Applications of Photon Doppler Velocimetry in Electromagnetic Forming

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Photon Doppler Velocimetry Applied to Impulse Electromagnetic Forming

- Photon Doppler Velocimetry is an enabling technology for the advancement of EM forming as velocity is a key parameter in all applications.
- A heterodyne velocimetry system based on the work of Strand and others was constructed for 4 channels of velocity data at peak velocities under 1000 m/s.
- The system was used successfully to measure velocities of electromagnetically driven samples in a variety of experiments relating to electromagnetic forming and materials characterization.
- The methodology has contributed data useful in determining material properties under high strain rates and benchmarks for numerical analysis of EM forming. The system will be described and several applications shown

Overview

Motivating Applications

Electromagnetic impulse driving of materials -

For characterization; ring expansion, powder compaction

For forming; welding, die impact, crimping, spring back, shearing

and others

PDV System

Major components, Technical details; power, reference levels, acquisition rates….

Experiments & Applications

Materials characterization; Ring expansion, powder compaction

Forming; Die impact, welding

Motivating Applications

Electromagnetic Forming (EMF) is a high rate forming process that offers advantages in agile manufacturing and studies of high strain rate & shock phenomena

- Currently, proper models are lacking for many high strain rate applications
  - Rapid transient nature of process makes characterization of parameters difficult
- PDV offers a relatively low cost method of monitoring velocity-time profiles for many geometries encountered in EMF
  - Such information can be used to benchmark material models and understand mechanistics of high rate deformation
- Develop constitutive relations for materials characterization
  - Stress-Strain-Strain rate relationships for bulk and powder materials
  - Ring expansion/compression
    - Creates uniaxial stress state at high loading rates
    - Possible to also employ high heating rates
    - Stress and strain data can be calculated from velocity profile established with PDV

Motivating Applications

- Ring expansion
  - Quantify high strain rate materials properties
  - Acceleration behavior of electromagnetically launched rings can be correlated to material flow stress
  - Rings can be high or low conductivity (with driver technique)
  - Repeatability and unambiguity of process is excellent, especially in comparison to Hopkinson bar experiments
- Impact welding
  - Solid state welding process for similar and dissimilar materials
  - Critical parameters: impact angle and velocity
- Die impact
  - Inertial forming of sheet metal parts in one sided die
  - Characterize strain rate and stresses in order to apply material failure models
- Powder compaction
  - Momentum transfer from electromagnetically tube used to compact granular materials

Motivating Applications

Forming

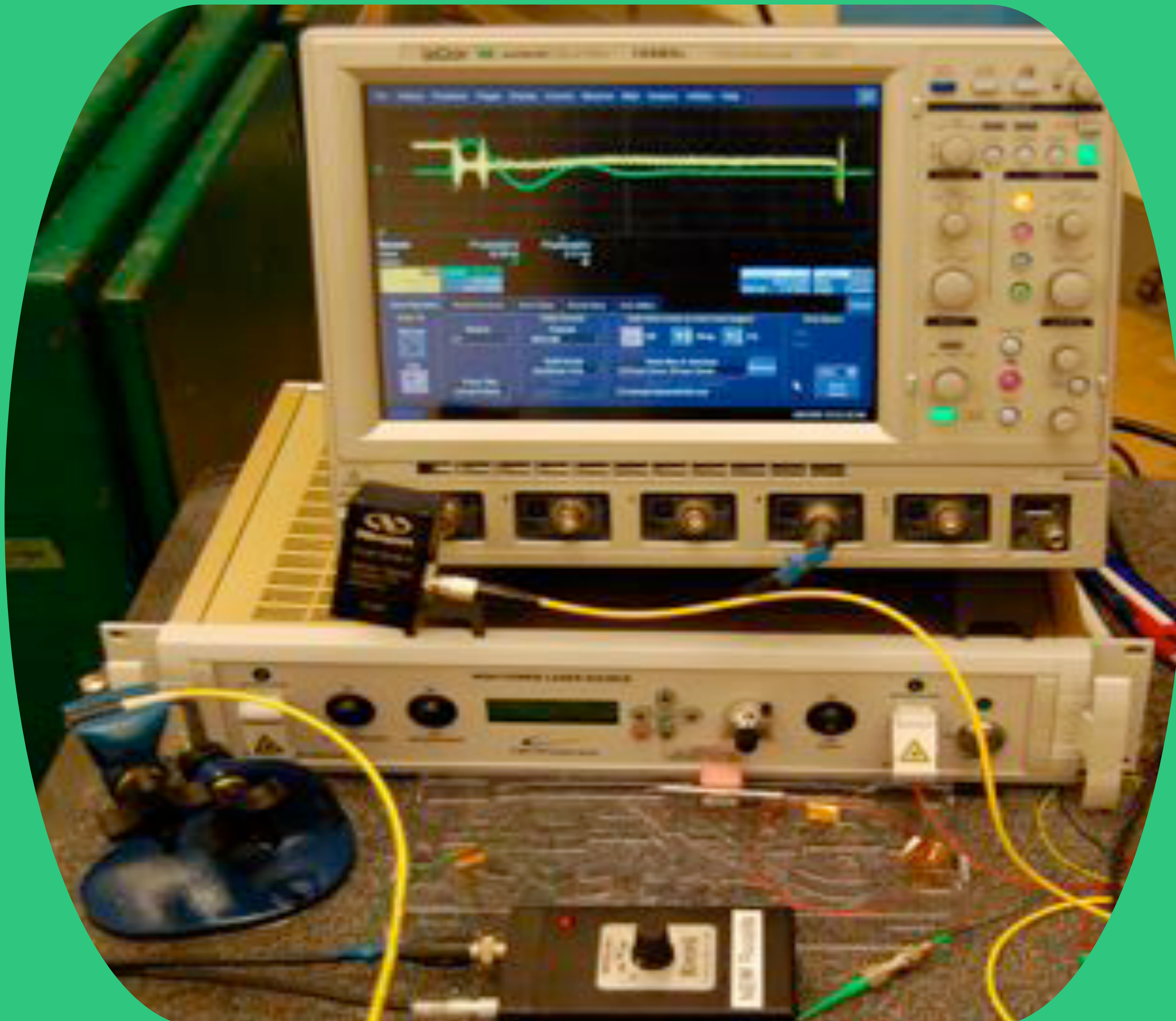
- High strain rate deformation can produce hyperplasticity in ductile materials
  - Strain rate sensitivity and inertial effects
  - Fundamental mechanisms not fully understood
- Extended formability, reduced spring back
- Possible to form many materials in full hard condition
- Process characterization by PDV

PDV Equipment

- NP Photonics 1 W erbium fiber laser
  - 1550 nm with <3 kHz line width
- Fiber components
  - Splitter, circulators, probes; JDS Uniphase & Oz Optics
- Newport Corp. 1 GHz photo detector 818BB
- LeCroy 1 GHz 4 channel Wavesurfer oscilloscope
  - Up to 5 GS/s data acquisition rate
    - With 10k/500k/2.5 M samples this is 2ms capture time

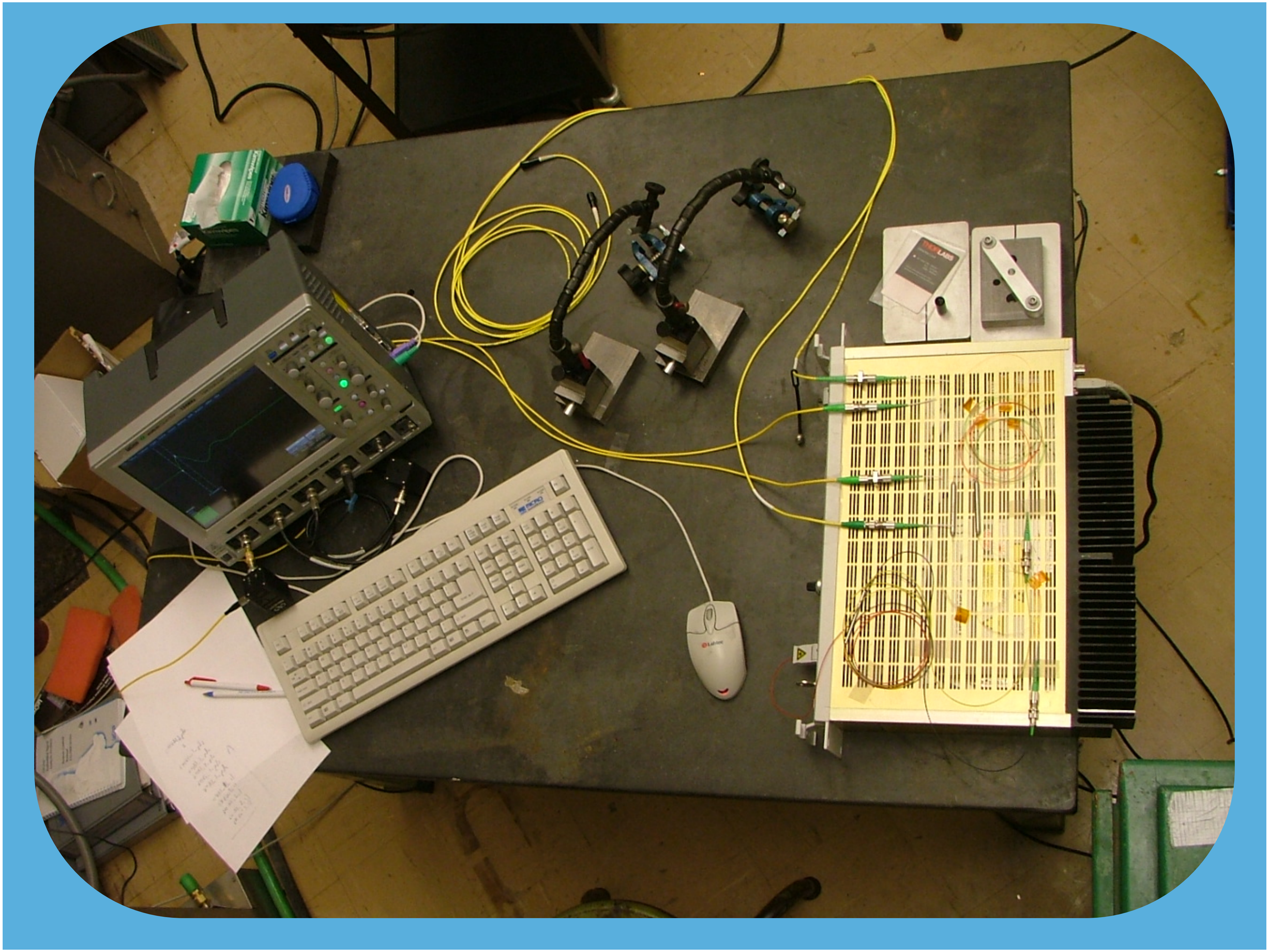
Windows based system – data processing software

- MatLab, Mathematica, Excel



PDV Equipment

- Data acquisition is triggered by a Rogowski probe
  - Also provides current trace from capacitor bank
- Data from photodectors is recorded on 1 or more channels
  - 1 GHz detectors allow measurements up to 775 m/s
- Data processing currently on desktop PC, soon directly on oscilloscope



PDV Equipment

- Various probes
  - Collimators & Focusors mostly Oz Optics
  - Inside diameter periscopic adaptor

- Temperature data

  Digital IR thermometer

Electromagnetic Ring Expansion

Has no wave propagation along direction of principal stress. Gives spatially uniform state of very nearly uniaxial stress for un-necked ring.

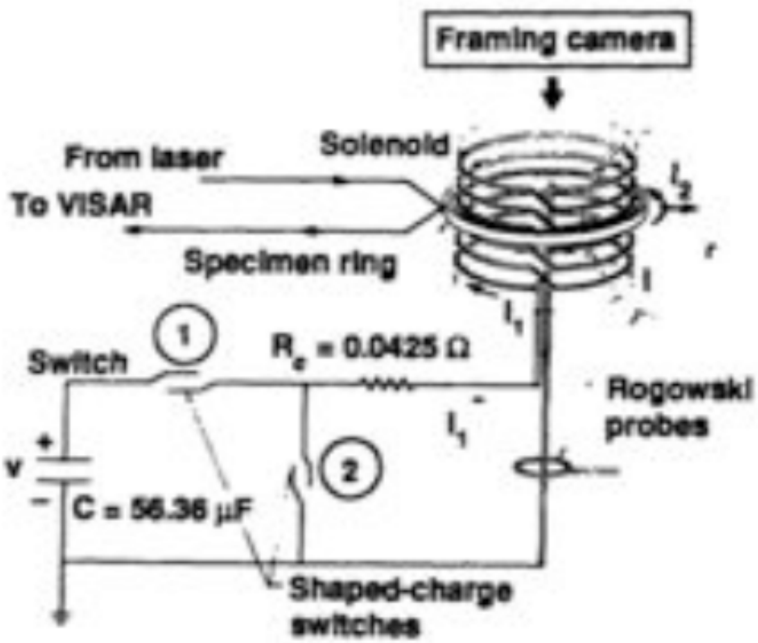
Introduced by F. L. Niordson, 1965.

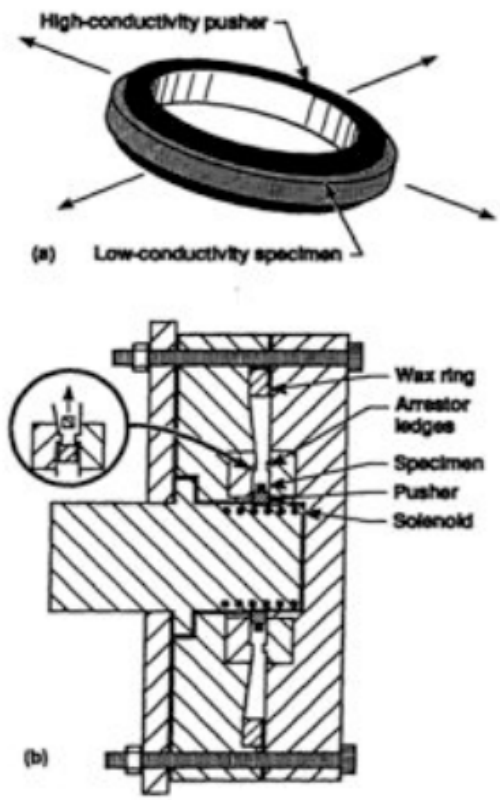
Further developed by Grady and Benson, 1983.

Quite refined by W. H. Gourdin and collaborators, 1988 and 1989.

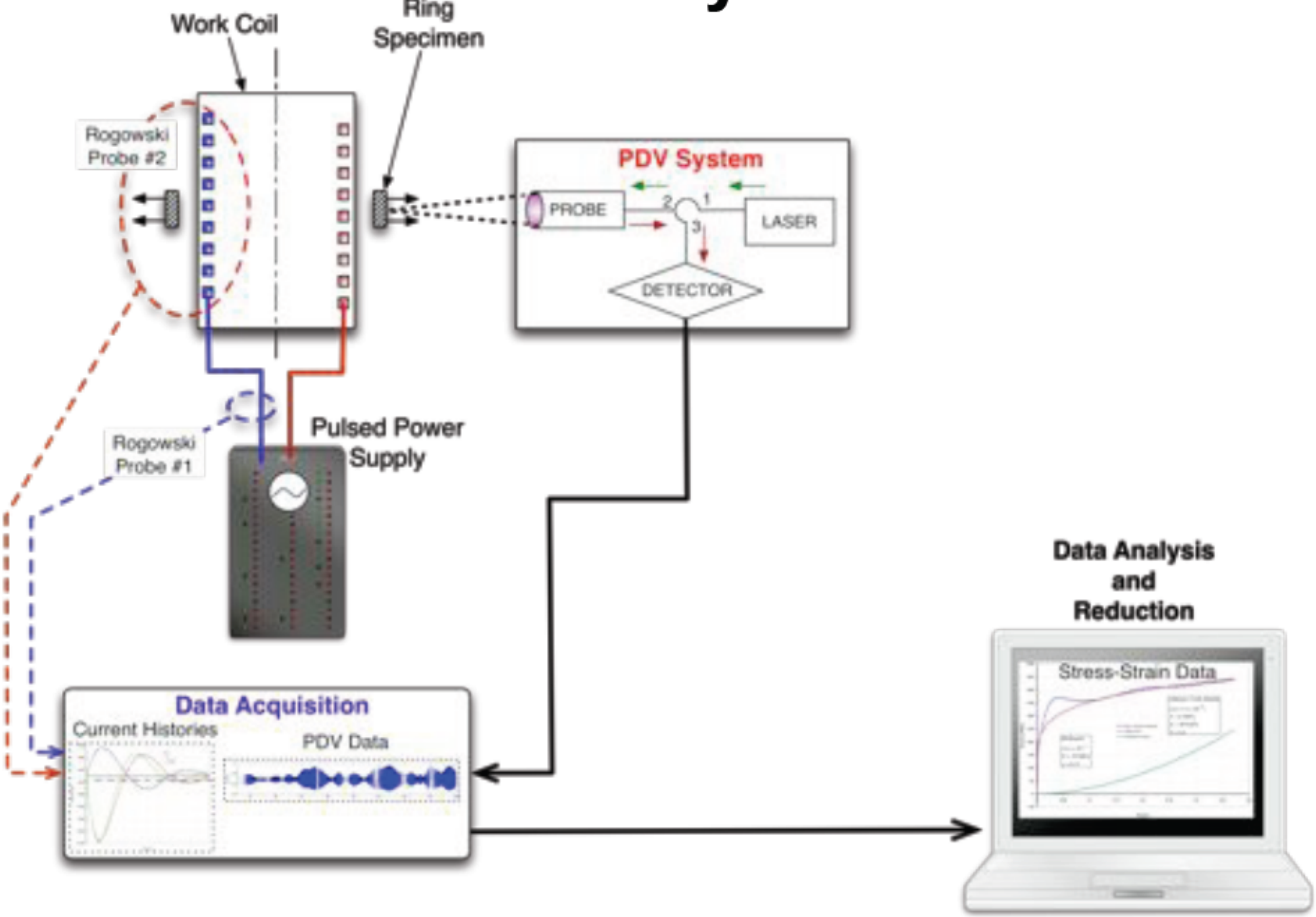
Gourdin's Accomoplishments

- Two key papers: *J. Appl. Phys.* ('88) *Rev. Sci. Instrum.* ('89), with Weinland and Bolling

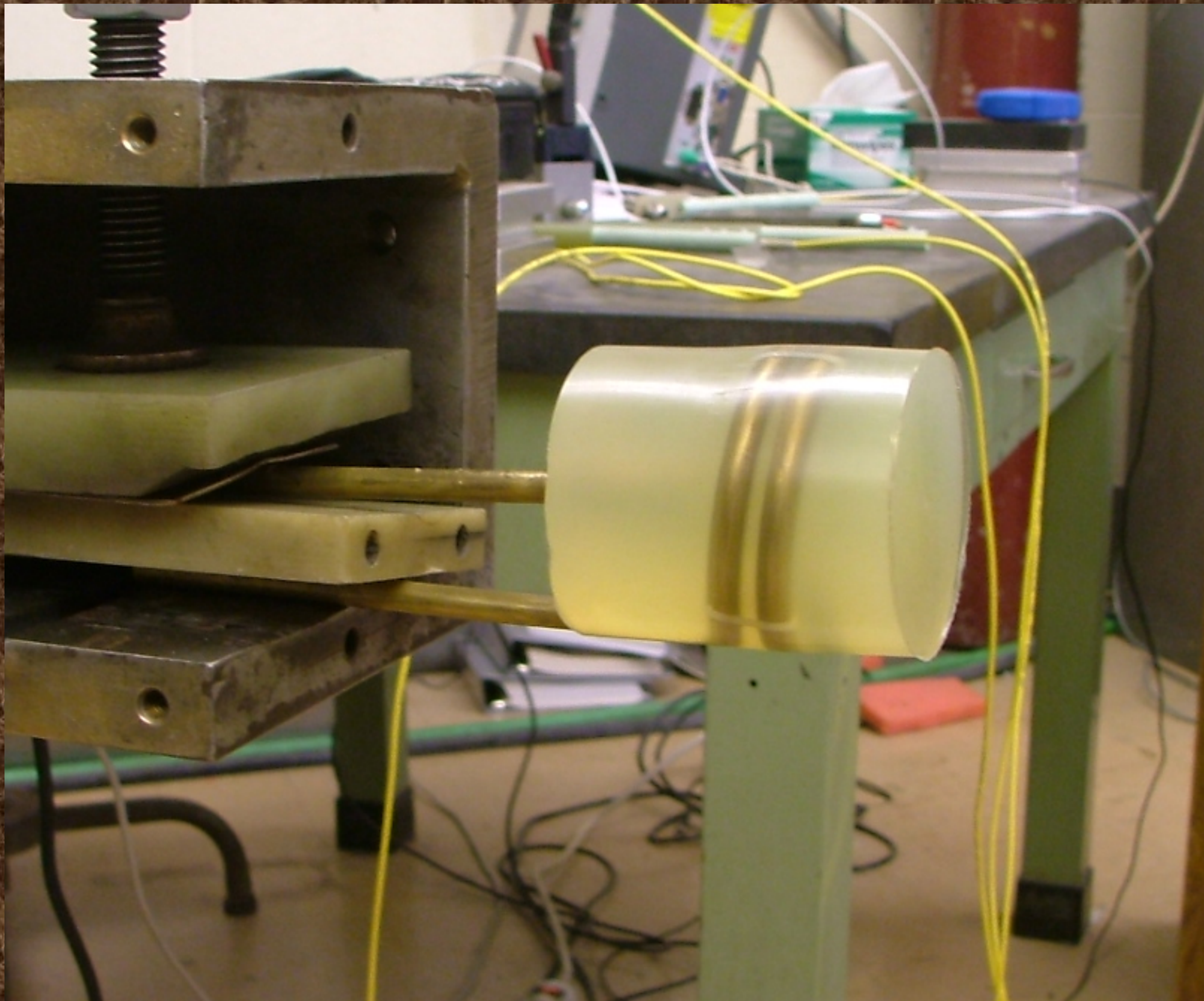




The System

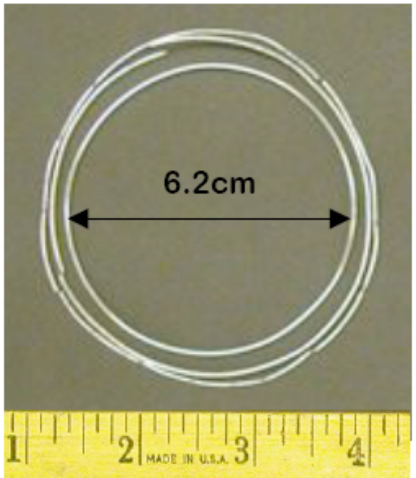


Work Coil
Ring Specimen
Rogowski Probe #2
PDV System
PROBE
LASER
DETECTOR
Rogowski Probe #1
Pulsed Power Supply
Data Analysis and Reduction
Stress-Strain Data
Data Acquisition
Current Histories
PDV Data



Better Ductility: High Velocity Ring Expansion

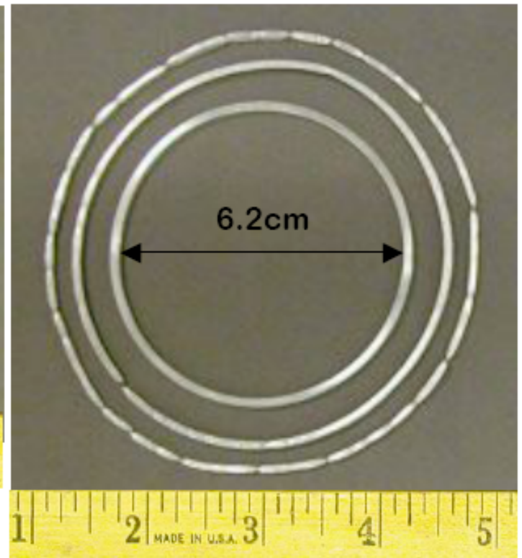
Three samples shown for each: original size, one rupture and multiple necks



1x1 rings: launched at 0.56 kJ and 0.96 kJ

Uniform Elong.=8%

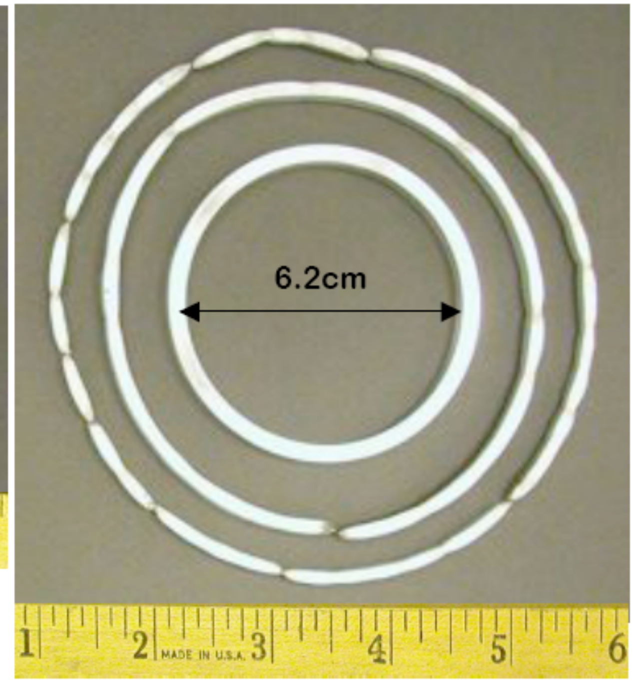
Total Elong. = 19%



2x2 rings: launched at 0.96 kJ and 2.4 kJ

Unif. Elong. =18%

Total Elong. = 38%



4x4 rings: launched at 3.36 kJ and 6.8 kJ

Unif. Elong. =30%

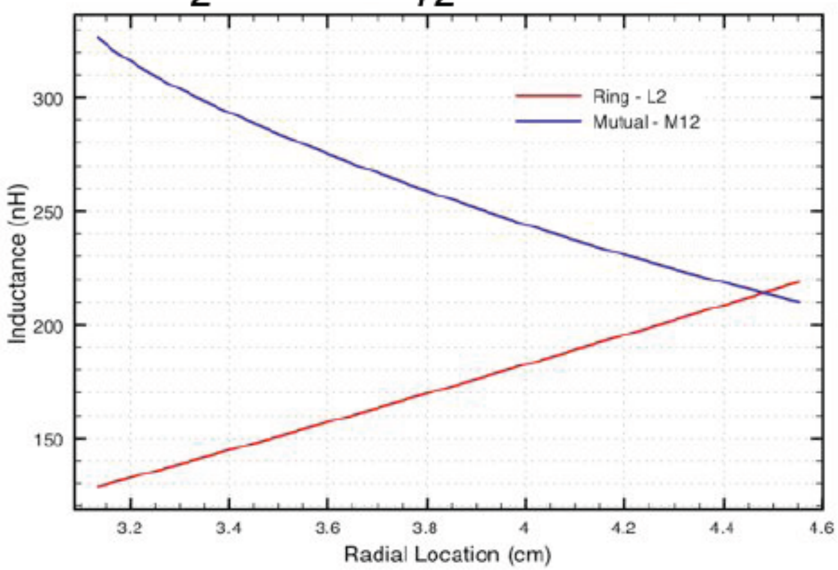
Total Elong. = 48%

Total elongation increases rapidly as the aspect ratio of the rings decreases

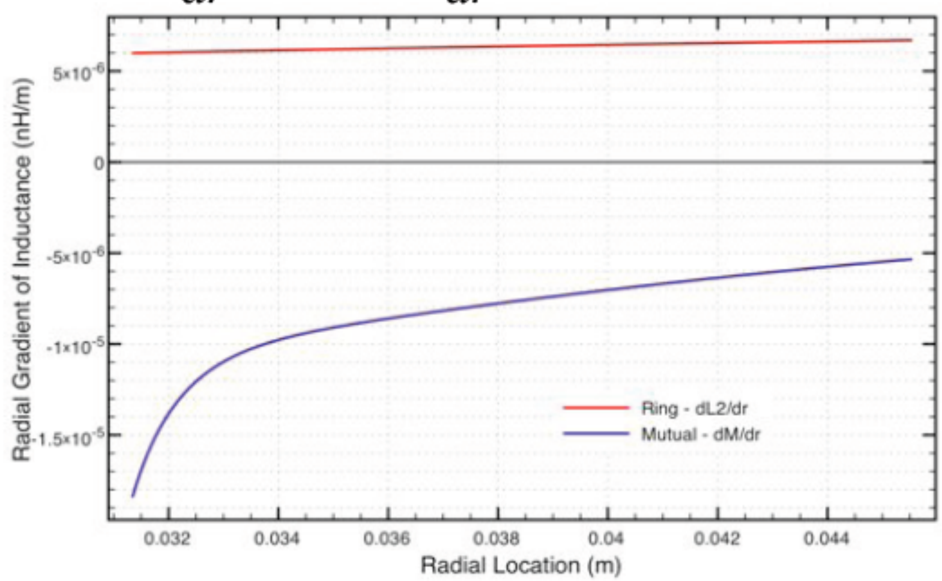
1D Analysis - Hoop approximation

Inductances related to the ring-coil system and their respective gradients are functions of ring geometry, they are obtainable…

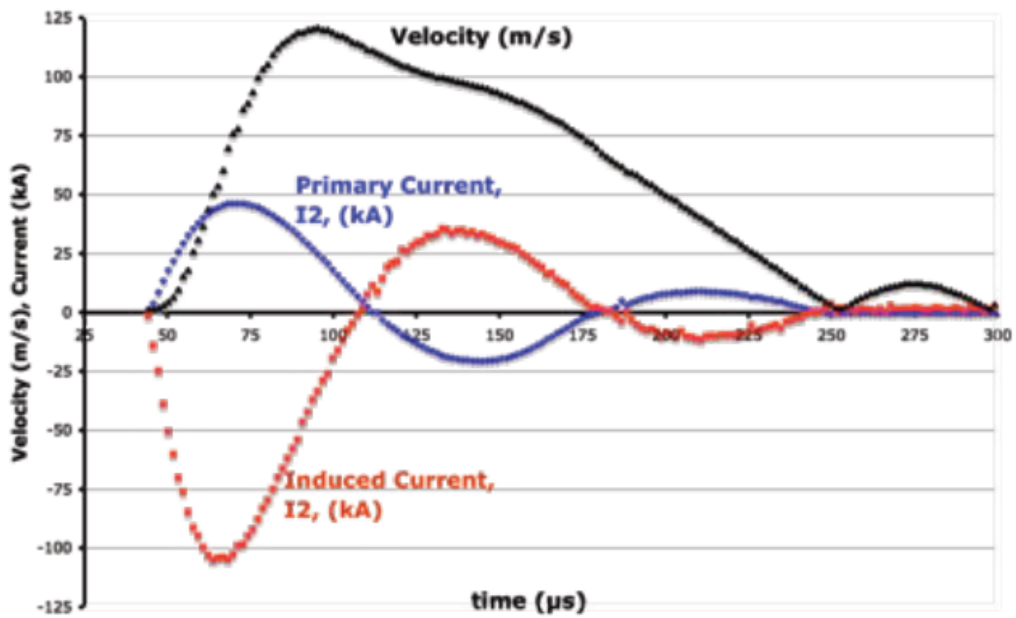
L_2 and M_{12} vs. radius



$\frac{dL_2}{dr}$ and $\frac{dM_{12}}{dr}$ vs. radius



Example Data Set

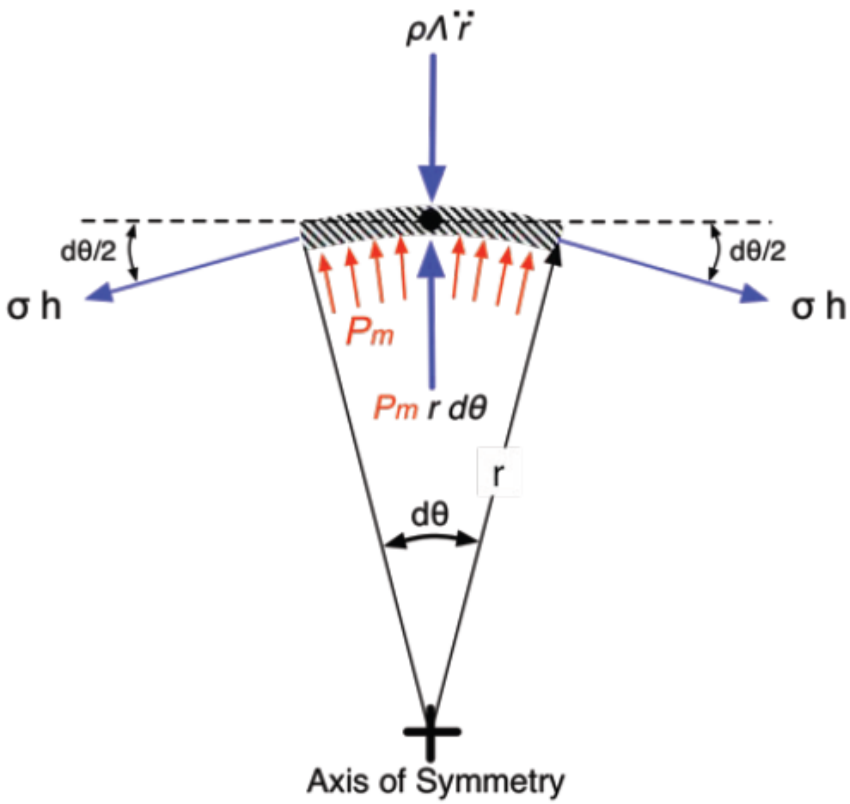


Annealed Cu 122 rings launched with 1.28kJ impulse with 5-turn brass coil with square x-section.

Ring has initial ID of 62mm, .9mm wall thickness and height of 9mm.

Ring has 45% hoop elongation, unbroken and 27% reduction in height after the experiment.

1D Analysis - Hoop approximation



Free Body Diagram
of forces on the ring

Sum these forces to get radial equation of motion

$$\rho\,\ddot{r} = \rho\frac{dV_r}{dt} = \frac{F_r^m}{\Lambda} - \frac{\sigma}{r}$$

Where F_r^m is the radial component of magnetic force, i.e., the radial Lorentz force on the ring

$$F_r^m = \frac{1}{2}\frac{dL_2}{dr}I_2^2 + \frac{dM}{dr}I_1 I_2$$

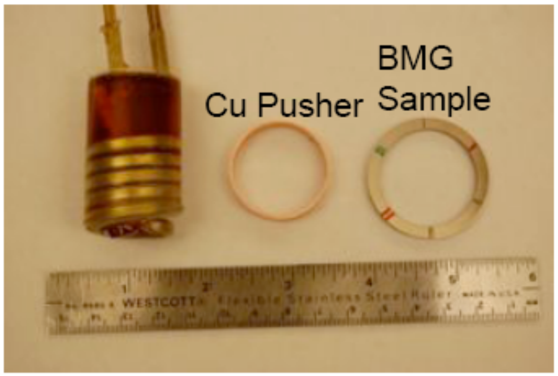
Solving for σ…

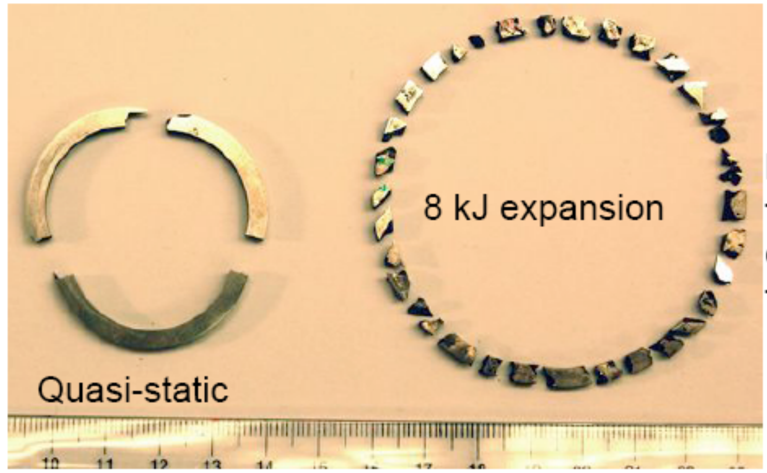
$$\sigma = \frac{F_r^m\, r}{\Lambda} - r\,\rho\,\ddot{r}$$

Λ is the volume of the ring

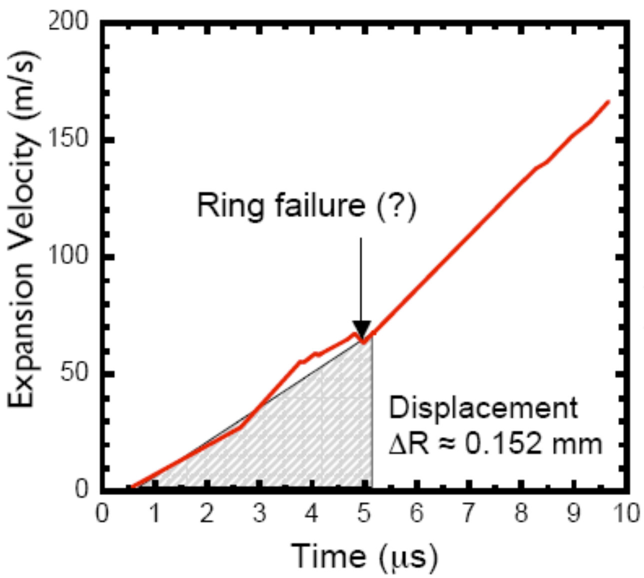
Expansion of a Bulk Metallic Glass

With K. M. Flores and J. Bennett, Department of Materials Science, OSU

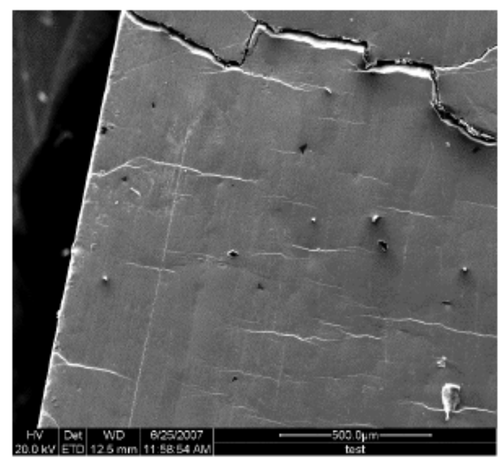




Majority of 35 fragments exhibit shear failure surfaces

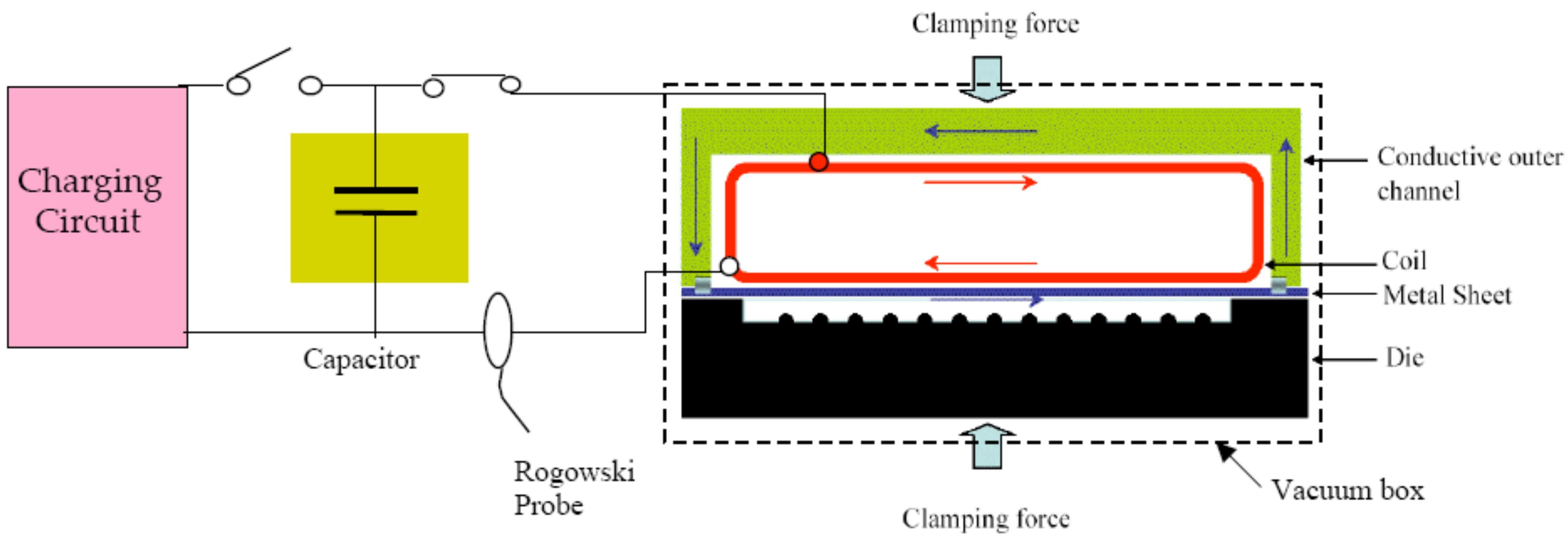


Radial velocity at failure: ~67.5 m/s
Strain rate at failure: ~3900 s^{-1}
Strain at failure: ~0.9%

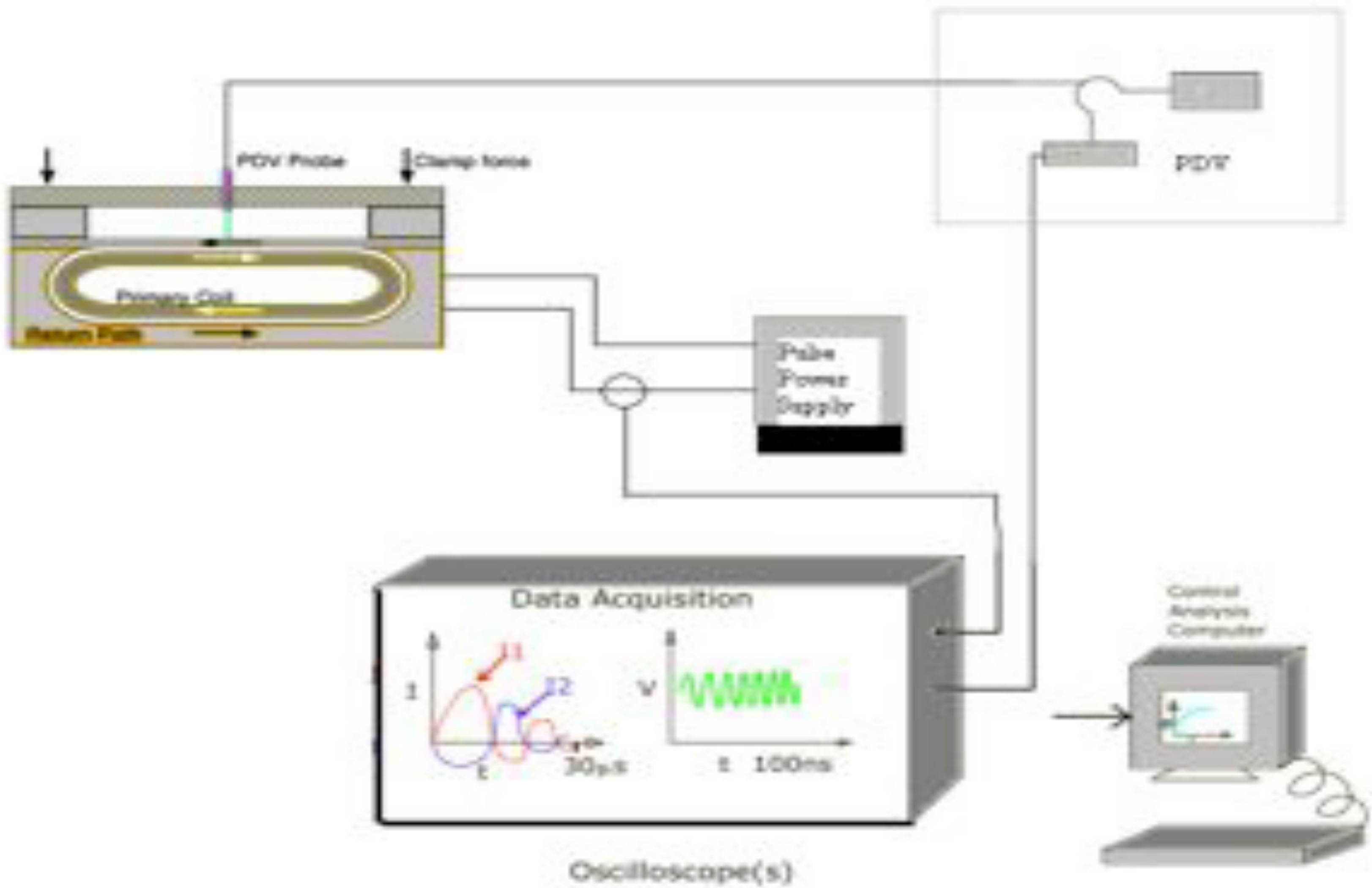


Interior surface, 10.4 kJ expansion

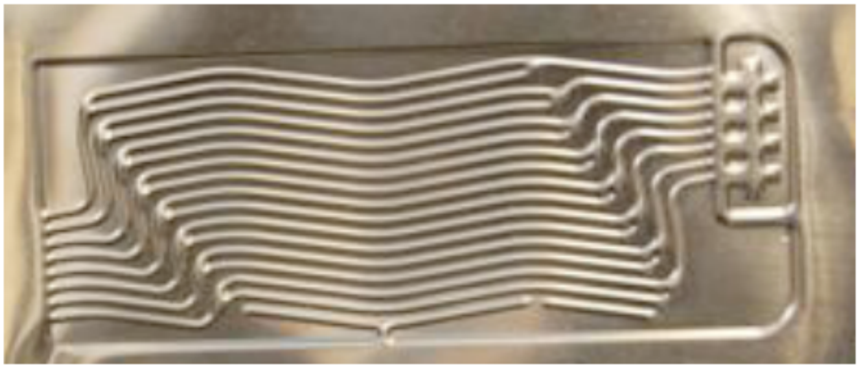
Electromagnetic Forming Schematic



- Typical current pulse: up to ~100kA, ~ 20μs
- Electromagnetic repulsion between coil and metal sheet launches the sheet into the die cavity at high velocity, ~ 200 m/s.
- Extremely high strain rates, up to 10^4 s^{-1}, can result in greater formability – "hyperplasticity."


PDV Probe
Clamp force
Primary Coil
Return Path
PDV
Pulse
Power
Supply
Data Acquisition
I
I1
I2
V
30μs
t
t 100ns
Oscilloscope(s)
Control
Analysis
Computer

Bipolar Plate Foring



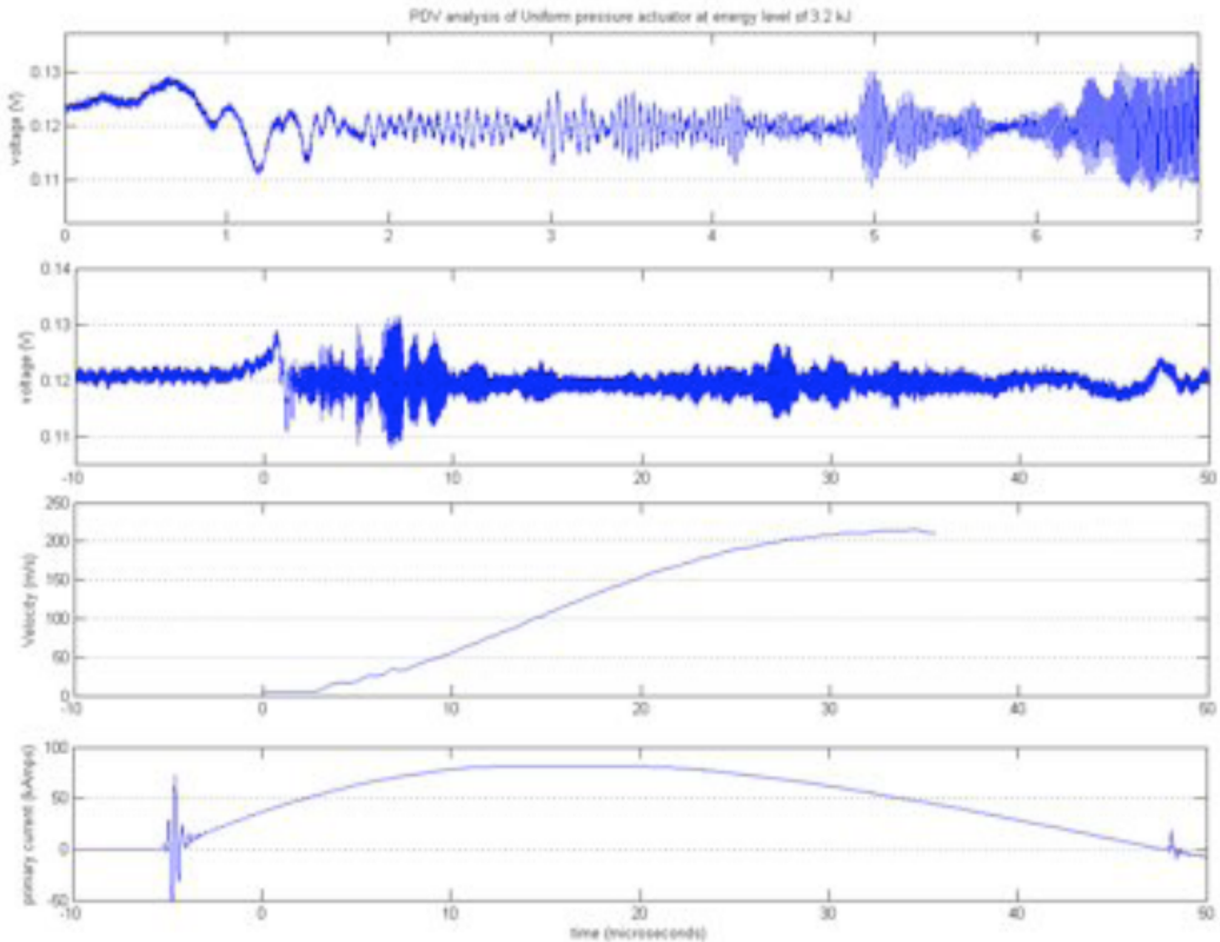
Urethane Pad Formed

Electromagnetic

316L 0.004”

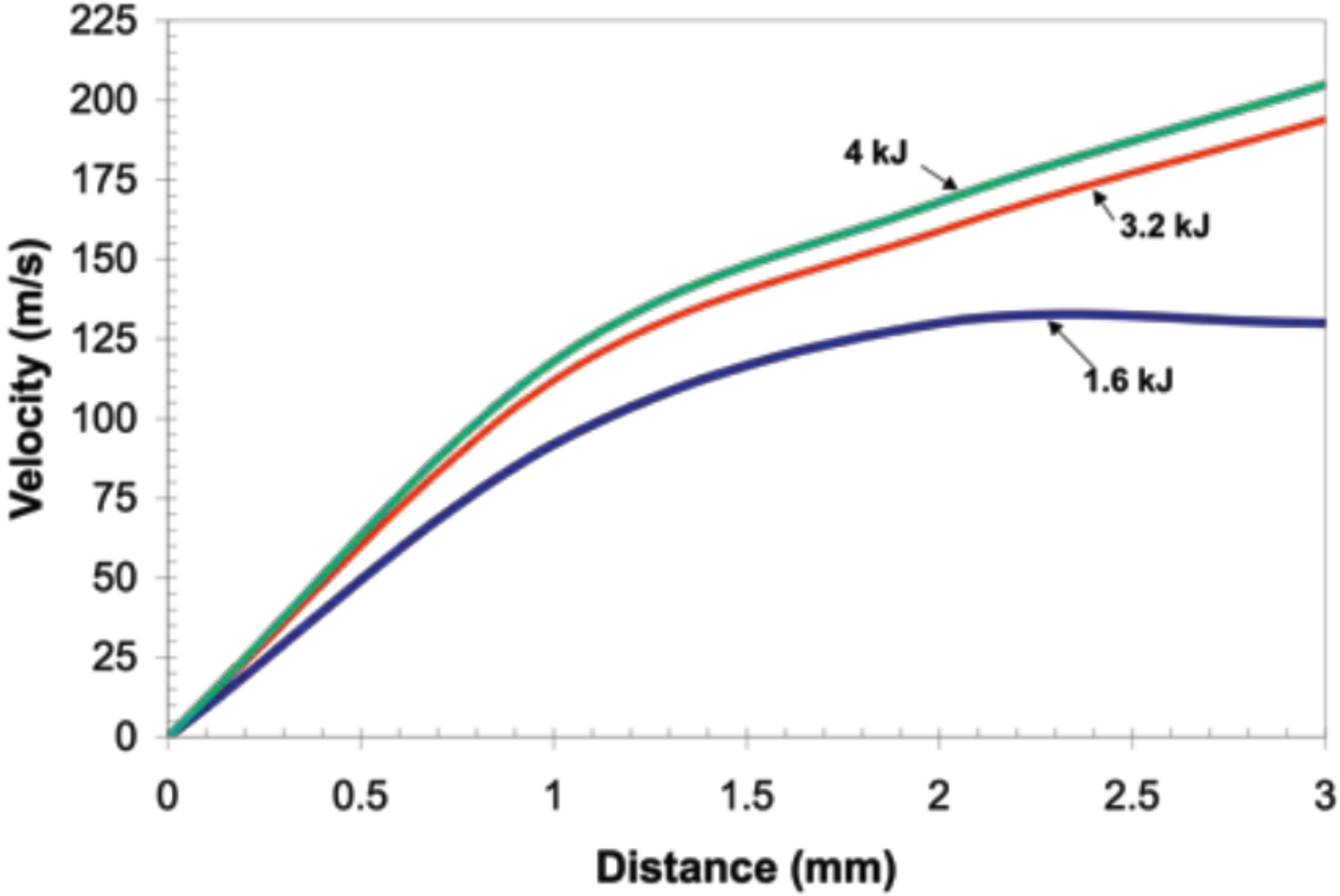
77 % full depth (4 kJ), Punch
Peak Velocity 205 m/s, 458 miles/hr

PDV Traces and Analysis



4 mm of standoff, 0.127 mm Cu driver, 0.1016 mm 316L sheet
3.2 kJ, 208 m/s, at 32 us

Photon Doppler Velocimetry



4 mm of standoff, 0.127 mm Cu driver, 0.1016 mm 316L sheet

Powder compaction

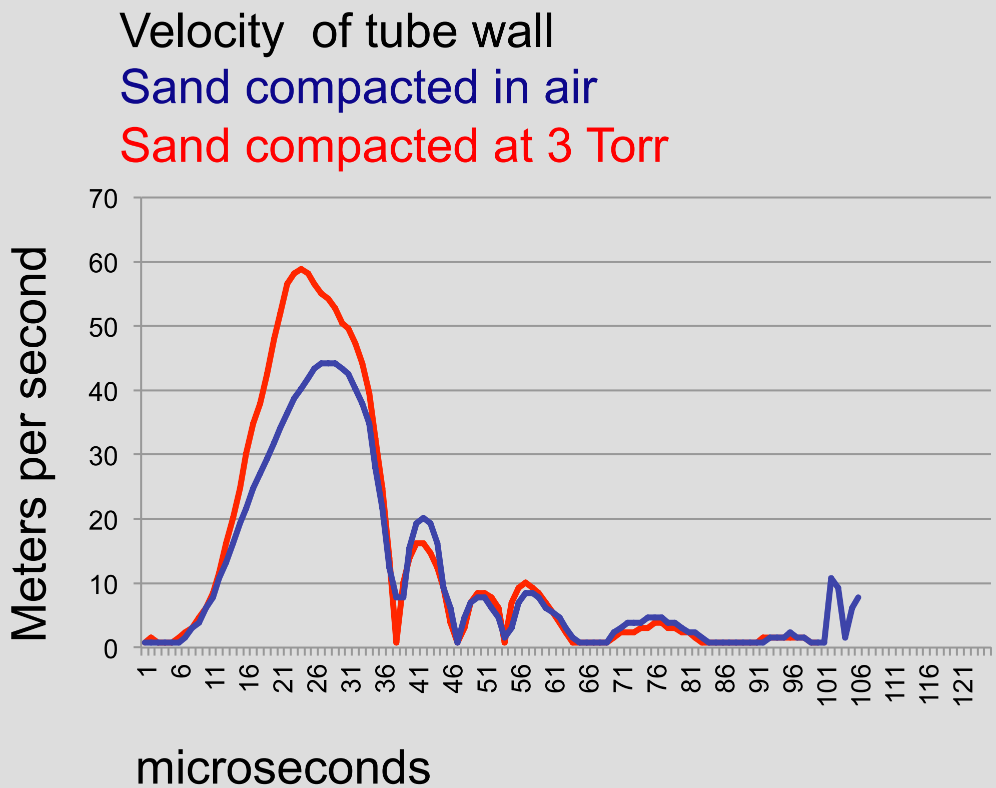
Coil for 19mm tube compression biaxial CF weave, PDV port

Another compression coil uniaxial CF fiber with PDV port

Samples 17 thru 22
17 empty
18-21 sand
21 sectioned - note retained sand
22 Tungsten Carbide

Powder compaction study sample tubes

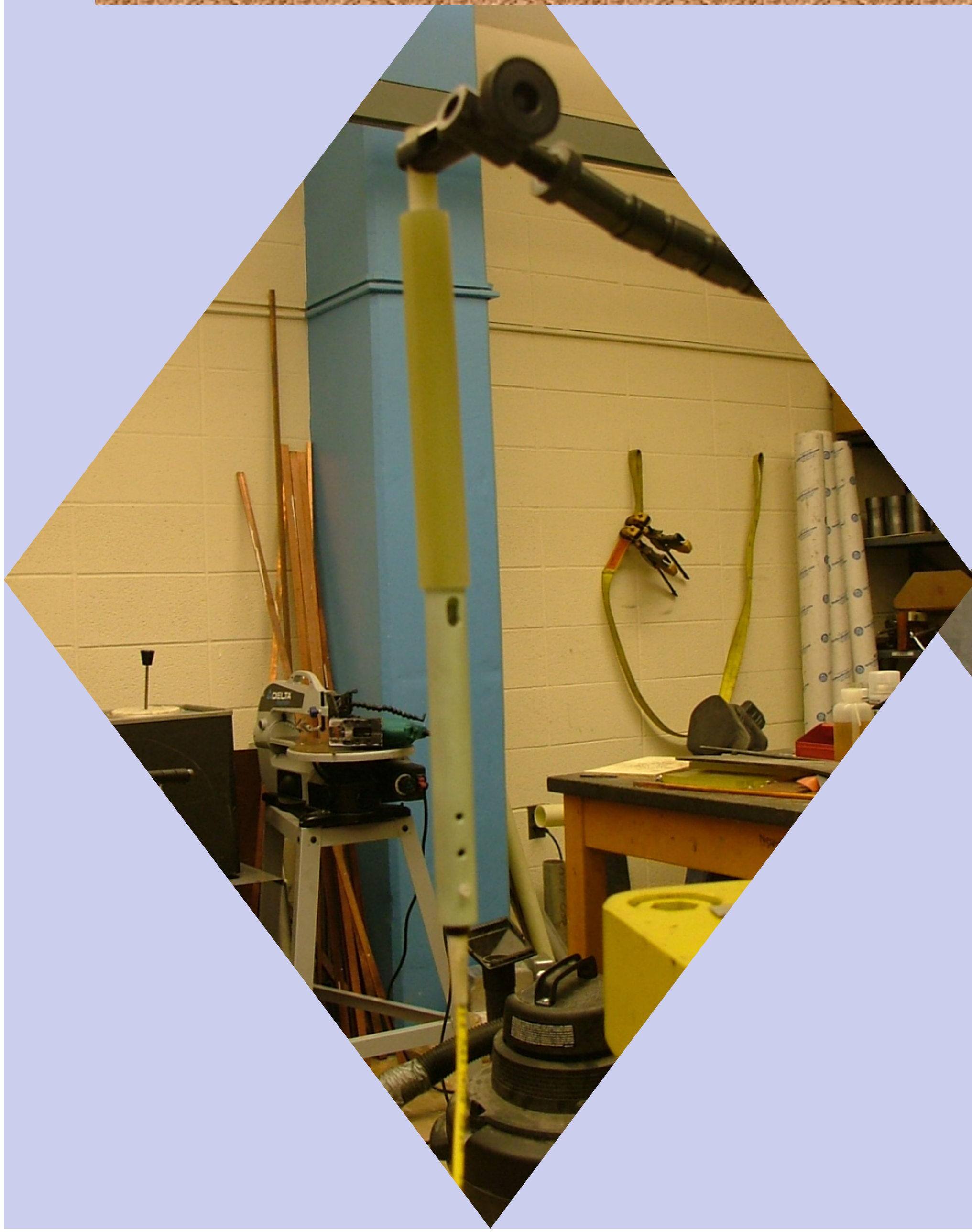
23 & 27 evacuated

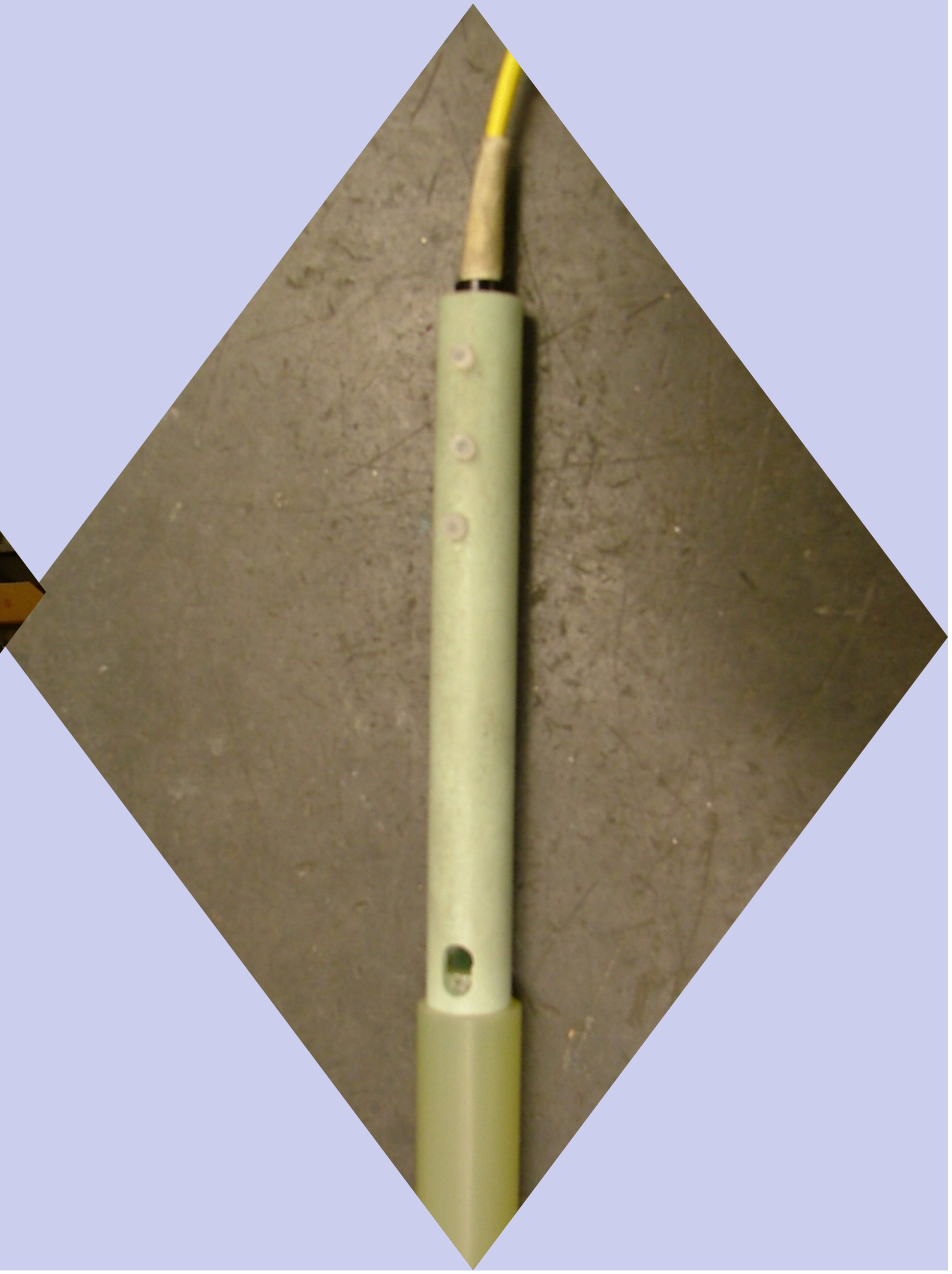

Velocity of tube wall
Sand compacted in air
Sand compacted at 3 Torr
Meters per second
70
60
50
40
30
20
10
0
1
6
11
16
21
26
31
36
41
46
51
56
61
66
71
76
81
86
91
96
101
106
111
116
121
microseconds

Buckling; modes & mechanisms

Buckling study samples

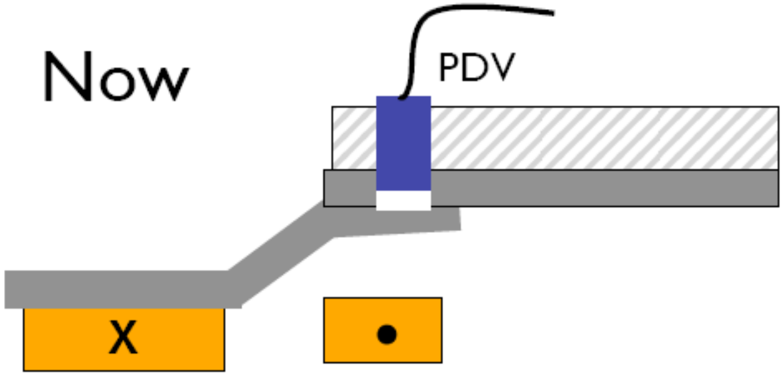
Periscope probe for tube i.d.

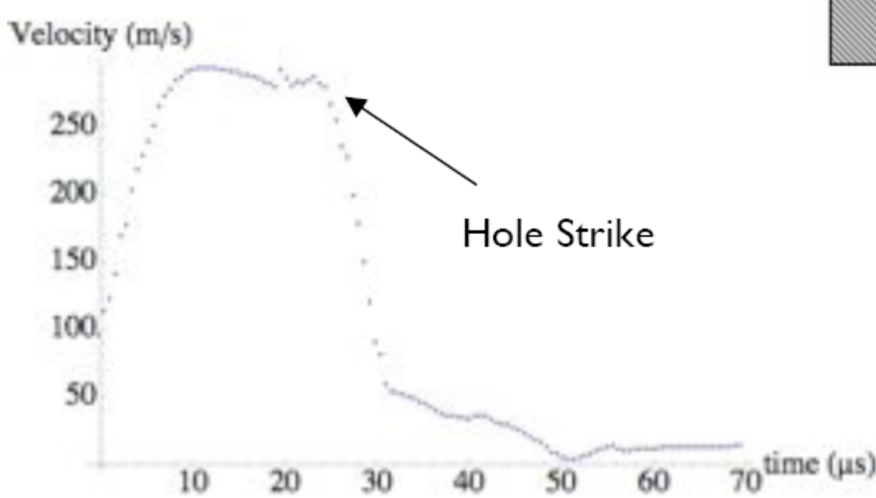




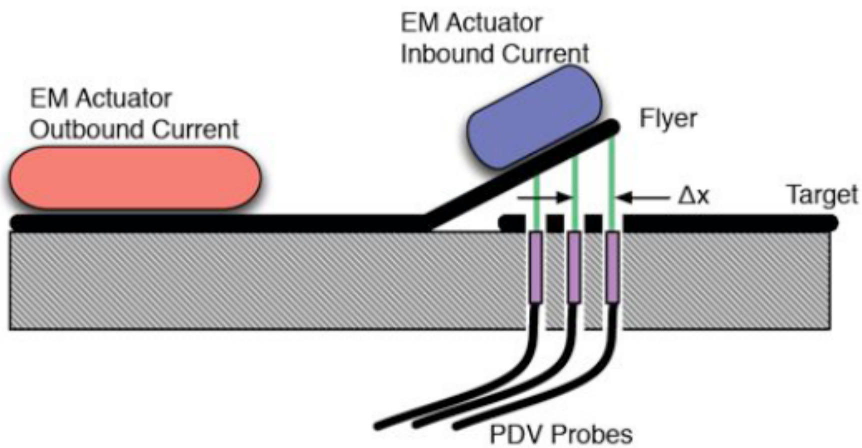
PDV Implementation with Welding

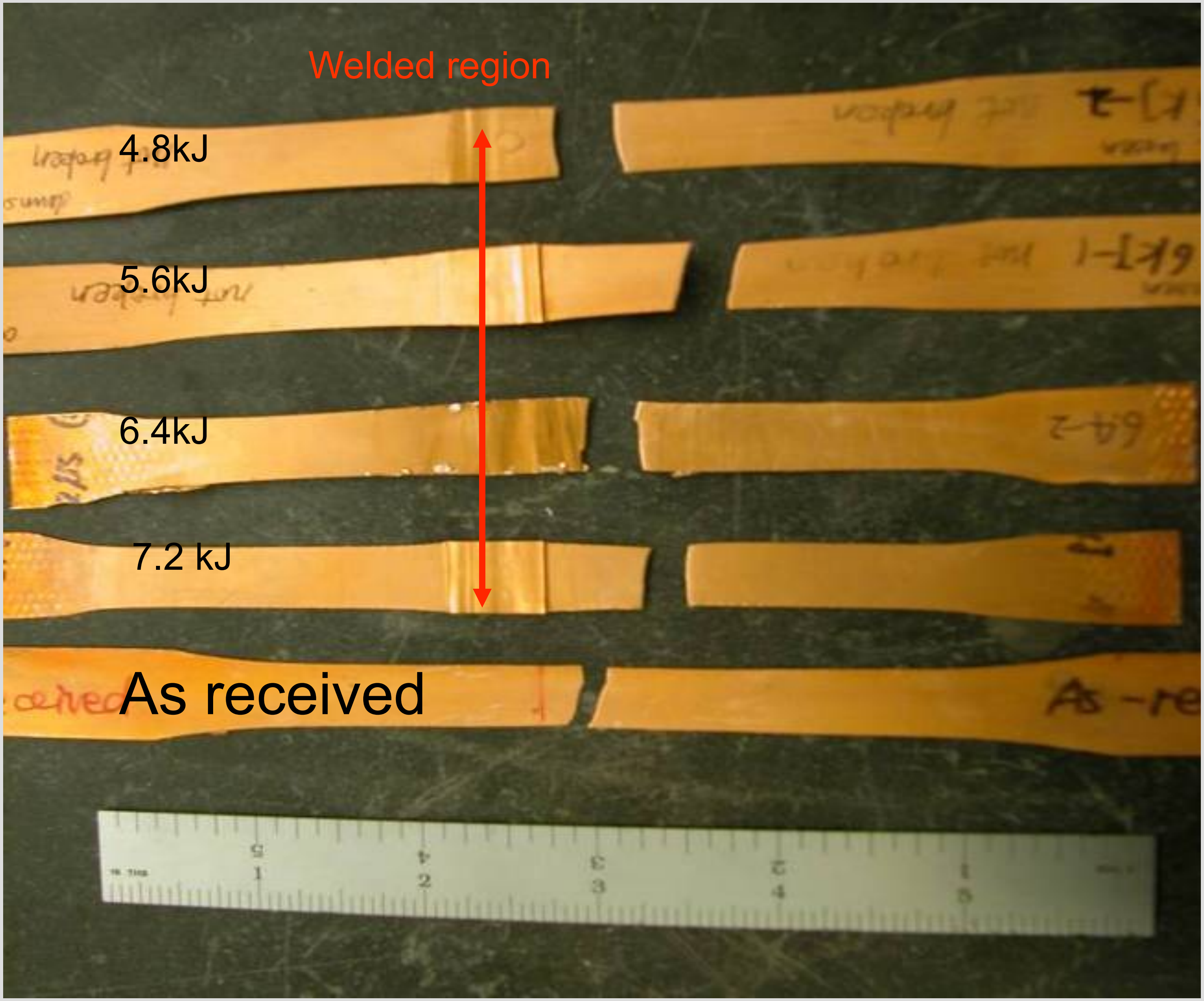
Now

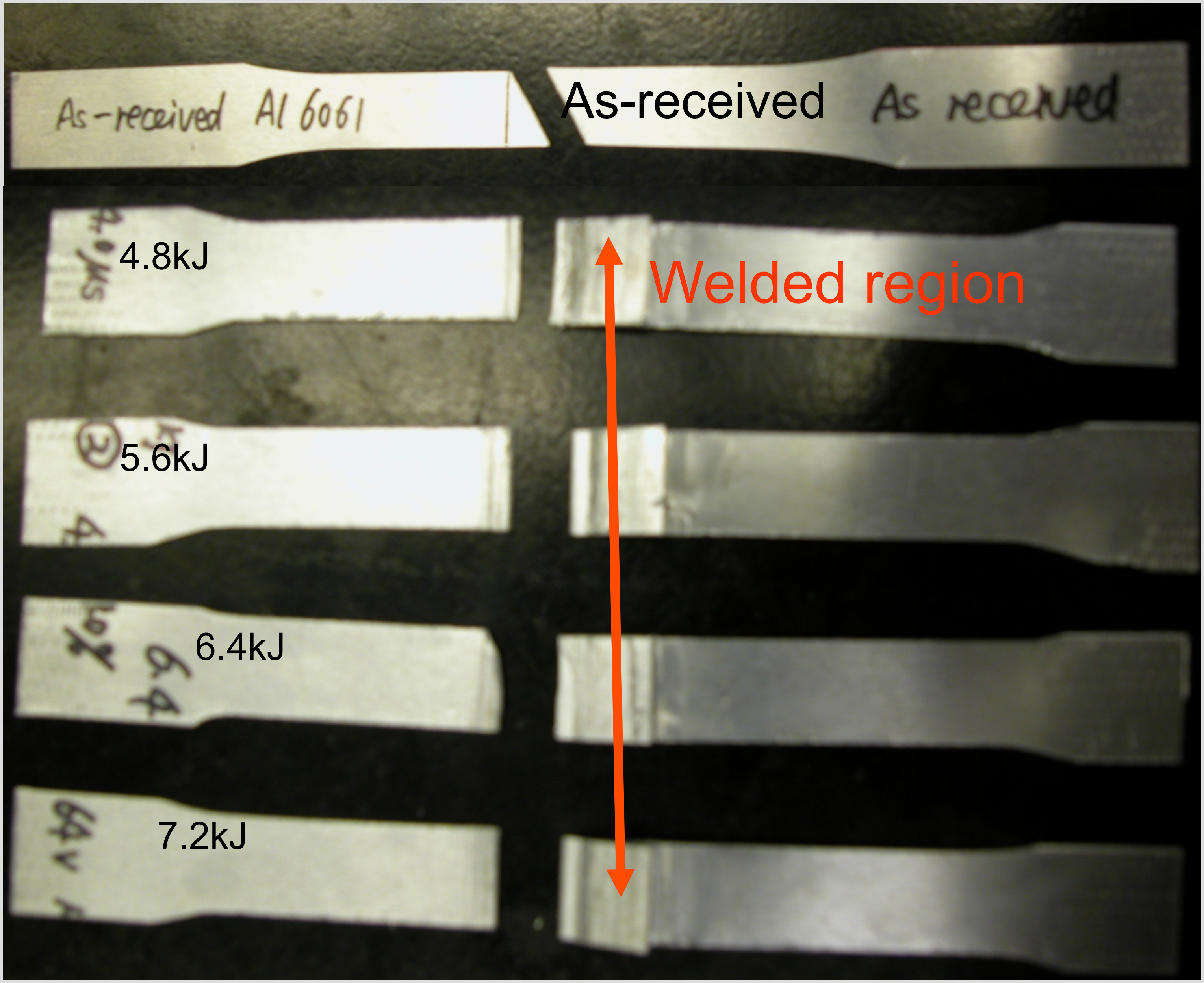




Later

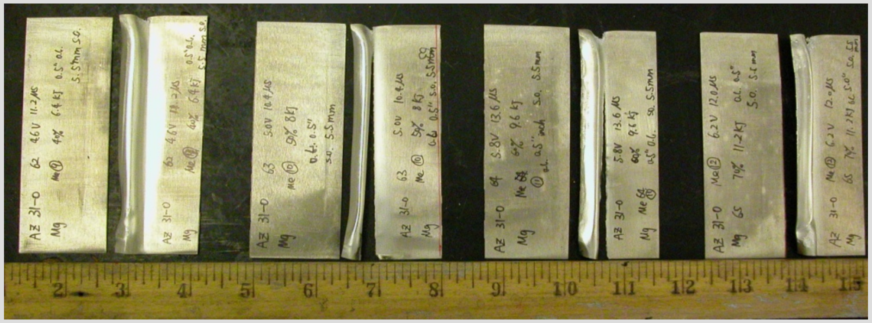



Welded region
4.8kJ
5.6kJ
6.4kJ
7.2 kJ
As received


As-received Al 6061
As-received
As received
4.8kJ
Welded region
5.6kJ
6.4kJ
7.2kJ

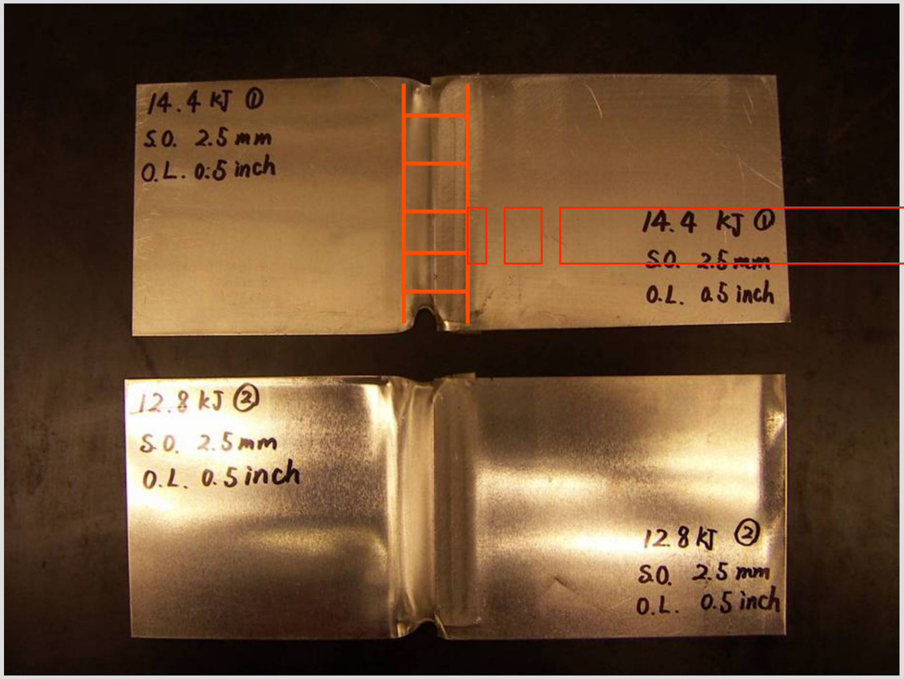
Trials on Dissimilar Welding

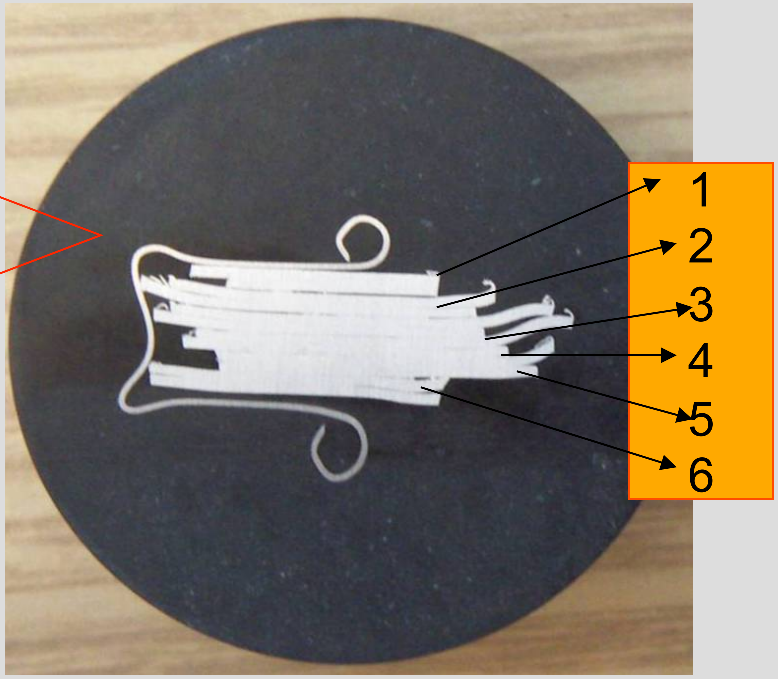
Al-Cu



Mg-Al

Preparation for Microscope Studies

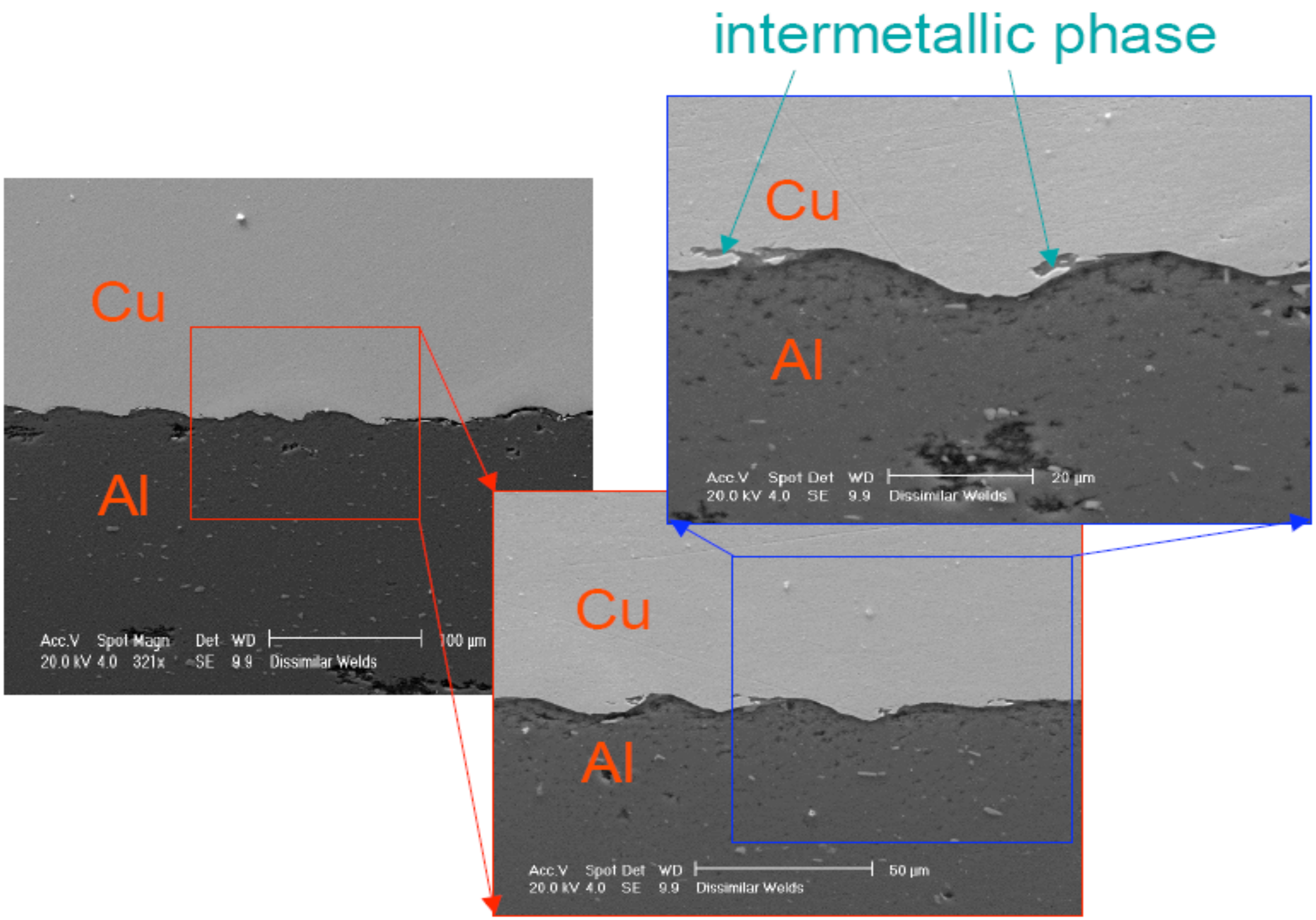




EM Welded Plates

Mounted Sample on Cross-section of Six Machine Cut Pieces

Lap Weld Cu to 6061Al



Concluding Remarks

- Much potential remains in high velocity forming.
- Velocity is the key design parameter.
- The Photon Doppler Velocimeter (PDV) makes these measurements much easier.


With my very
best wishes
to you
Wallace Beery


Best Regards
Glenn Daehn