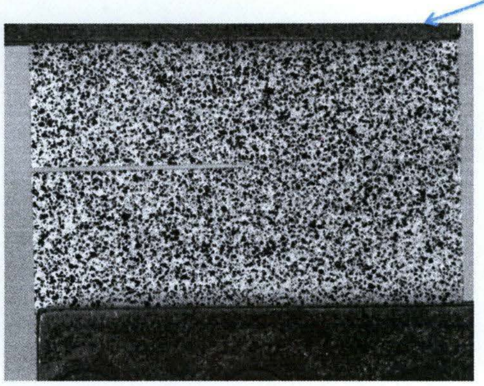
# Mixed-Mode Strength



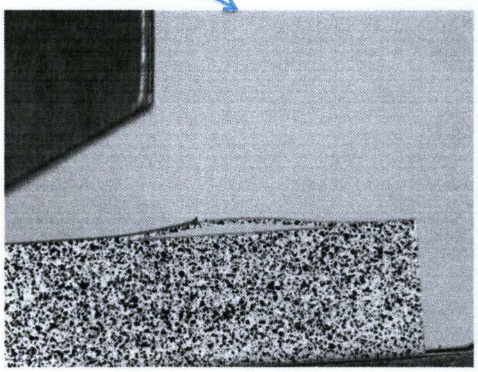

- Al-Al-Notch: Visible amount of crack growth followed by brittle failure;
- Al-DU-Corner: Brittle failure, deformation field surrounding DU tip prior to failure awaiting DIC result;
- Al-DU-Notch:
  - Negative shear: Brittle failure with interesting pattern;
  - Positive shear: Brittle failure.

# Al-DU-Notch Sample Mixed-Mode Failure Pattern



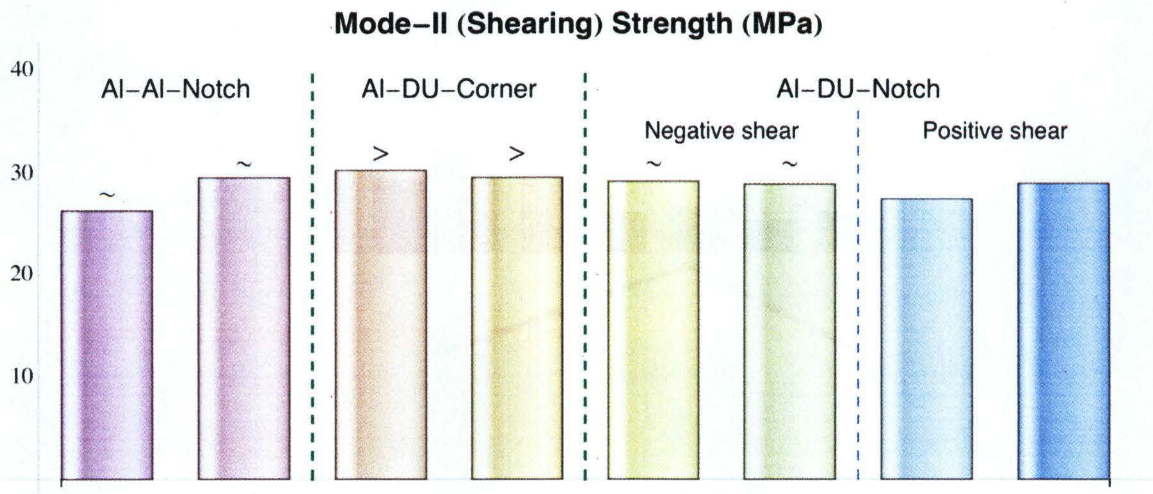



Moment before failure



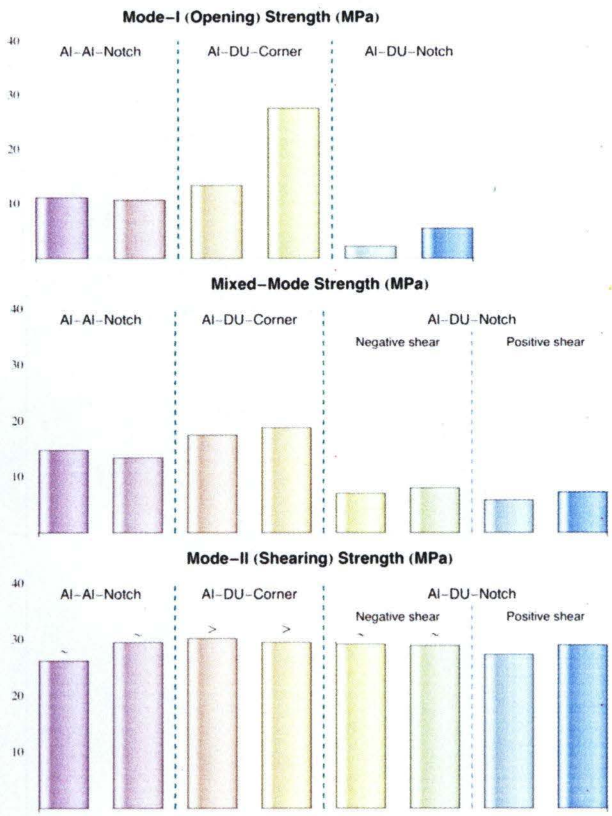
Instant of failure

# Mode-II (Shearing) Strength




- Al-Al-Notch: Visible amount of crack growth, no sample failure, waiting for DIC results;
- Al-DU-Corner: Bolt hole failed before sample failure;
- Al-DU-Notch:
  - Negative shear: Visible amount of crack growth, no sample failure, waiting for DIC results;
  - Positive shear: Extensive deformation near notch tip followed by brittle failure, waiting for DIC results.

# Comparison of Different Configurations




## Summary:

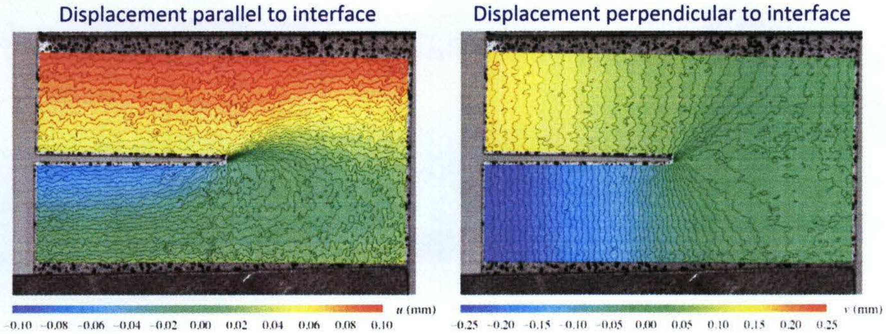
- Total of 22 compact tension (CT) tests;
- Three different sample configurations: Al-Al-Notch, Al-DU-corner, Al-DU-Notch;
- Three different loading modes: Mode-I (opening), mixed-mode, and mode-II (shearing);
- Detailed DIC analysis will follow.

## How about displacement measurement:

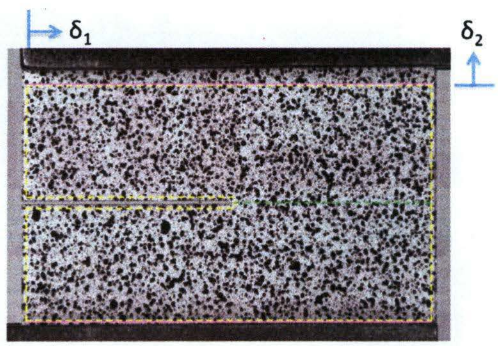
- Crosshead motion of test machine was monitored;
- But it does not represent the displacement experienced by the sample;
- Overall displacement of the CT specimen is determined through DIC analysis.

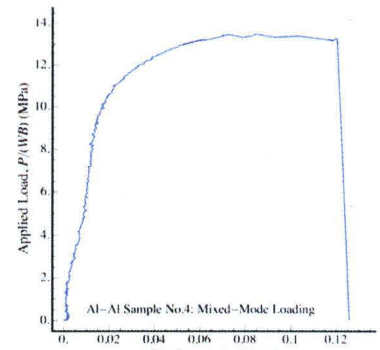
# Overall Displacement of CT Specimen

Displacement parallel to interface | Displacement perpendicular to interface



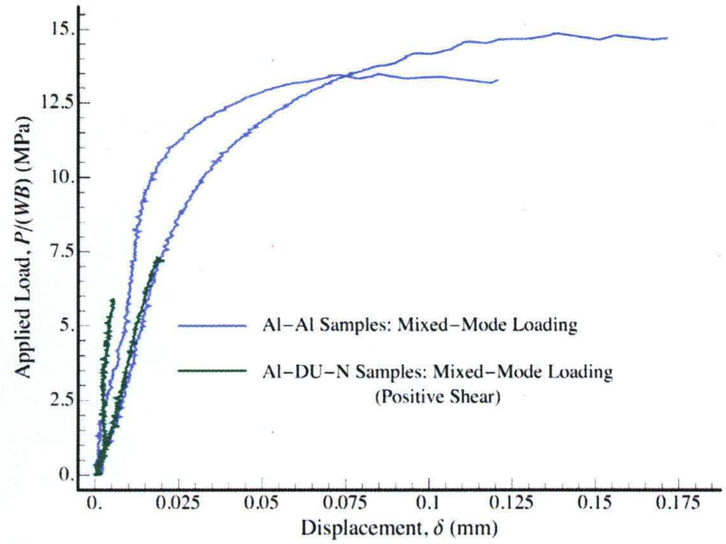

Displacement field from DIC




- Yellow dashed line represents DIC data region;
- Green dashed line is kept horizontal for eliminating rigid-body rotation;
- The relative average motion of the two pink lines provides the overall displacement of the CT specimen.

# Sample Overall Response for Mixed-Mode Loading



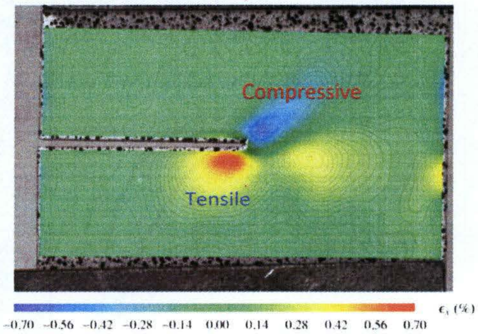

Al-Al sample exhibits elasto-plastic type behavior prior to final failure.

Al-DU-notch sample exhibits elastic behavior followed by brittle failure.

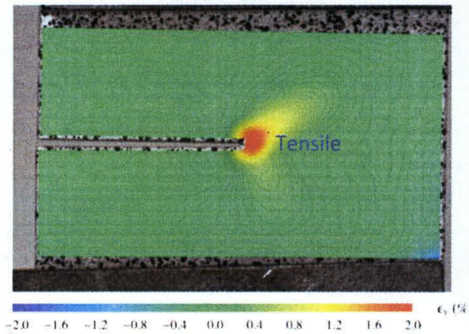
- Other alternatives for representing overall displacement of CT can also be extracted from DIC data:
  - e.g., Displacement at the base of the pre-notch, usually measured using crack-opening gage.

# Strain Fields of Al-Al Sample for Mixed-Mode Loading

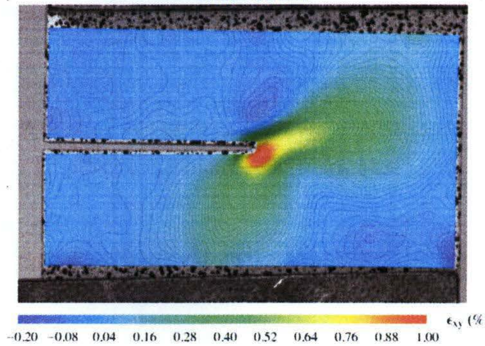
Normal strain parallel to interface




Normal strain perpendicular to interface




Shear strain



- Full-field distribution of in-plane strain is obtained also from DIC. These fields can be compared to FEA simulations.

# Summary

- Total of 22 compact tension (CT) tests were performed to measure the strength subject to different loading modes.
- Three sample configurations were considered:
  - Interfacial crack along Al-Al seam after HIPing;
  - Corner of Zr/DU-10wt%Mo layer at the Al-Al seam;
  - Interfacial crack along Al and Zr/DU-10wt%Mo layer.
- Three different loading modes were evaluated: Mode-I (opening), mixed-mode, and mode-II (shearing).
- Subject to mode-I (opening) load, sample strength show much wider scatter.
- When more shearing component is introduced in the applied load, the strength of all samples increases substantially.
- DIC technique is applied to obtain full-field deformation maps at any given moment.

- Other experimental techniques have been or are being developed to access the bonding strength and toughness of the Al/Zr/DU-10wt%Mo interface:
  - Uniaxial tension: Opening mode strength measurement;
  - Controlled bulge test: Opening mode dominated toughness measurement.