U.S. ARMY COMBAT CAPABILITIES DEVELOPMENT COMMAND ARMY RESEARCH LABORATORY

High-Rate Indentation

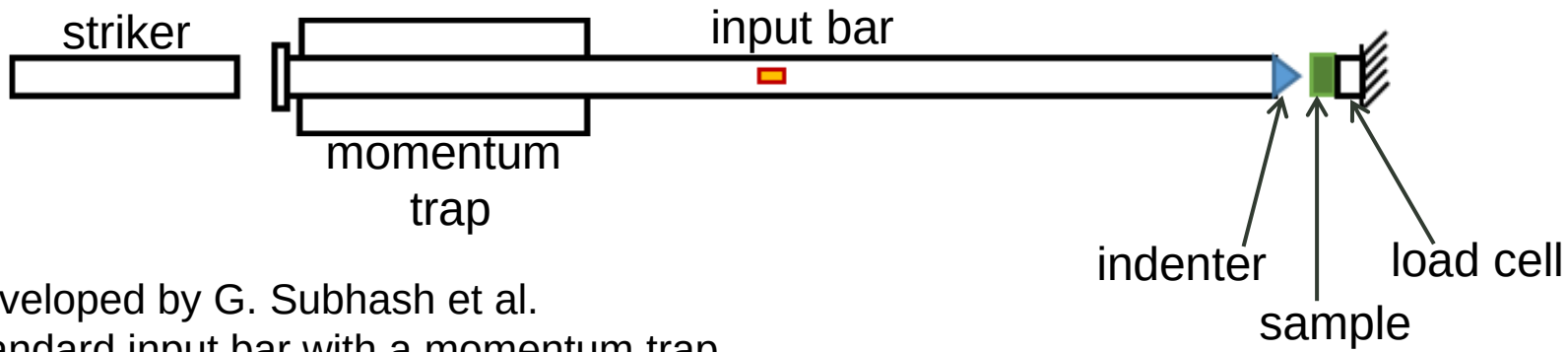
Daniel Casem, Jeff Lloyd, John Clayton
CCDC Army Research Laboratory
Emily Retzlaff
US Naval Academy

PUBLIC RELEASE

I. BACKGROUND

- Develop “high through-put” methods for high-rate mechanical characterization.
- Indentation is a good candidate.
- Convention indentation is non-destructive, quick, easy, inexpensive; can be automated.
- Possible to use an inverse approach to determine constitutive model parameters:
  - *Weaver, J.S., Kalidindi, S.R., “Mechanical characterization of Ti-6Al-4V titanium alloy at multiple length scales using spherical indentation stress-strain measurements,” Materials and Design 111 (2016) 463–472.*
  - *Fernandez-Zelaia, P., et al., “Estimating mechanical properties from spherical indentation using Bayesian approaches,” Materials and Design 147 (2018) 92–105.*
- Objective for 2022 – Can high-rate properties be estimated from high-rate (Kolsky bar) indentation data using a hybrid experimental-numerical approach.
- At present, will only discuss the experiments.

II. DYNAMIC INDENTATION HARDNESS TESTER



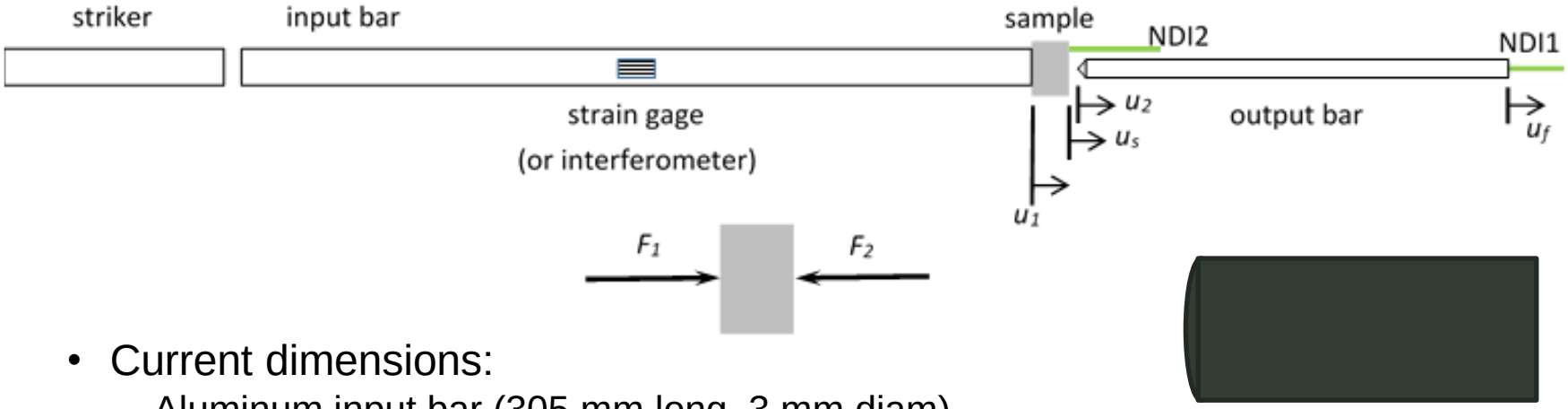
- Developed by G. Subhash et al.
- Standard input bar with a momentum trap.
- Indenter is mounted at the end of the input bar.
- Sample is mounted on a load cell, which measures indentation load.
- By setting the gap between the flange on the input bar and the momentum trap, a single load can be applied to the sample.
- Indention size is obtained from recovered sample.

G. Subhash, B.J. Koeppel, A. Chandra, Dynamic indentation hardness and rate sensitivity in metals, ASME J Eng Mater Technol 121 (1999) 257-263.

- Can be difficult to control load.
- Measurement of indentation depth is not very accurate.

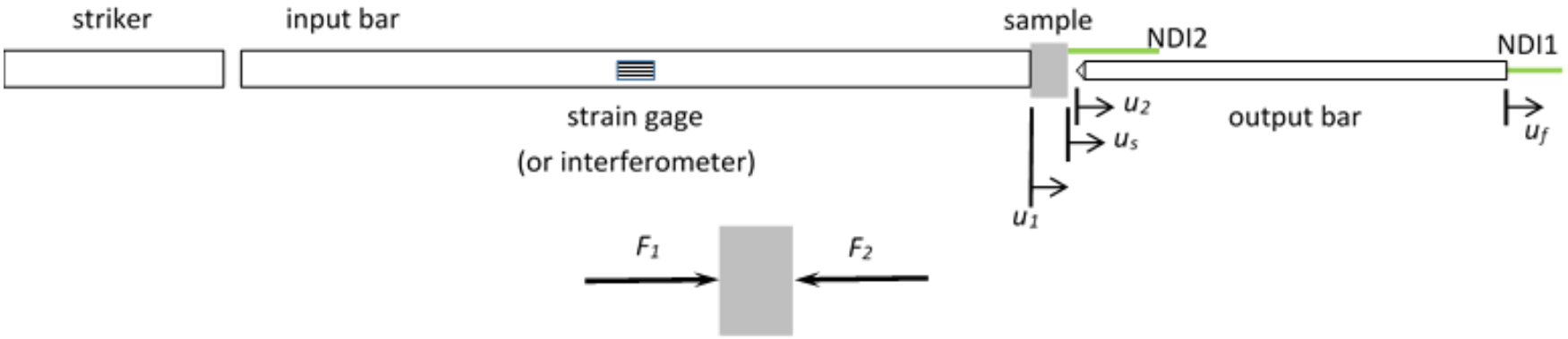
III. CURRENT HIGH-RATE INDENTATION METHOD

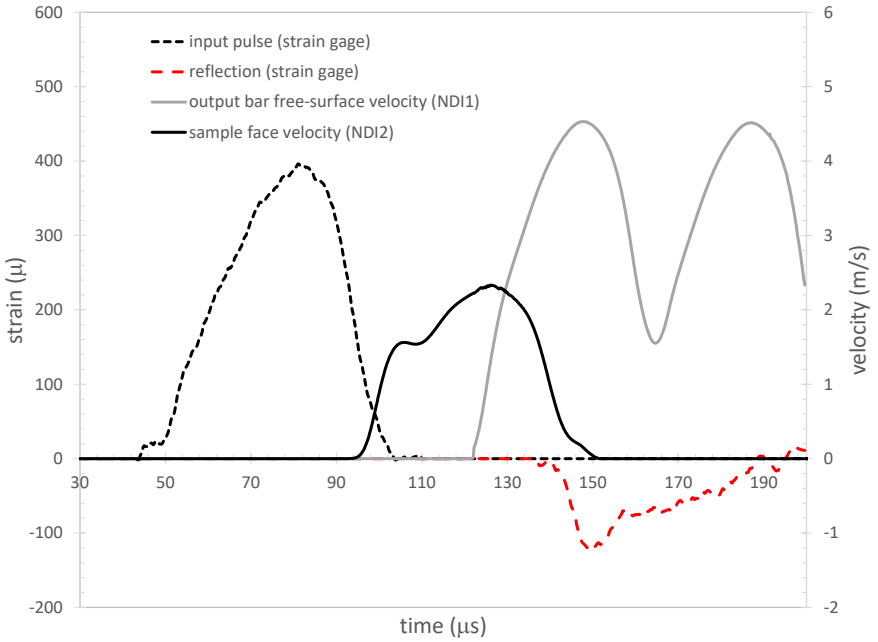
- Overall approach - Miniaturize everything to maximize loading rates.
  - Reduces inertial effects.
  - Decreases the rise-time of the bars.
  - Interferometer measurements are very accurate; **gives accurate measure of indentation depth**.
- Basic configuration:
  - Standard input bar and striker.
    - No flanges or momentum trap.
    - Pulse shaper/tapered strikers may be used.
  - Sample is glued to the end of the input bar.
  - Output bar has the indenter attached/machined directly into the end.

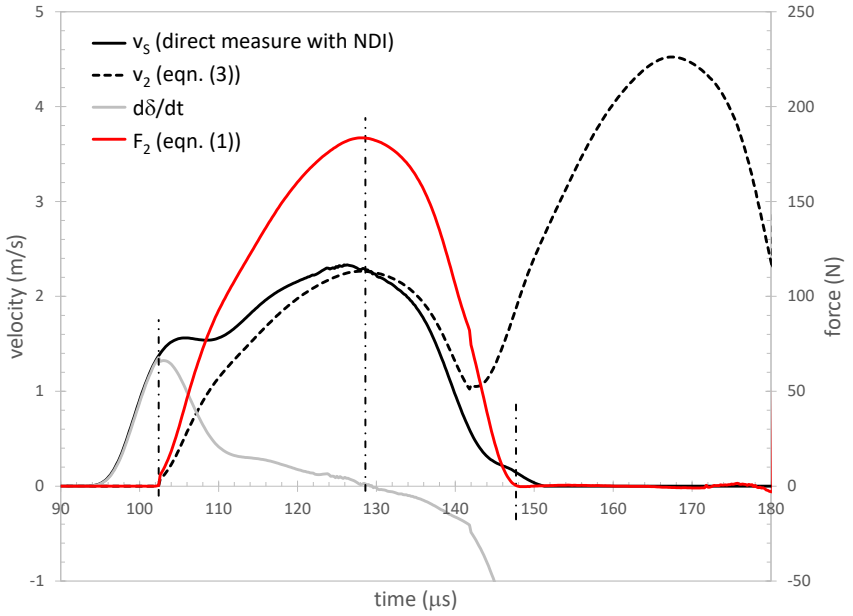


- Current dimensions:
  - Aluminum input bar (305 mm long, 3 mm diam)
  - Steel output bar (100 mm long, 1.6 mm diameter)
  - Spherical indenter shape (R=6.35 mm) machined on the end of the output bar.

IV. APPLICATION – 6061-T6 ALUMINUM, R = 6.35 mm

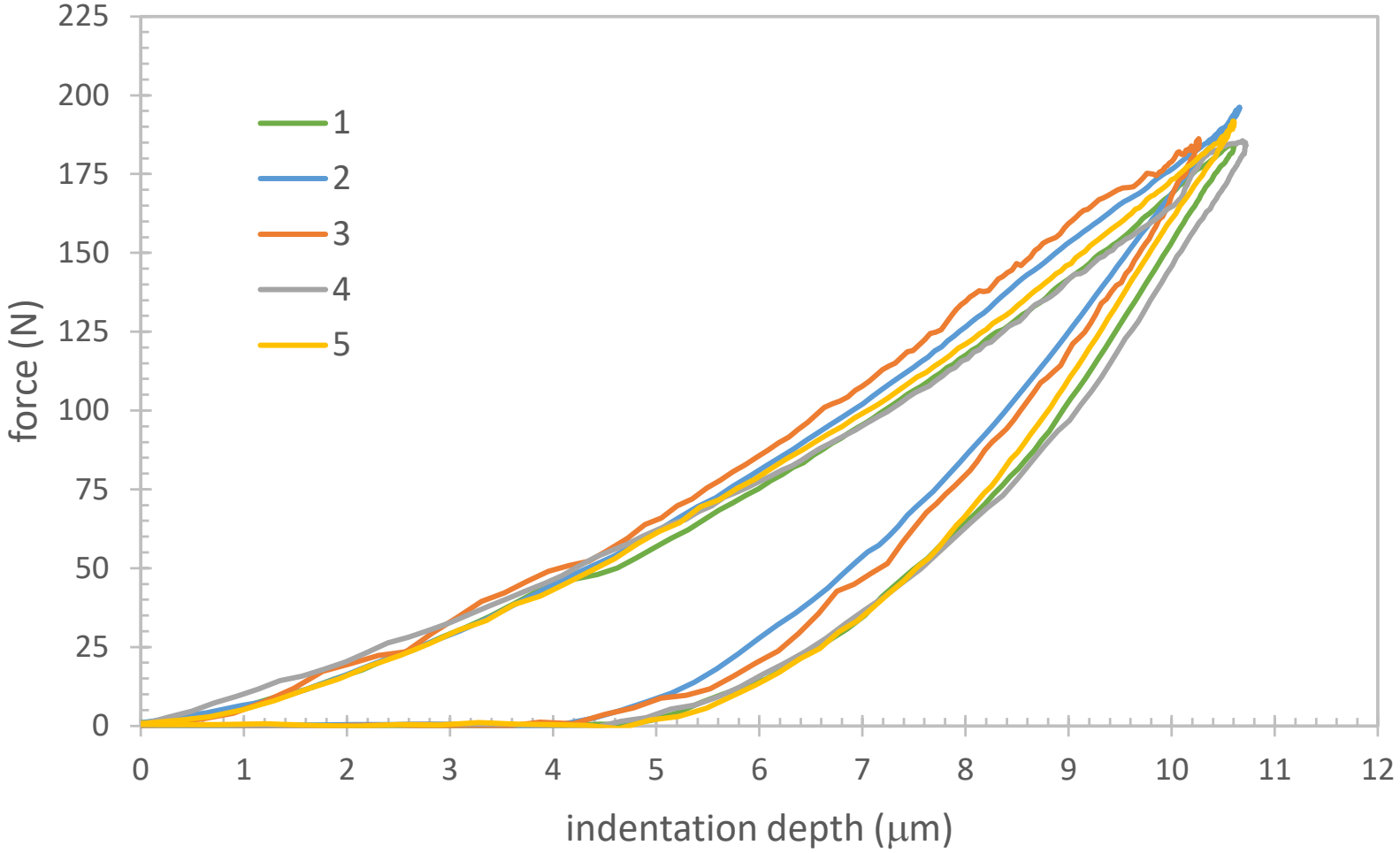






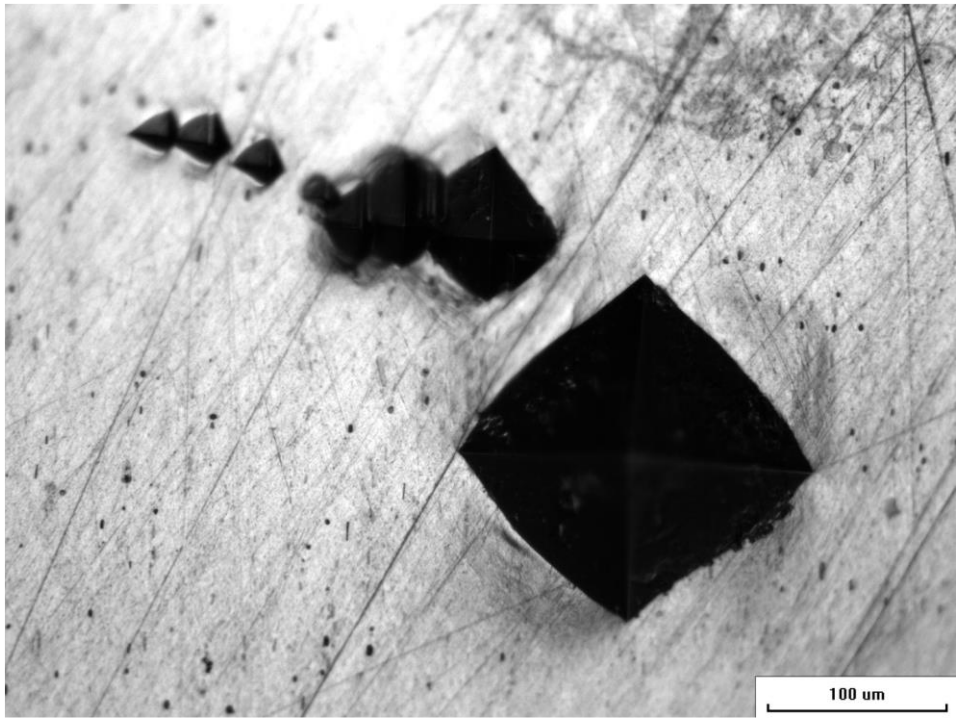
Note about 30 us loading time

IV. APPLICATION – 6061-T6 ALUMINUM, R = 6.35 mm



5 repeated tests, note shallow indents

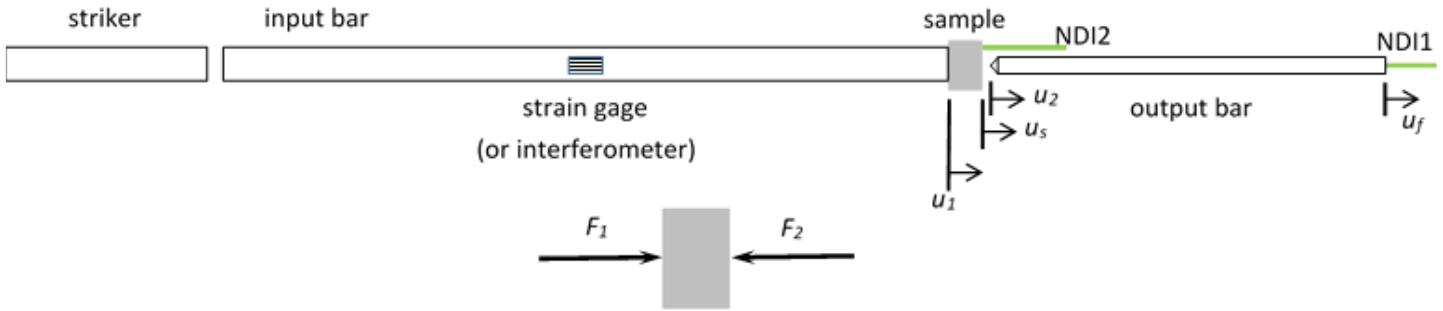
NOTE - RECOVERY IS POSSIBLE



John J Pittari III, Jared C Wright, Ryan M Zegarski, and Jeffrey J Swab, “Modification and Validation of a Dynamic Indentation Test Apparatus”, ARL-TR-9082 (2020).

Da Silva, M.G. and Ramesh, K.T., 1997. The rate-dependent deformation and localization of fully dense and porous Ti-6Al-4V. Materials Science and Engineering: A, 232(1-2), pp.11-22.

Multiple Vickers indentations on aluminum; this can result if stress wave reverberations are not carefully controlled.

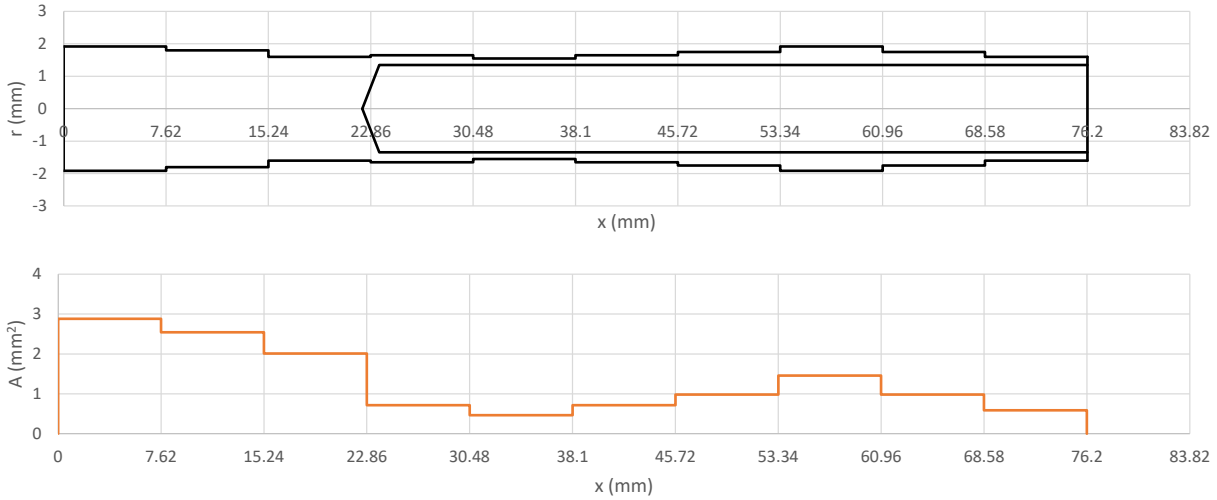


V. PROOF OF CONCEPT – PARTIAL UNLOAD AND RE-LOAD

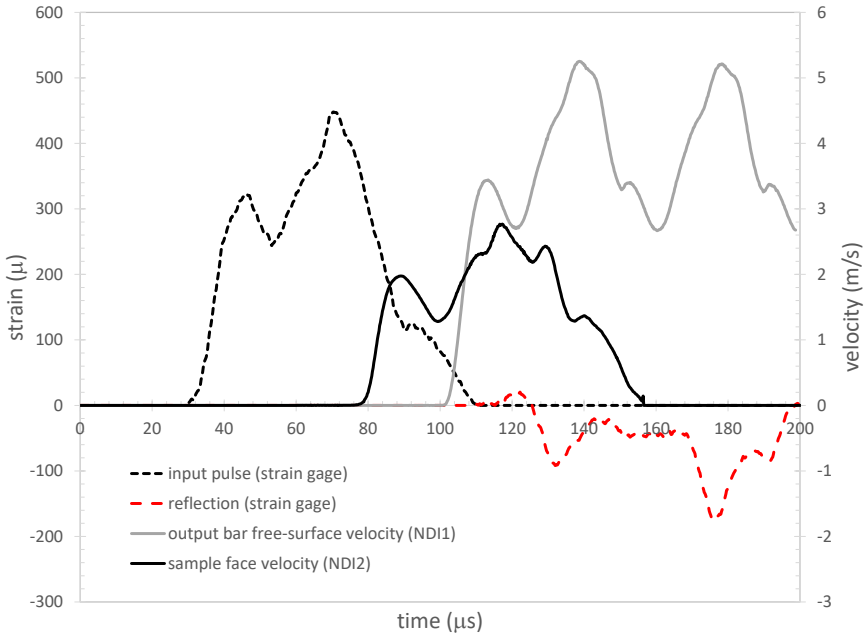
- Partially unload and reload a sample allows the contact area between the indenter and the sample to be estimated
- Improves the accuracy of inferred mechanical data
- Commercial indentation does this directly, or with CSM.
- Can be done in a Kolsky bar by using a variable impedance striker.
- Shape can be designed very precisely.

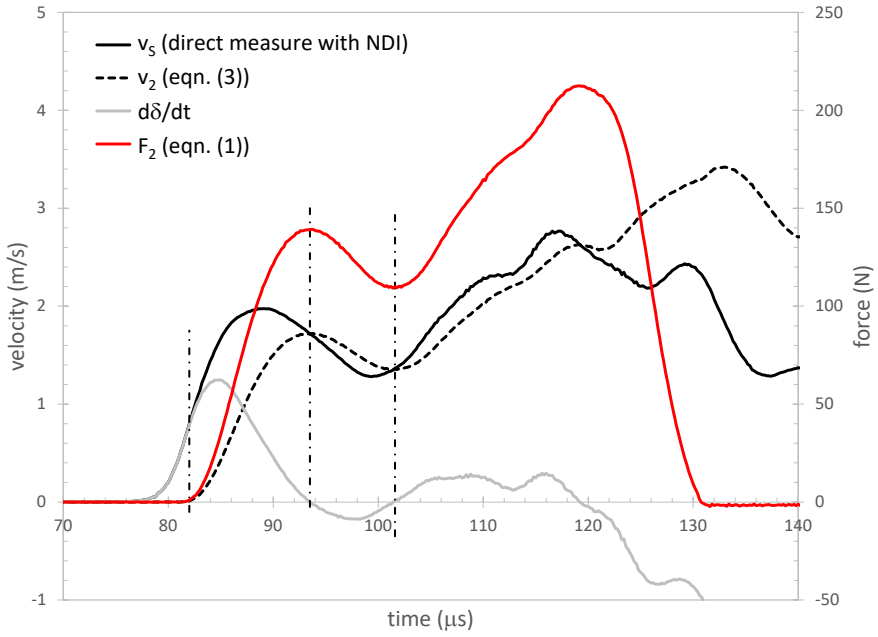
Oliver, W., Pharr, G.: Measurement of hardness and elastic modulus by instrumented indentation: advances in understanding and refinements to methodology. J. Mater. Res. 19(1), 3–20 (2004).

Pathak, S. and Kalidindi, S.R., 2015. Spherical nanoindentation stress–strain curves. Materials science and engineering: R: Reports, 91, pp.1-36.

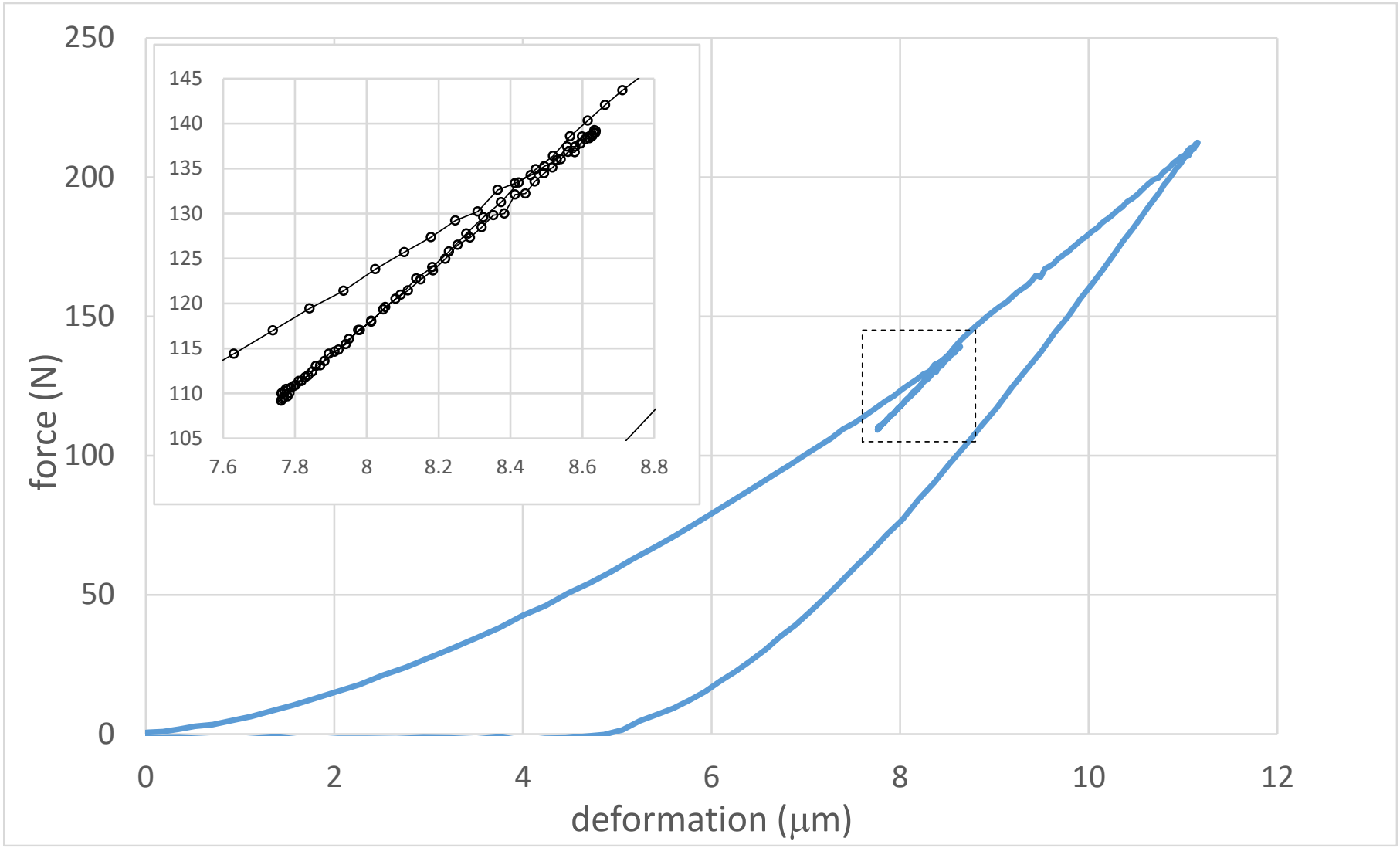


V. PROOF OF CONCEPT – PARTIAL UNLOAD AND RE-LOAD





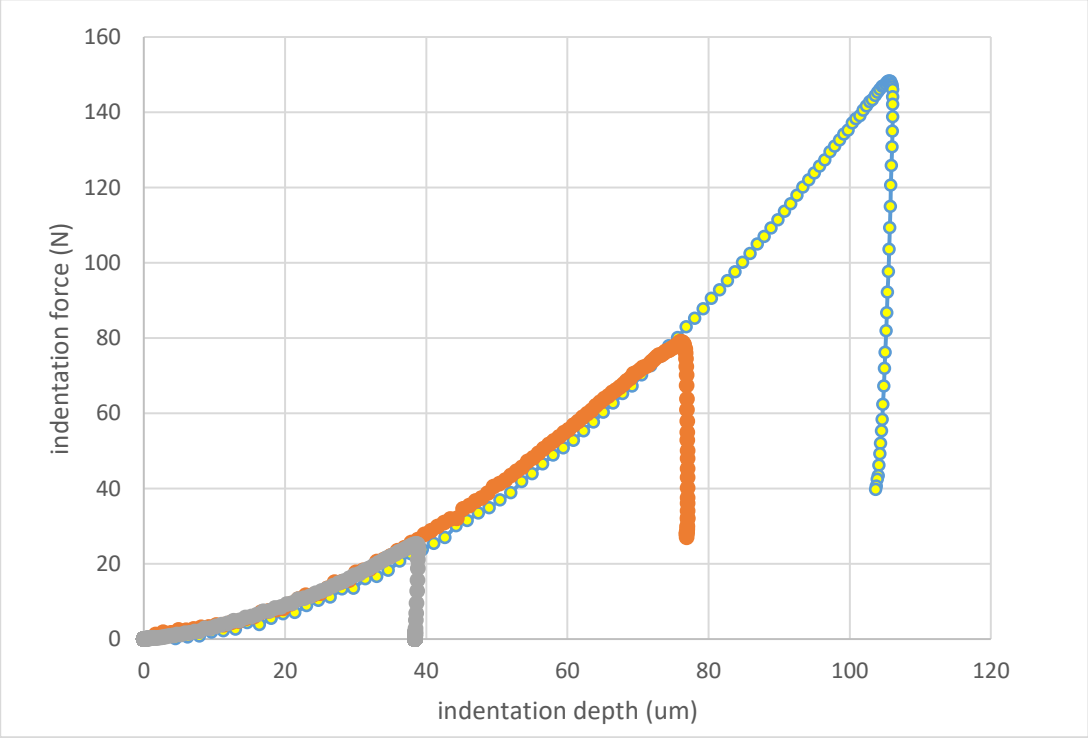
V. PROOF OF CONCEPT – PARTIAL UNLOAD AND RE-LOAD



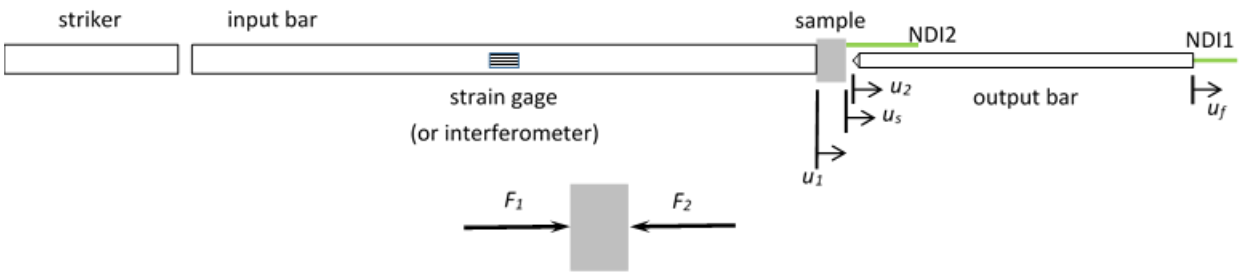
IV. OTHER INDENTERS ARE POSSIBLE

Three repeated tests Vickers idents on OFHC Cu.

- Three repeated tests, with different indentation depths (controlled by varying striker speed).
- Loading times ~ 10 us (markers are 0.2 us apart).
- Final indentation size can be measured from recovered sample.



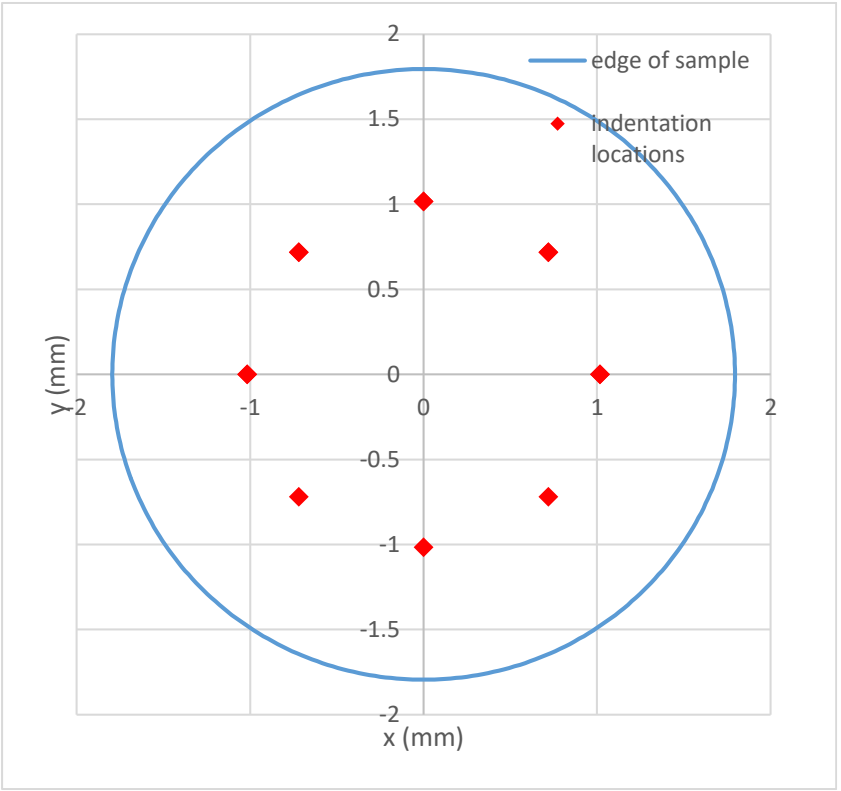
VII. CONFIG FOR HIGHER THROUGH-PUT



Multiple tests can be conducted on a single sample if:

1. the axes of the bars are offset, and
2. the sample/input bar is rotated between each test.

- This causes some bending waves in the input bar due to the non-centric loading, but that should be negligible.
- Between each test, input bar/sample is rotated (e.g., 45 degrees) so that a new spot can be loaded.
- Resulting indentation pattern with 8 tests on one sample is shown.
- Spacing between centers of indentations is 0.778 mm.
- Spacing from center of indents to edge is also 0.778 mm.



VIII. CONCLUSION

Summary – A high-rate indentation method is being developed based on miniature Kolsky bars.

Applied primarily to 6061-T6 aluminum (R=6.35 mm spherical indenter)

- Loading times in the range of 5 us to 100 us
- Various types of indenters possible
- Recovery possible for a wide range of cases
- Multiple unloads/reloads possible (maybe up to 5)

Inverse approach to determine constitutive model parameters currently being evaluated.

Fairly simple – willing to try other material, indenters, loads, etc.