A QUANTITATIVE NON-DESTRUCTIVE RESIDUAL STRESS ASSESSMENT TOOL FOR PIPELINES

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Generation 2 Materials Technology, LLC

OUTLINE

- Project Background
- Challenge
- Chosen Approach
- Tasks
- Results
- Discussion of Results
- Industry Interests and Desires
- Expected Outcome
- Recommended Additional Work

PROJECT BACKGROUND

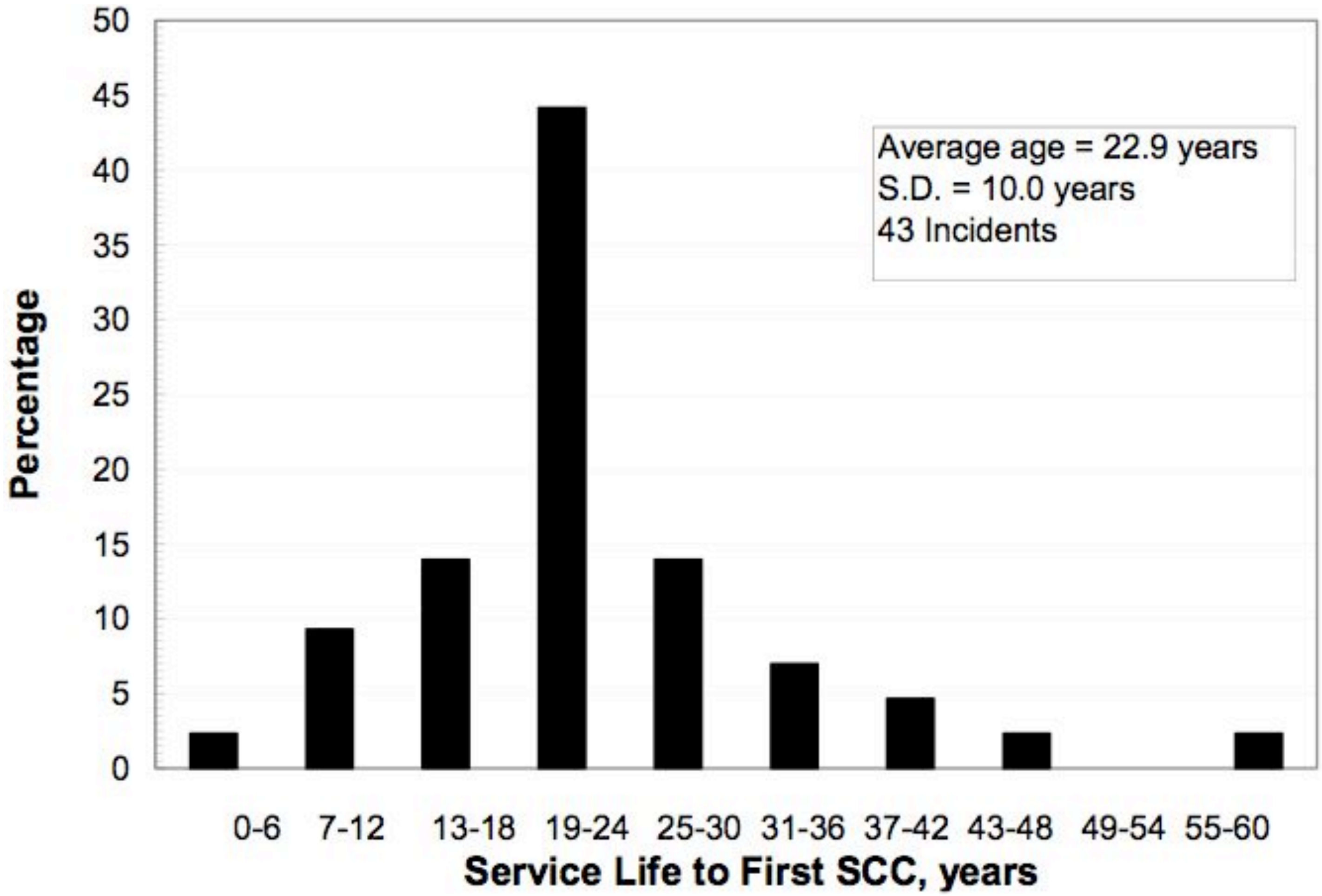
- Mechanical damage is the leading cause of pipeline failures.
- Mechanical damage exhibits a variety of features:
  - Denting
  - Removal of metal surface
  - Cold-work of the material below the surface
  - Cracking when the pipe is re-rounded by internal pressure
  - Residual stresses and strains due to plastic deformation
  - Coating damage

PROJECT BACKGROUND

- Mechanical damage occurs at different periods during construction of pipelines.
  - Wrinkles, ripples, or buckles commonly occur during laying and bending of the pipelines.
  - Dents, surface damage, and coating damage more often arise during removal and movement of third-party construction equipment [Maxey, 1986].

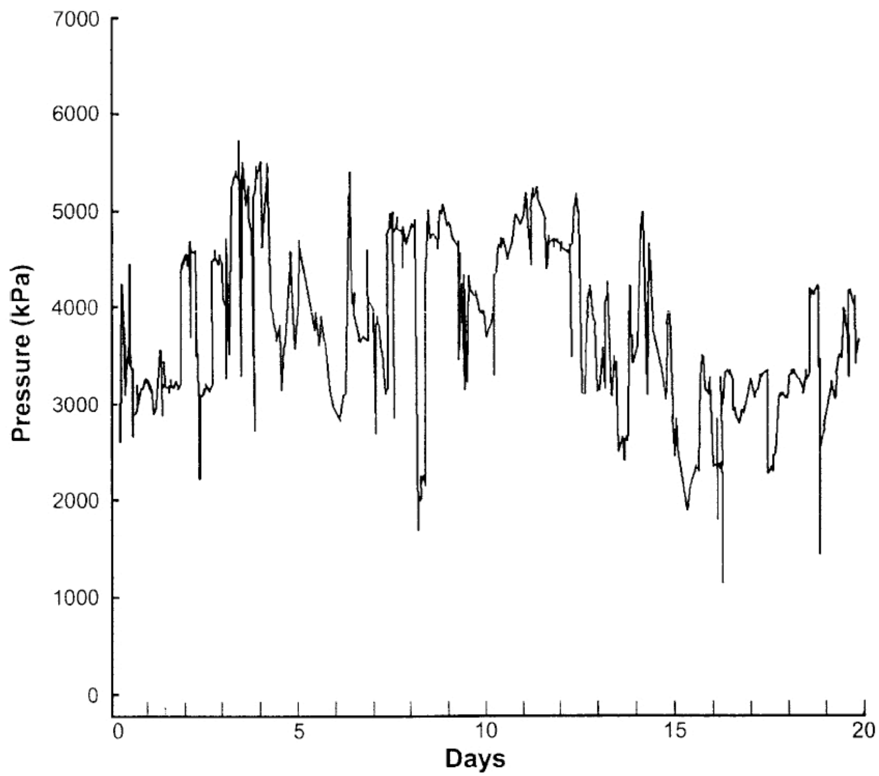
PROJECT BACKGROUND

- Mechanical damage can lead to immediate failure, but otherwise results in a delayed or time-dependent failure.



PROJECT BACKGROUND

- The mechanical damage and residual stresses associated with the damage lower the overall fatigue strength of the steel and its weldments.
- The size and shape of the flaw determines the level of stress necessary for crack initiation [Vuherer et al., 2007].



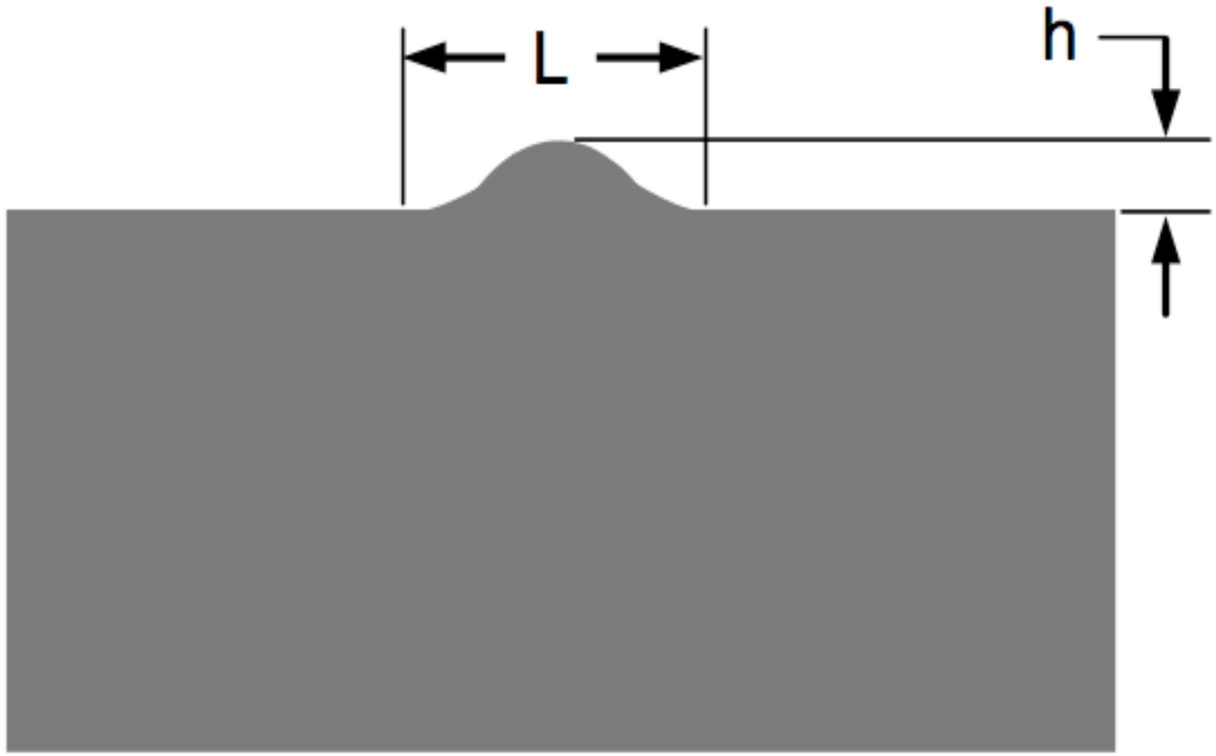
EXISTING DAMAGE INSPECTION PRACTICES

- The current practices for inspection of mechanical damage typically involves the use of inline inspection data from caliper tools followed by exterior inspection with UT and caliper tools to measure the angle of the dent.

	Plain dents		Dents at welds	Dents with cracks or gouges	Dents with corrosion
	Constrained	Unconstrained			
ASME B31.8	Up to 6% OD or 6% strain		Up to 2% OD or 4% max strain for ductile welds. No safe limit for brittle welds	No safe limit	Up to 6% OD for dent and metal loss, as per corrosion criterion
API 1156	No limit provided rock remains in place	Up to 6% OD. >2% requires a fatigue assessment	Up to 2% OD	Not allowed	Not considered
EPRG	Up to 7% at a hoop stress of 72% SMYS		Not allowed	Not allowed	Not allowed
PDAM	Up to 7% of pipe diameter		Not allowed	Assess as dent and defect combination	
Z662	Up to 6 mm for <102 mm OD Up to 6% for >102 mm OD		Not allowed	Not allowed	Not allowed

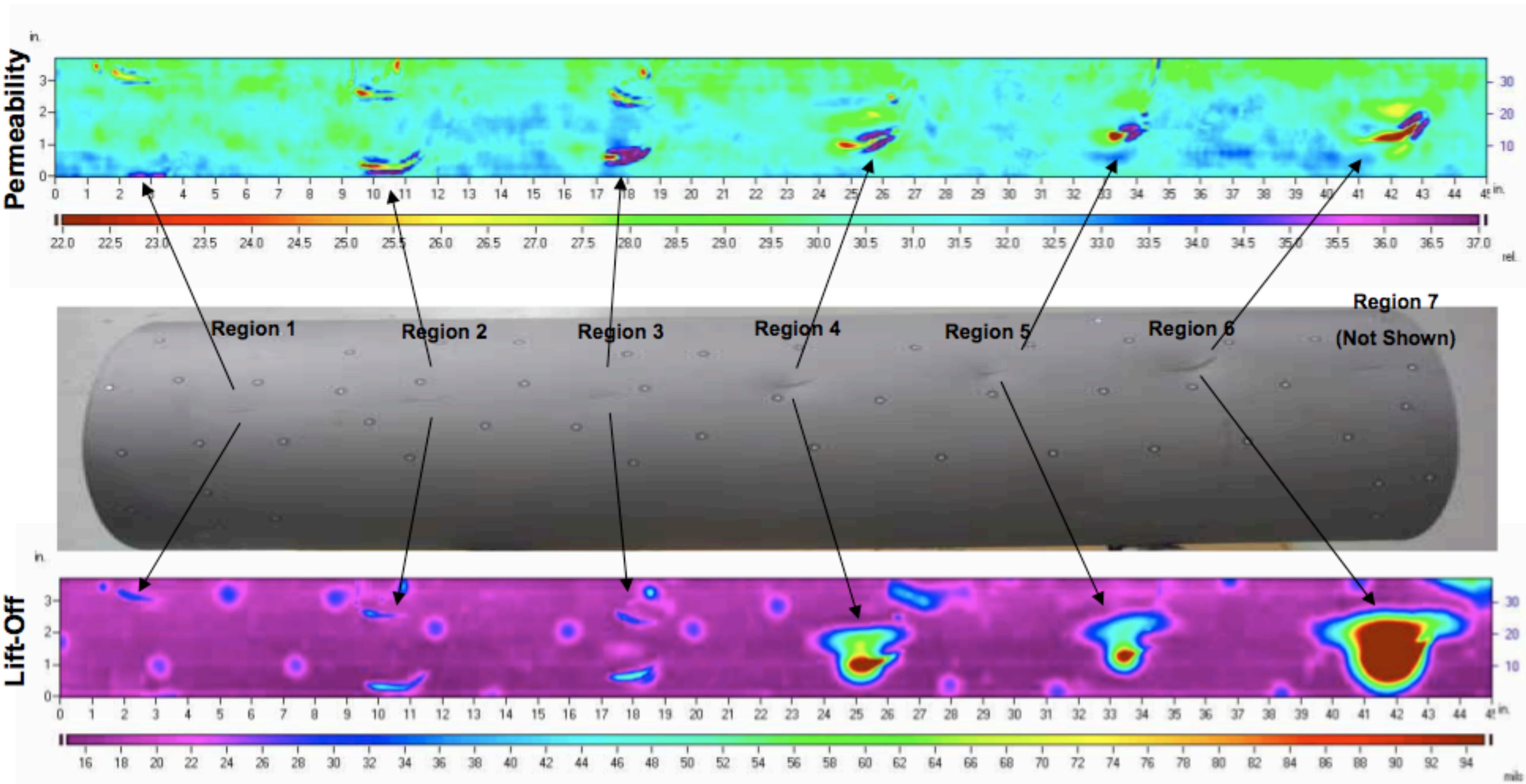
EXISTING WRINKLE BEND CRITICALITY CRITERIA

Height/Width Ratio ≡ h/L



[Alexander and Kulkarni, 2008]

ADVANCED EDDY CURRENT ARRAY DAMAGE DETECTION



N. Goldfine, 2010, PRCI Presentation, http://primis.phmsa.dot.gov/matrix/FilGet.rdm?fil=5529&nocache=1855

CHALLENGE

The challenge is to develop a real-time sensor that can provide through-thickness residual stress characterization of mechanically damaged pipelines because:

- Mechanical damage and deformations, including dents, bends, wrinkles, and other forms, are the leading cause of all pipeline failures.
- When mechanical damage or deformation of a pipe occurs, both macro and micro-scale gradients of stress are established around the damage area.
  - Depending on the size, shape, and the extent of the damage, these stresses can vary in complex ways both around and through the thickness of the damaged region.
- The geometry-based methods currently used should be based on actual critical stress intensity factors determined by design criteria, modeling, and other means instead of outdated geometric measurements.
- By mapping and characterizing the residual stresses around the entire region, any regions above or near the critical stress can be handled appropriately with a defined maintenance or operation program.

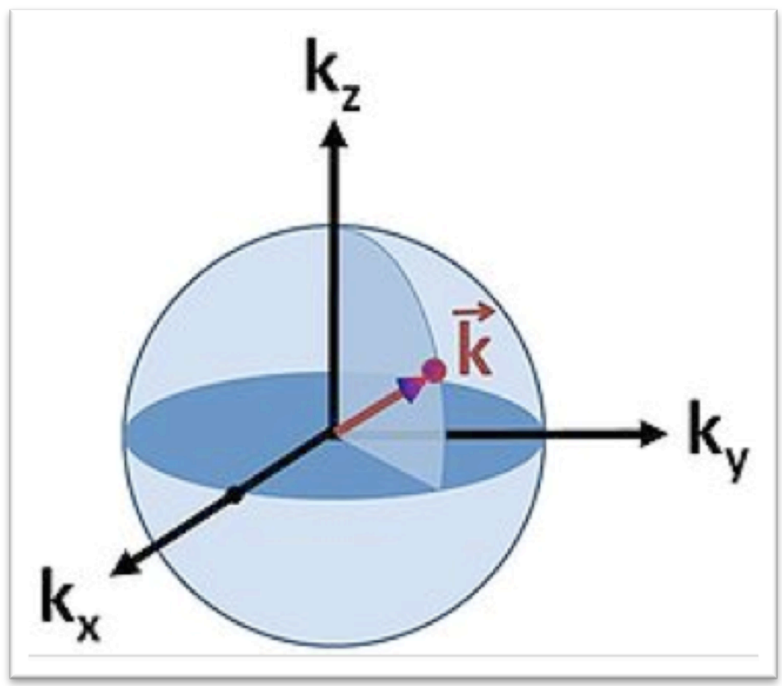
CHOSEN APPROACH

Next Generation Of Material Property Sensors

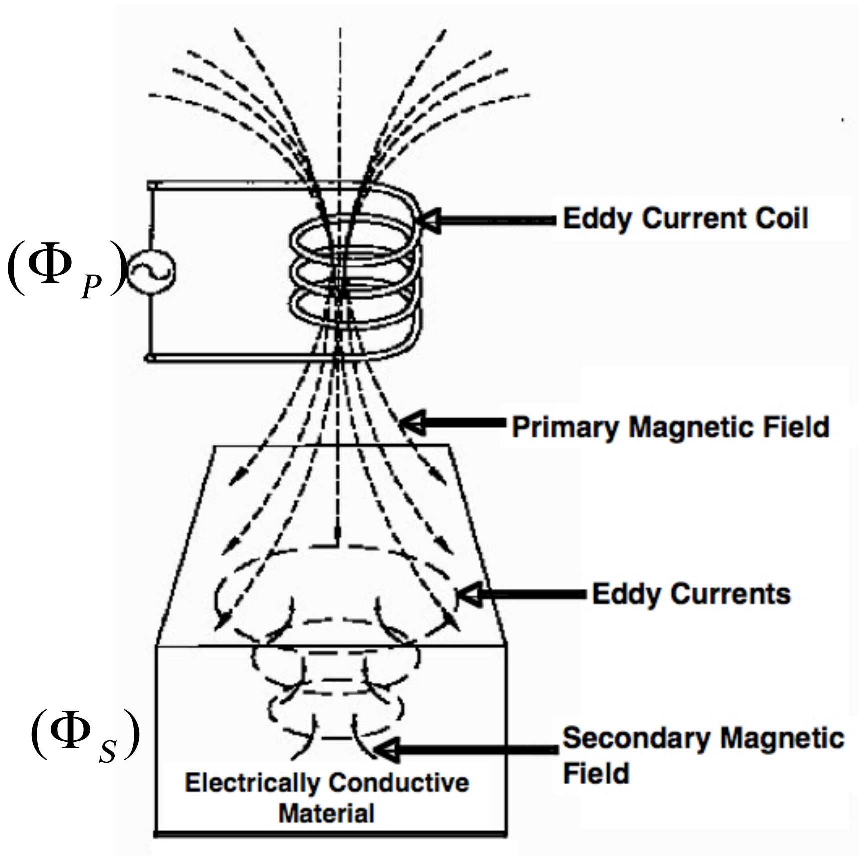
$$S = \left(\pm\frac{k}{e}\right)(27.1)\left(r+\frac{3}{2}\right)\left(\frac{m_e}{h^2}\right)\left(kTn^{\left(-\frac{2}{3}\right)}\right)$$

$$m_e = \frac{\hbar^2}{\left(d^2E/dk^2\right)}$$

- S — Electronic Property Measurement
- *r* — Scattering parameter
- *h* — Planck constant
- *k* — Boltzmann's constant
- *n* — Free electron concentration
- m_e — Effective mass (m*)



CHOSEN APPROACH



B.P.C. Rao

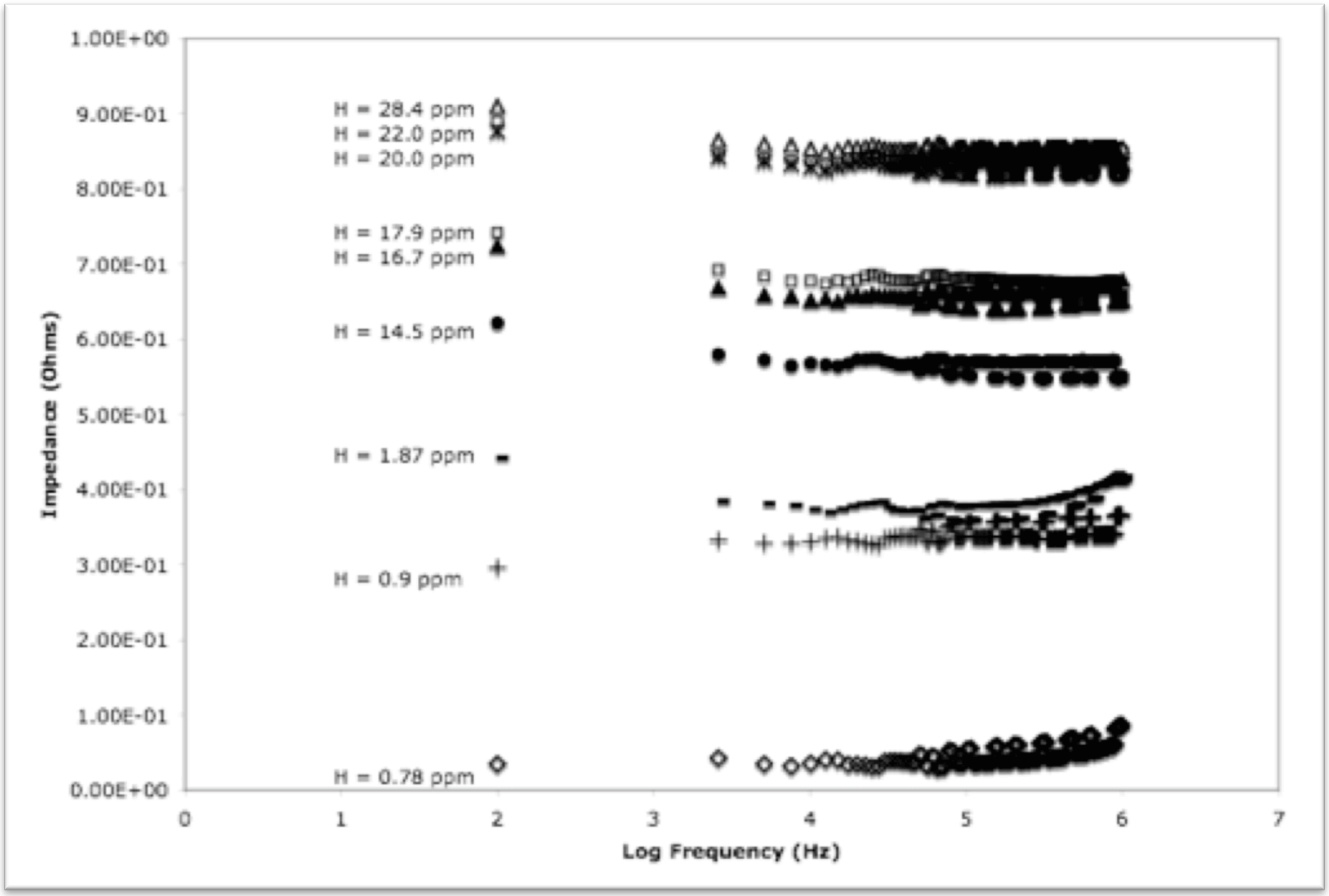
$$\underbrace{\int E \bullet dl}_{\textbf{EMF}} = \underbrace{-\frac{d\phi}{dt}}_{\textbf{Flux}}$$

$$\Phi_E = \Phi_P - \Phi_S$$

$$Z = \sqrt{\left(\omega L - \frac{1}{\omega C}\right)^2 + R^2}$$

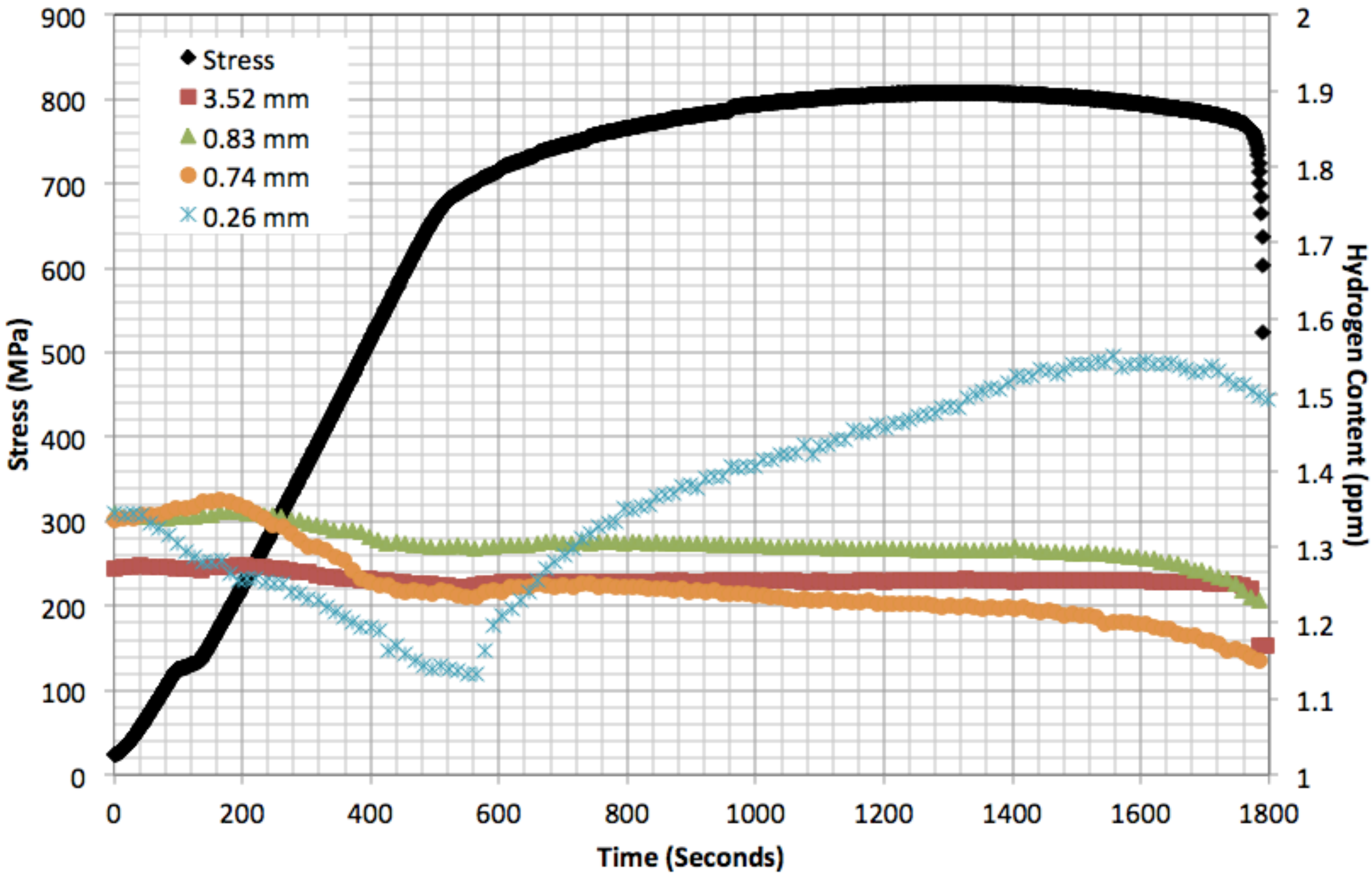
SUPPORT OF CHOSEN APPROACH

Electromagnetic Hydrogen Measurements On Pipeline Steel



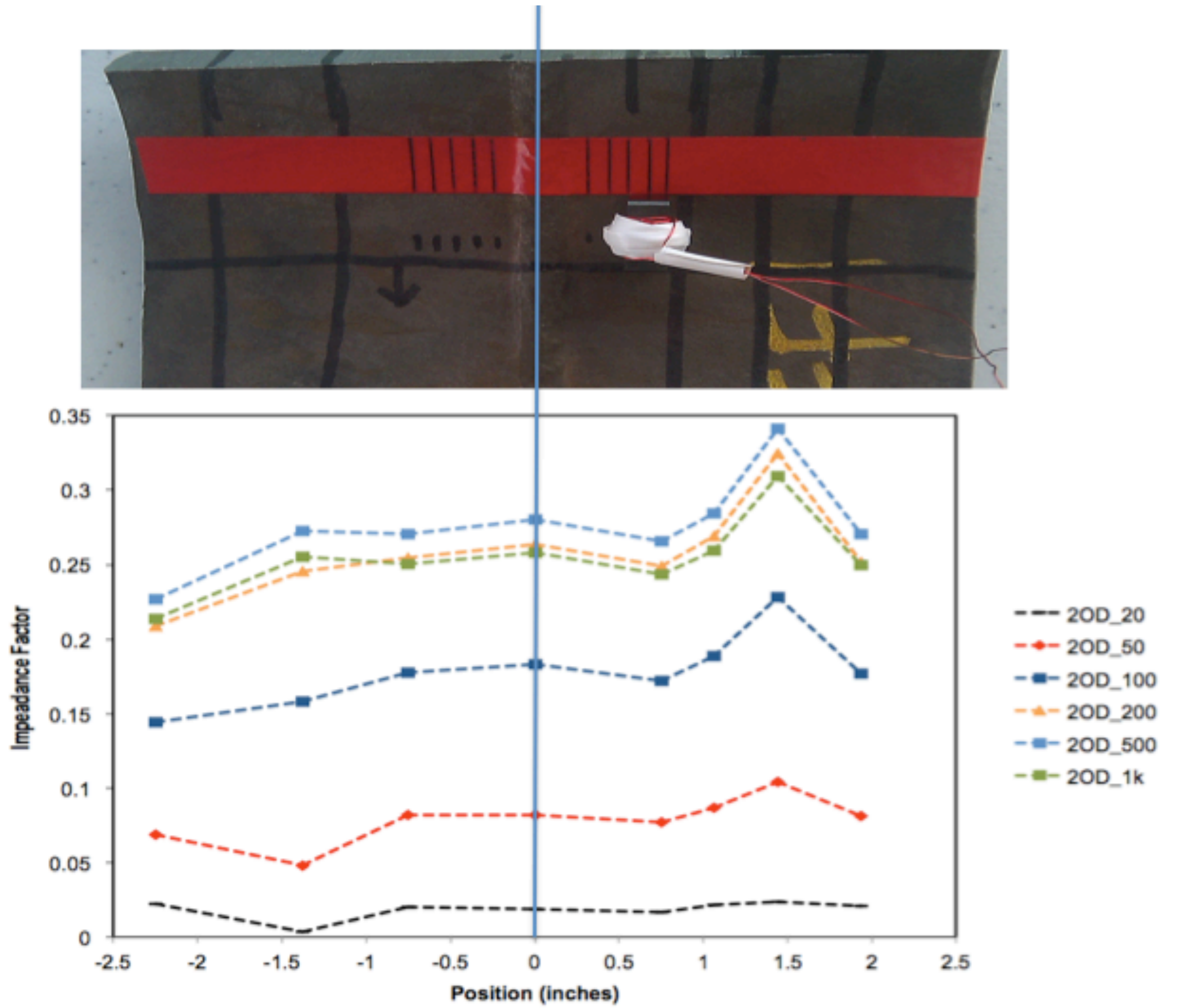
Lasseigne, 2006

SUPPORT OF CHOSEN APPROACH



Lasseigne et al, 2011

SUPPORT OF CHOSEN APPROACH



SUPPORT OF CHOSEN APPROACH

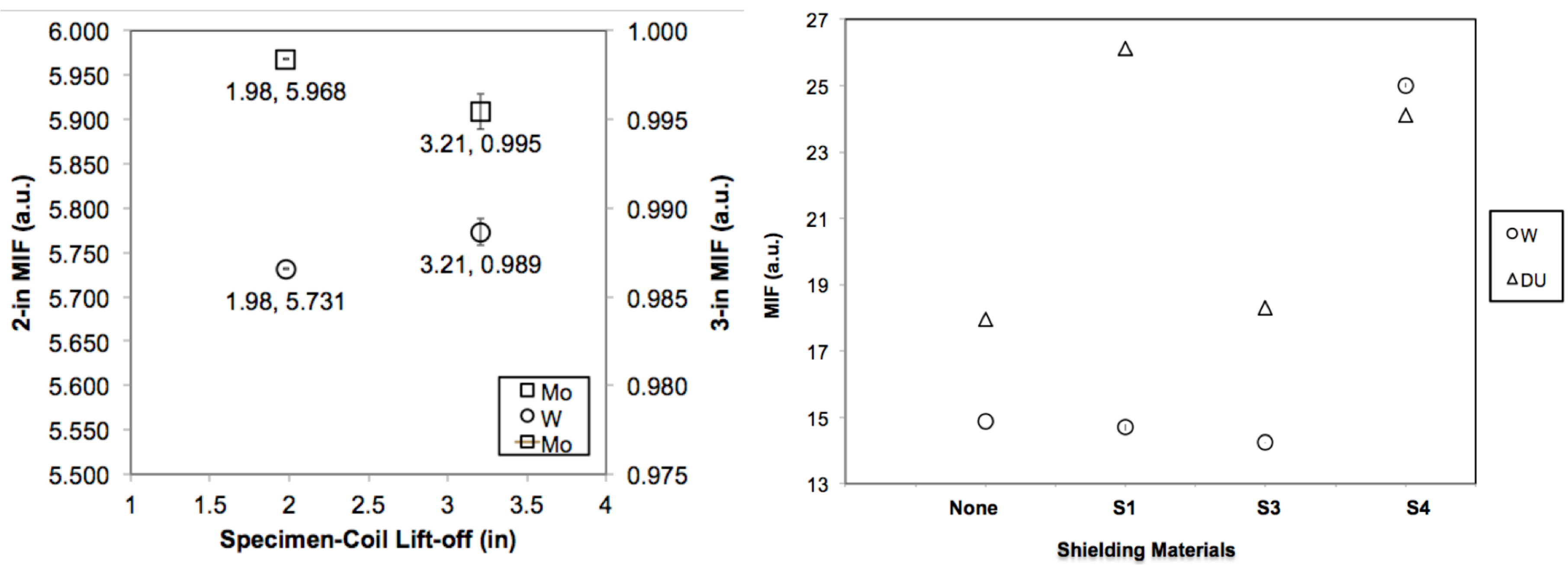
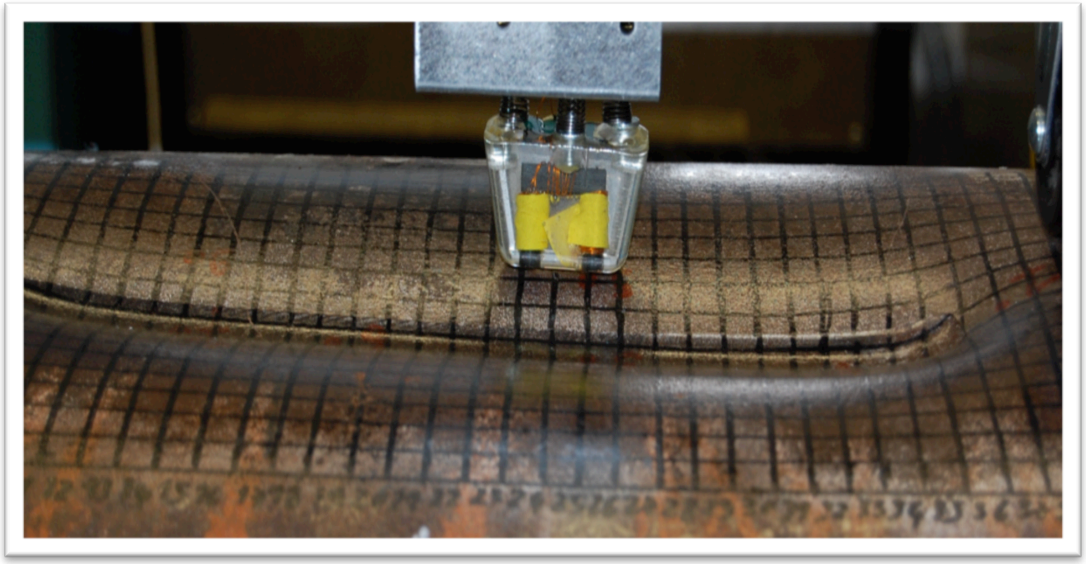
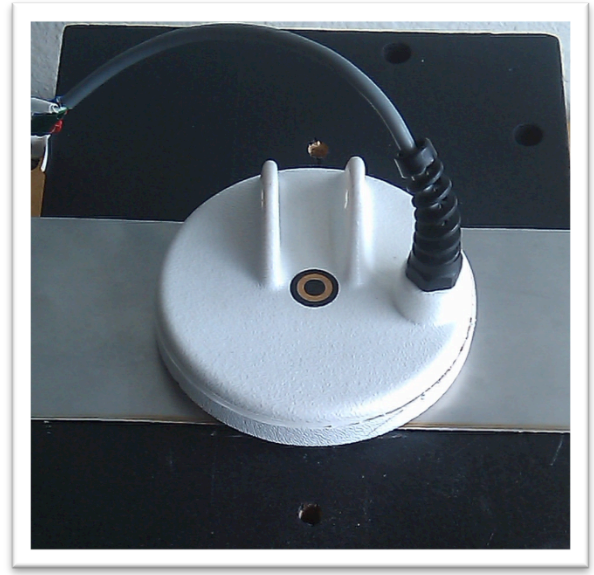
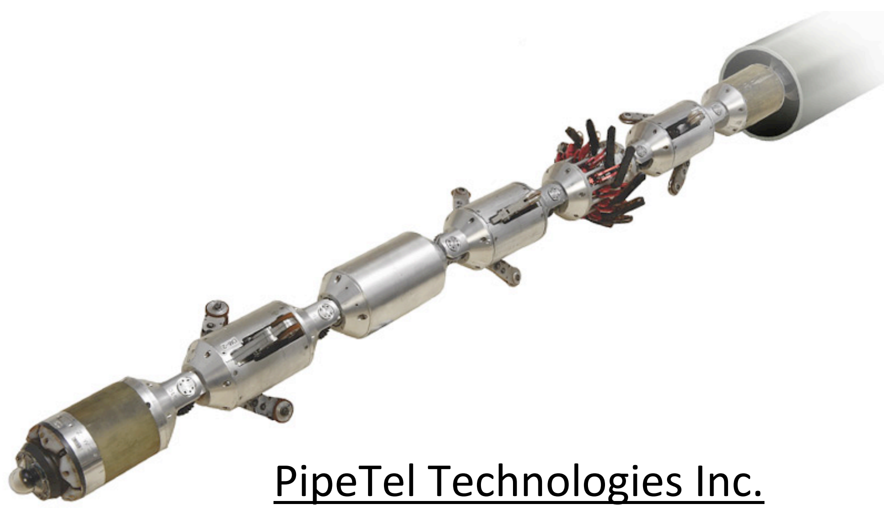


Figure 1: (a) Electromagnetic measurements on tungsten and molybdenum at two different stand off distances of 2 and 3 inches with austenitic stainless steel shielding. (b) Shielded electromagnetic measurements on molybdenum, tungsten, and depleted uranium using three different shielding materials with standoff of approximately 1.25 inches.

CHOSEN APPROACH







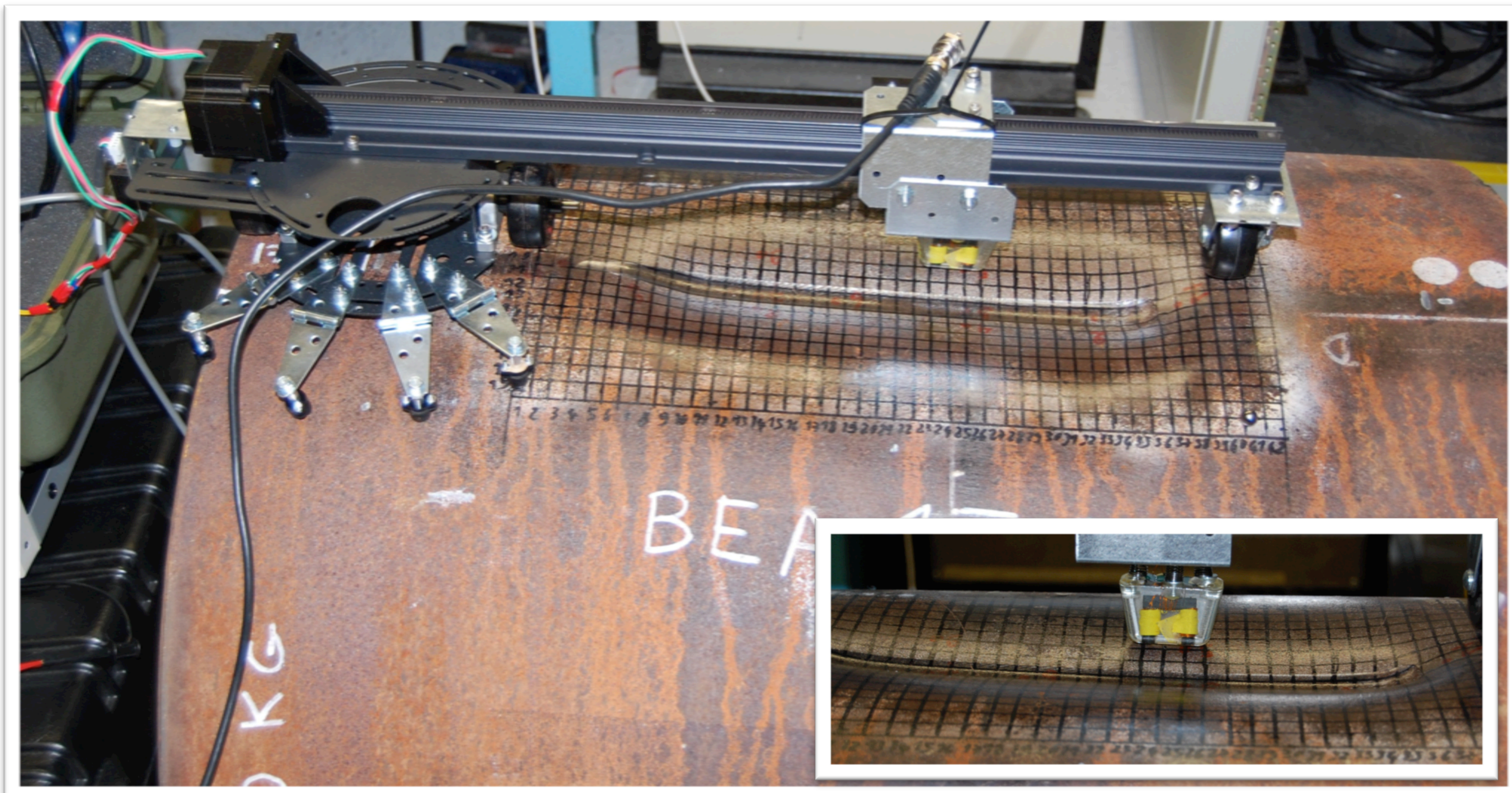
PipeTel Technologies Inc.

TASKS

1. Development of the electromagnetic (includes low frequency impedance) analysis probe system to be able to assess residual stress at mechanically damaged regions;
2. Determination of the residual stress levels present in mechanically damaged pipelines steels;
3. Determination of the ability for low frequency impedance to monitor residual stress at the levels present in mechanically damaged pipeline steels;
4. Demonstration of the ability of electromagnetic measurements to measure the residual stress as a function of time in pipeline steel;
5. Determination of the repeatability of electromagnetic measurements as a function of damage severity; and
6. Demonstration of the use of an electromagnetic monitoring to assess damage severity.

TASK 1

- Development of the electromagnetic (includes low frequency impedance) analysis probe system to be able to assess residual stress at mechanically damaged regions;



TASK 2

- Determination of the residual stress levels present in mechanically damaged pipelines steels

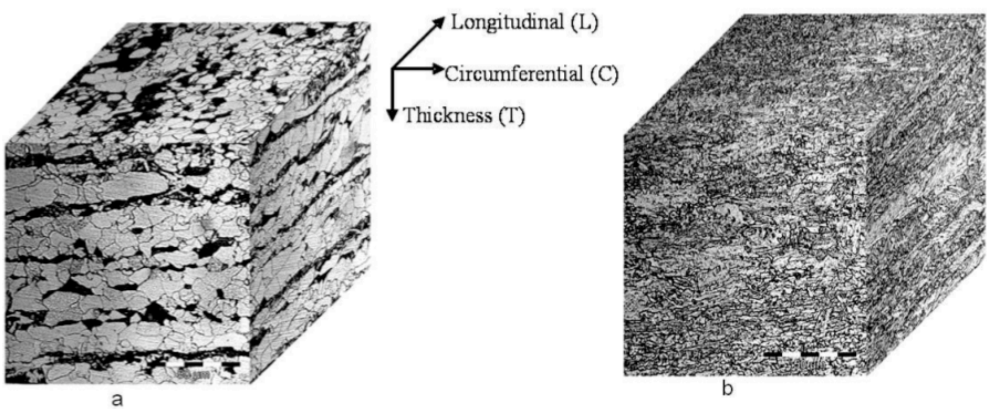
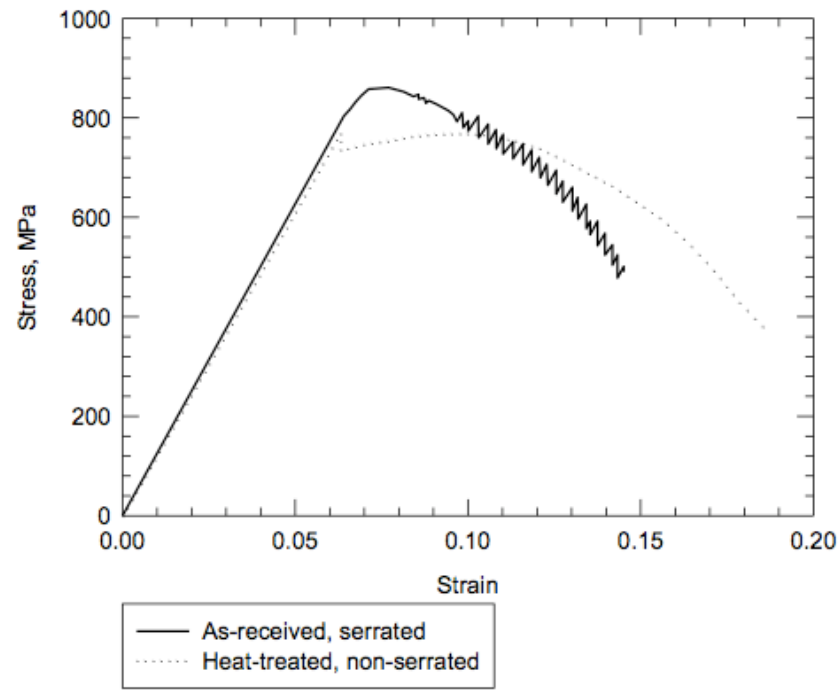
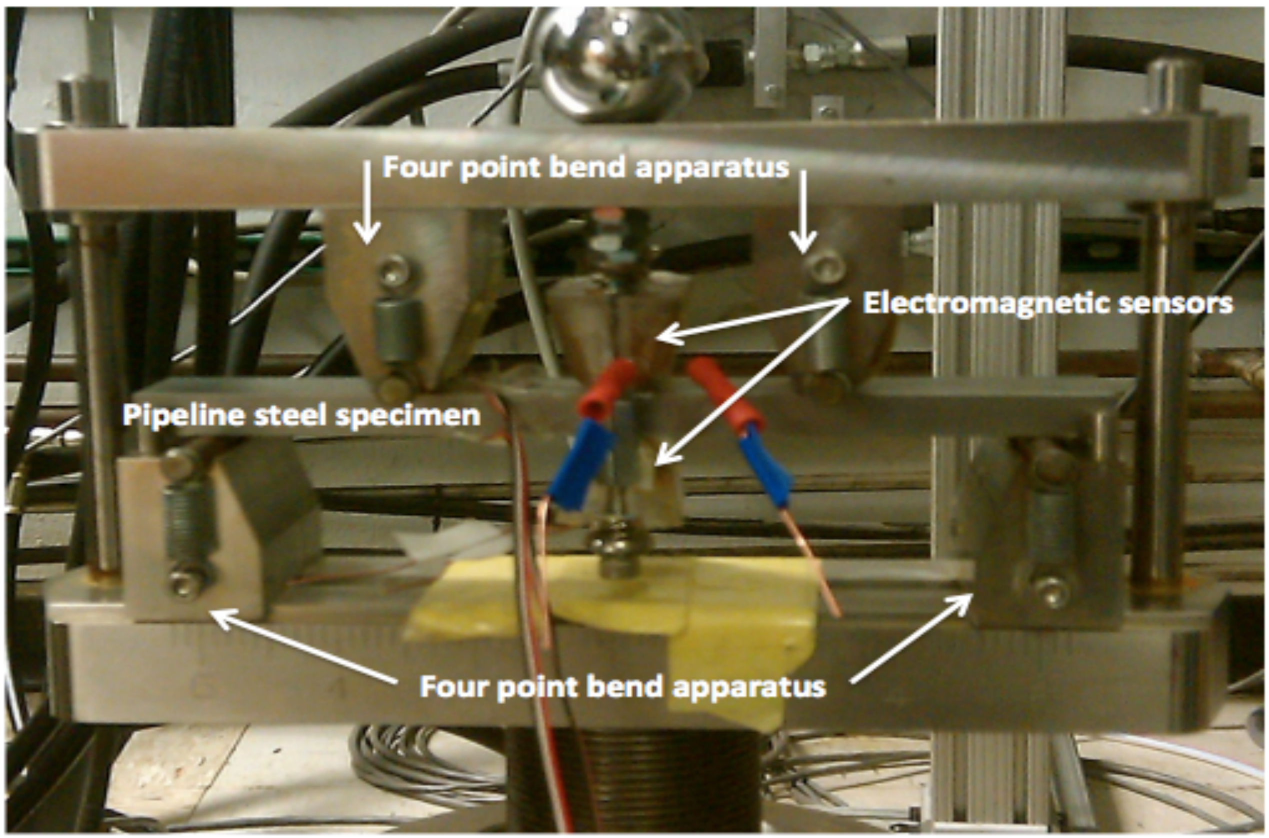


Figure 1. Microstructure (magnification 458 times) of: (a) grade X65 and (b) grade X100

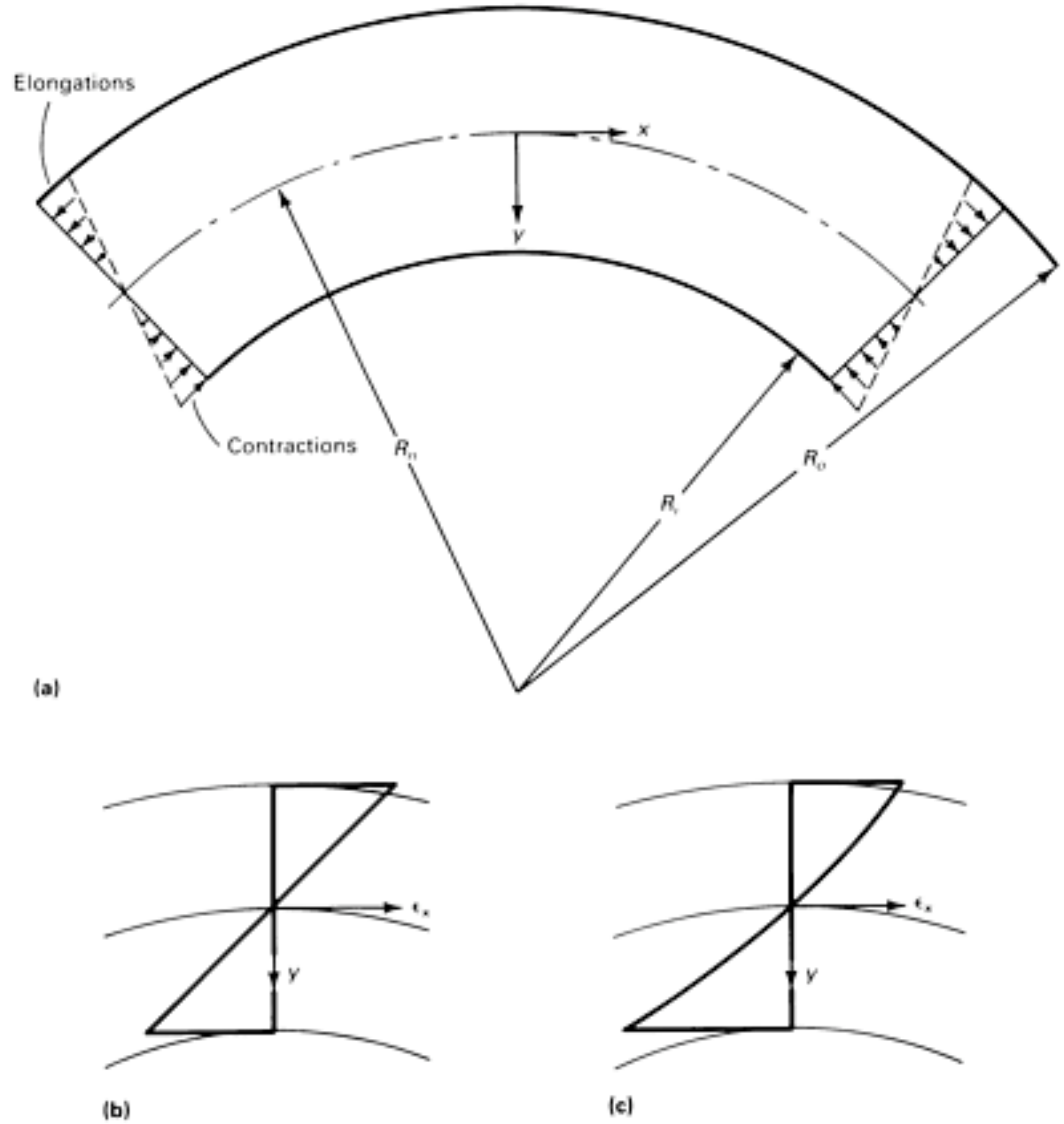


TASKS 3 AND 4

- Determination of the ability for low frequency impedance to monitor residual stress at the levels present in mechanically damaged pipeline steels;
- Demonstration of the ability of electromagnetic measurements to measure the residual stress as a function of time in pipeline steel;

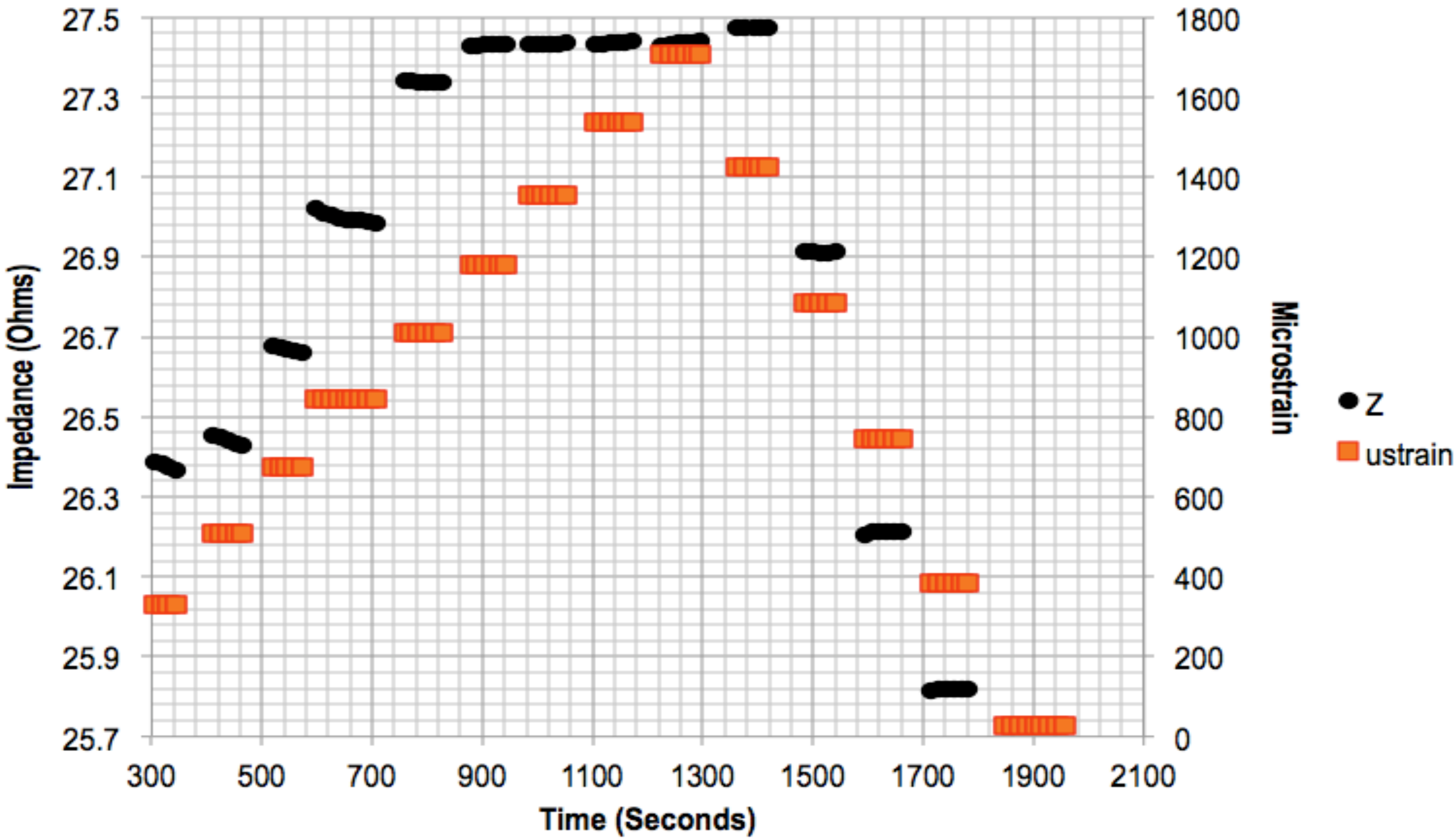


FOUR POINT BEND RESIDUAL STRESS DISTRIBUTION

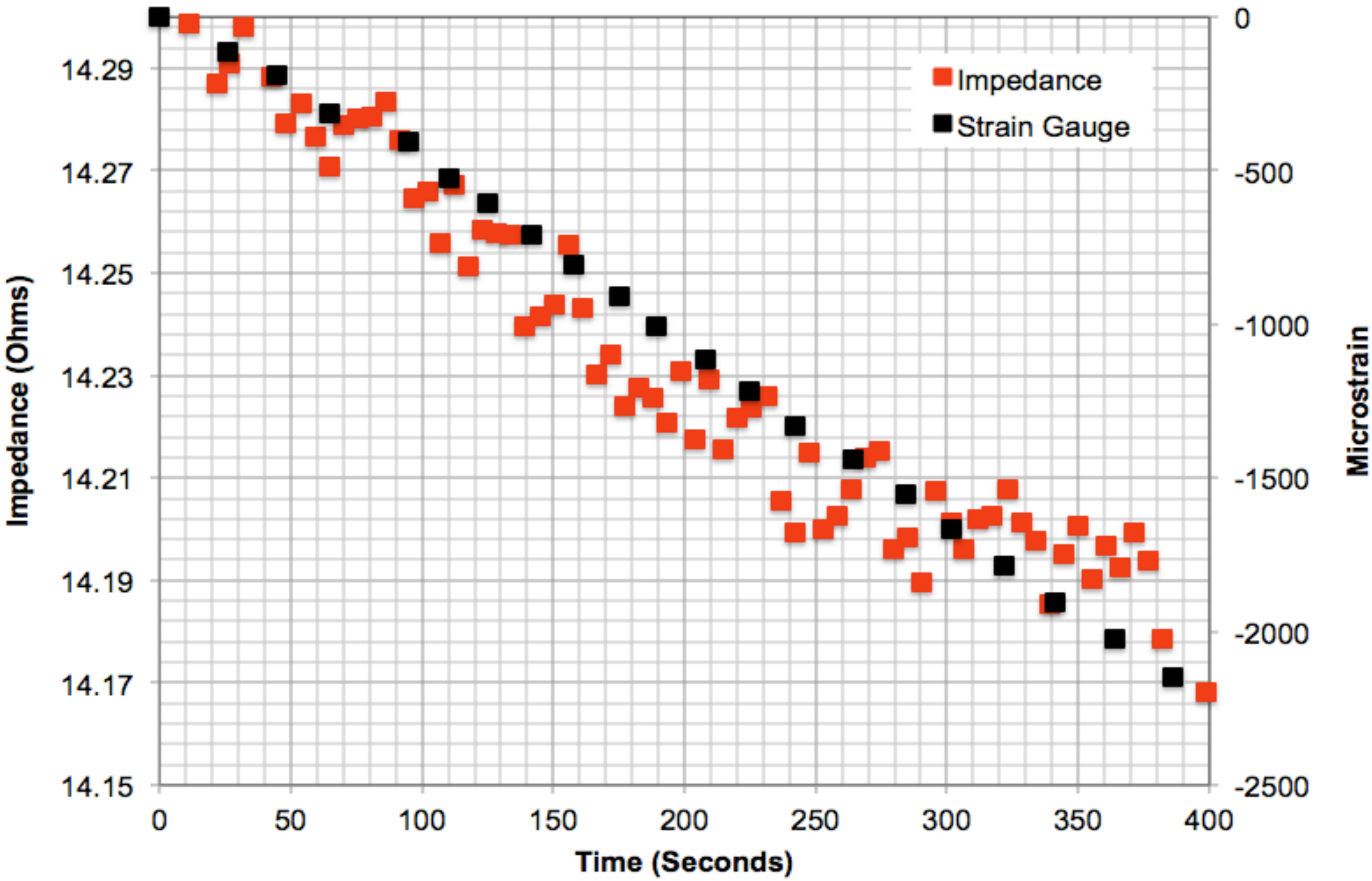


(ASM Handbook Volume 8: **Stress-Strain Behavior in Bending** P. Dadras, Wright State University)

FOUR POINT BEND TENSION



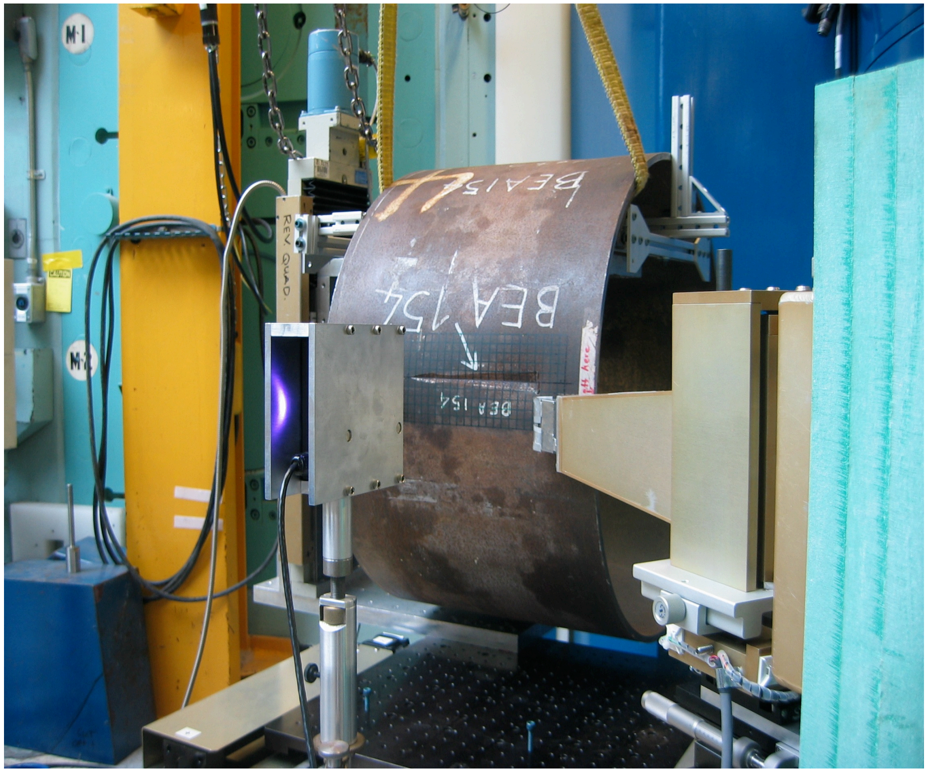
FOUR POINT BEND COMPRESSION

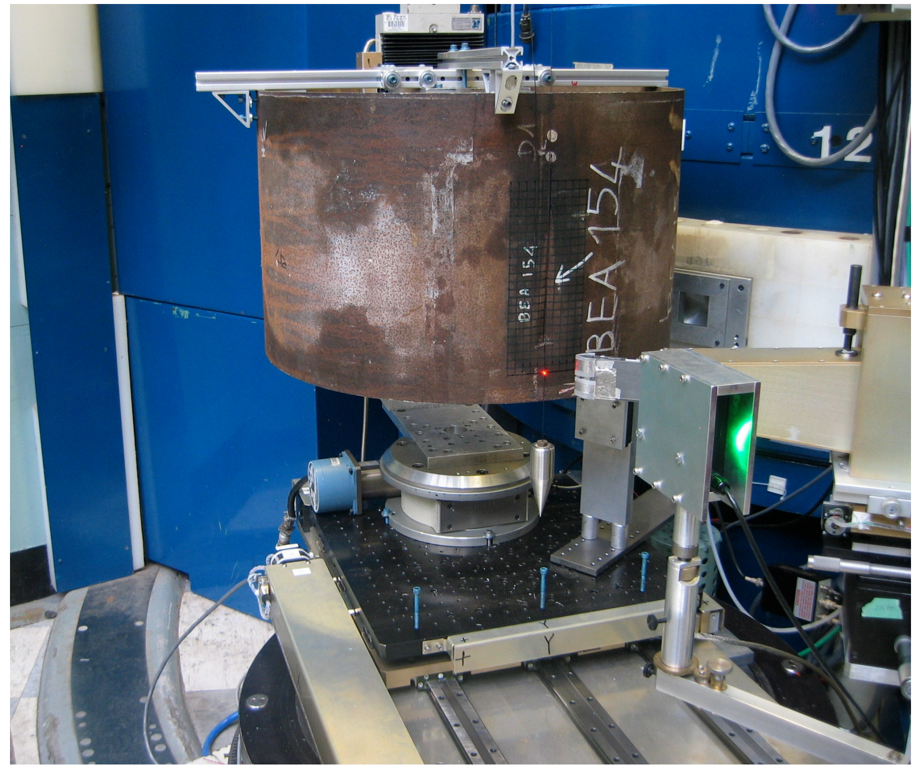


TASKS 5 AND 6

- Determination of the accuracy and repeatability of electromagnetic measurements as a function of damage severity; and
- Demonstration of the use of an electromagnetic monitoring system to assess damage severity.

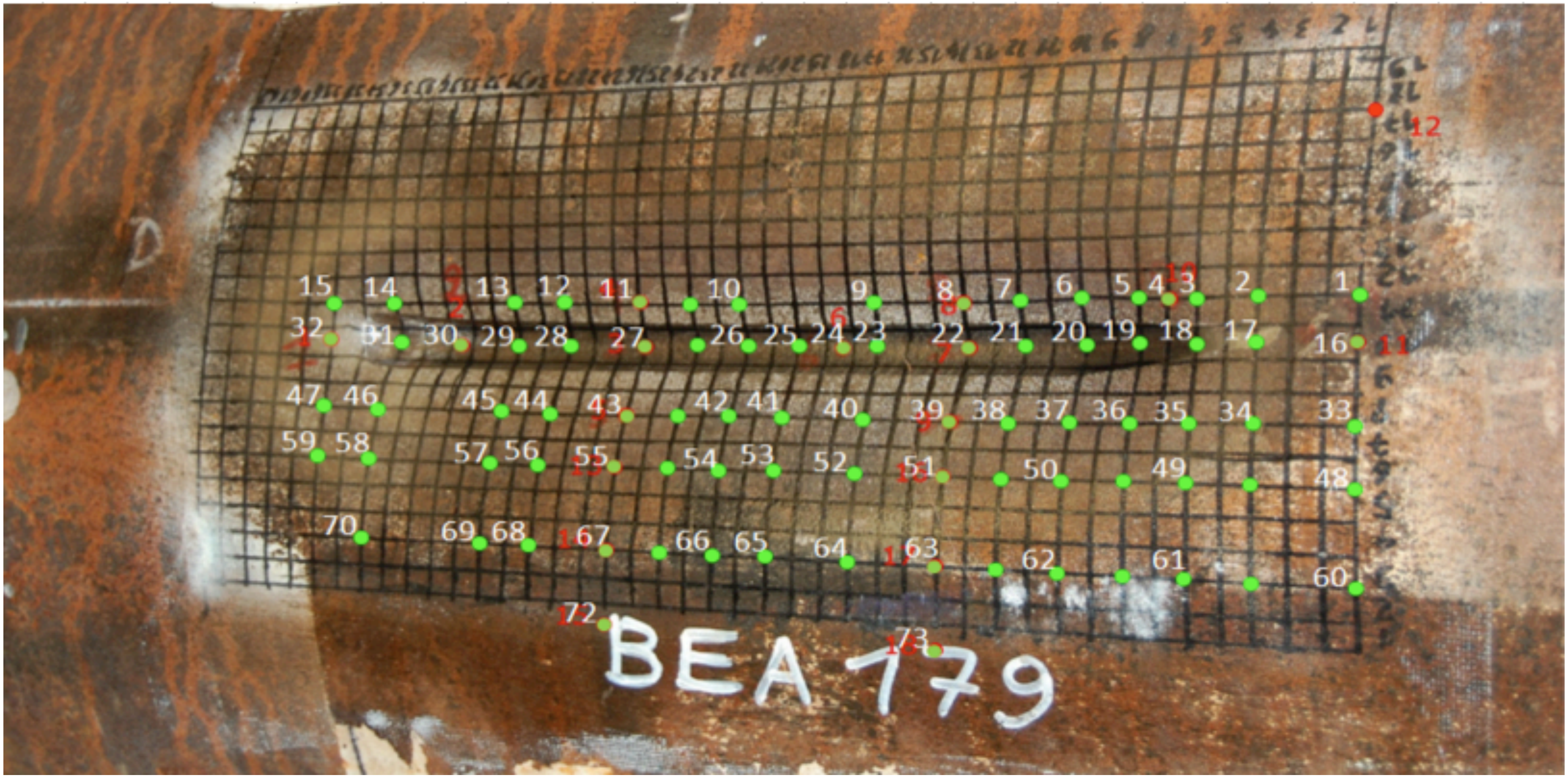
NEUTRON DIFFRACTION MEASUREMENTS





- Neutron diffraction is the only method comparable to an electromagnetic residual stress sensor to determine residual stress as a function of depth into the material.
- X-ray diffraction type measurements are insufficient because only provides surface residual stress measurement.

NEUTRON DIFFRACTION MEASUREMENTS



NEUTRON DIFFRACTION MEASUREMENTS

Stresses (MPa)						
Sum	Position	Depth	Hoop	Axial	Radial	Axial Stress in ksi
312.755	2	2	43	151	-37	21.60364199
3.555451	2	4.75	13	3	-14	0.49910063
-311.169	2	7.5	-2	-222	69	-31.66021204
215.6362	3	2	30	123	-45	17.56275484
-23.1897	3	4.75	-5	-56	49	-7.930906078
-1636.89	3	7.5	-245	-427	-146	-61.03394401
480.3126	4	2	85	191	-36	27.2437884
-361.669	4	4.75	-73	-125	17	-17.90214256
-1565.38	4	7.5	-260	-365	-158	-52.0975687
748.0225	5	2	165	211	-1	30.11923759
19.70892	5	4.75	20	-77	67	-10.97486523
-1172.69	5	7.5	-160	-293	-133	-41.87750491
284.2362	6	2	105	72	-35	10.22066551
-150.181	6	4.75	38	-137	24	-19.5491077
-391.269	6	7.5	61	-223	-34	-31.81967
113.5882	7	2	83	15	-42	2.141368142
-172.171	7	4.75	51	-156	18	-22.28535008
-1326.95	7	7.5	-197	-370	-97	-52.79739142
-127.927	8	2	64	-60	-68	-8.573149254
-573.306	8	4.75	-46	-231	-10	-32.95431789
-779.906	8	7.5	-68	-309	-12	-44.19206831
-478.092	9	2	-10	-126	-103	-18.01054529
-602.566	9	4.75	-44	-257	0	-36.7770002
-295.72	9	7.5	56	-253	49	-36.15274887
-1057.82	10	2	-118	-291	-119	-41.63794206
-793.849	10	4.75	-66	-341	10	-48.73069512
-616.16	10	7.5	-55	-271	18	-38.6827859
-1078.73	11	2	-97	-316	-126	-45.20735931
-1077.99	11	4.75	-103	-396	-40	-56.57471509
-831.817	11	7.5	-39	-326	-51	-46.57075368
-590.528	16	2	-97	-37	-162	-5.256363212
-21.4843	16	4.75	63	-49	-25	-7.058095921
258.8714	16	7.5	59	-50	121	-7.118684282

RESULTS

WRINKLE BEND RESULTS

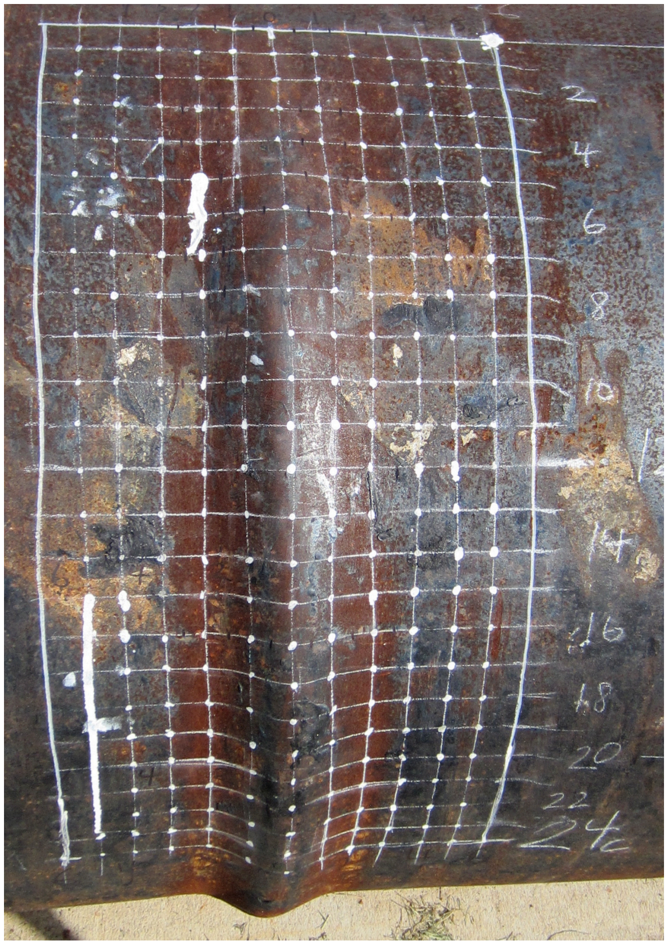
- Diameter of Pipe: 30 inches
- Length of all seven wrinkle bends: 48 inches
- Height of all seven wrinkle bends: 0.75 inches
- Width of all seven wrinkle bends: 4 inches
- h/L (height to width) ratio for all seven wrinkle bends: 0.1875

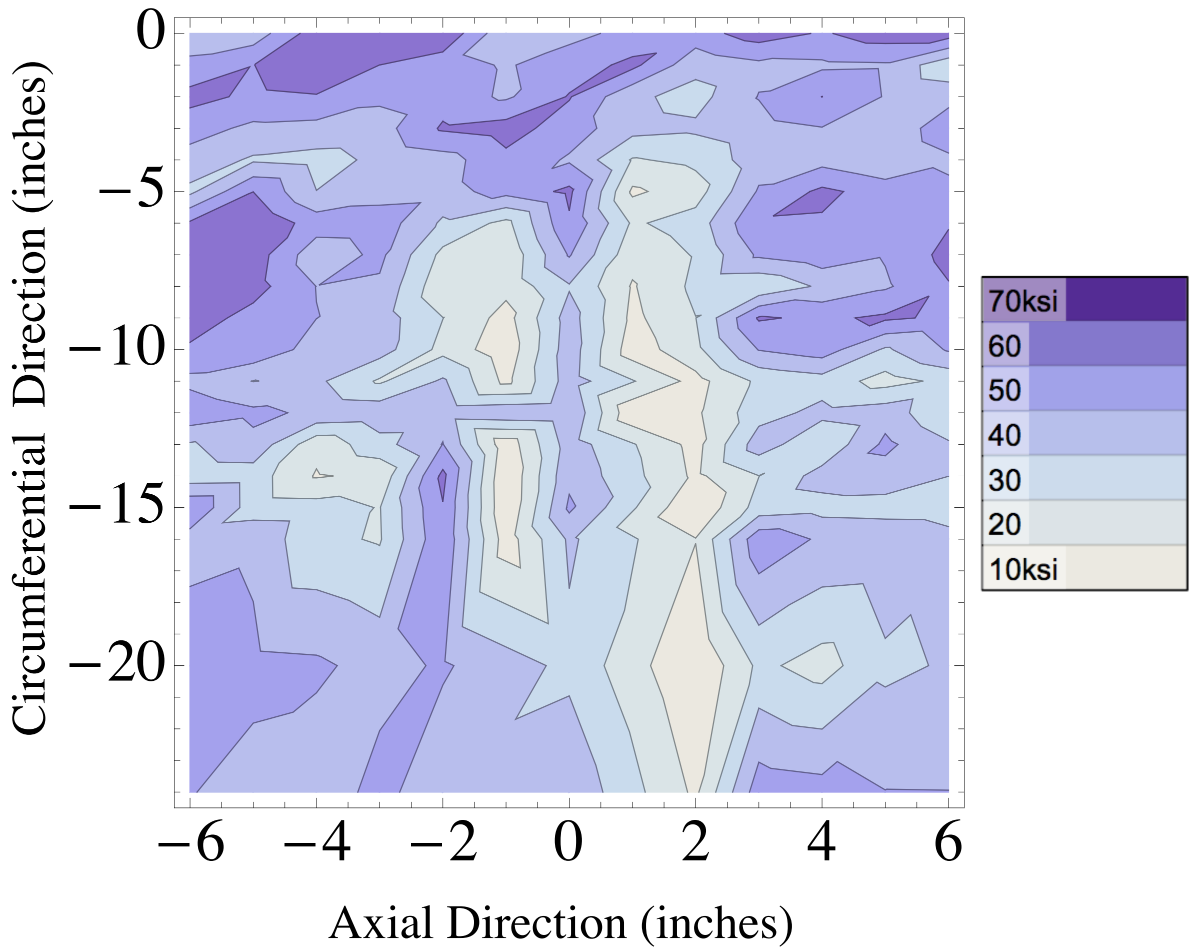
CHEMICAL ANALYSIS

C	Si	Mn	P	S	Ni	Cr	Mo
.28	.07	1.03	.01	.03	.06	.01	.001
V	**Cu**	**W**	**Ti**	**Sn**	**Co**	**Al**	**B**
.002	.03	<.001	.001	<.001	.02	.003	<.001
Nb	**Zr**						
.003	.003						

WRINKLE BEND RESULTS

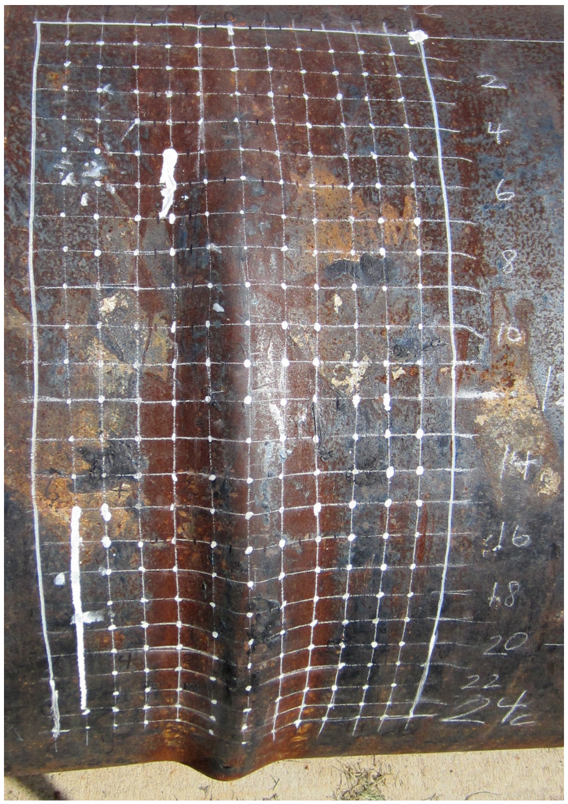
Residual Stress Map at the Surface of Wrinkle Bend #5

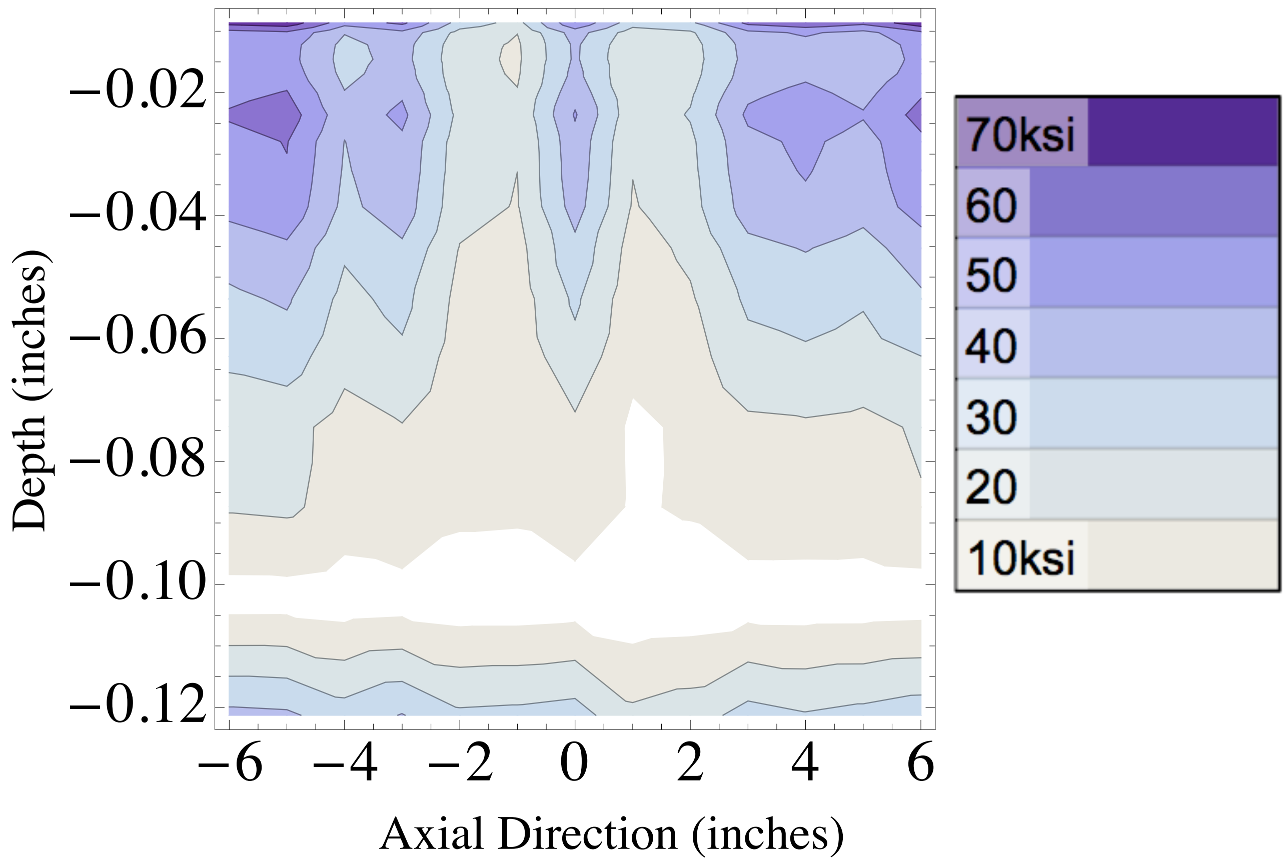




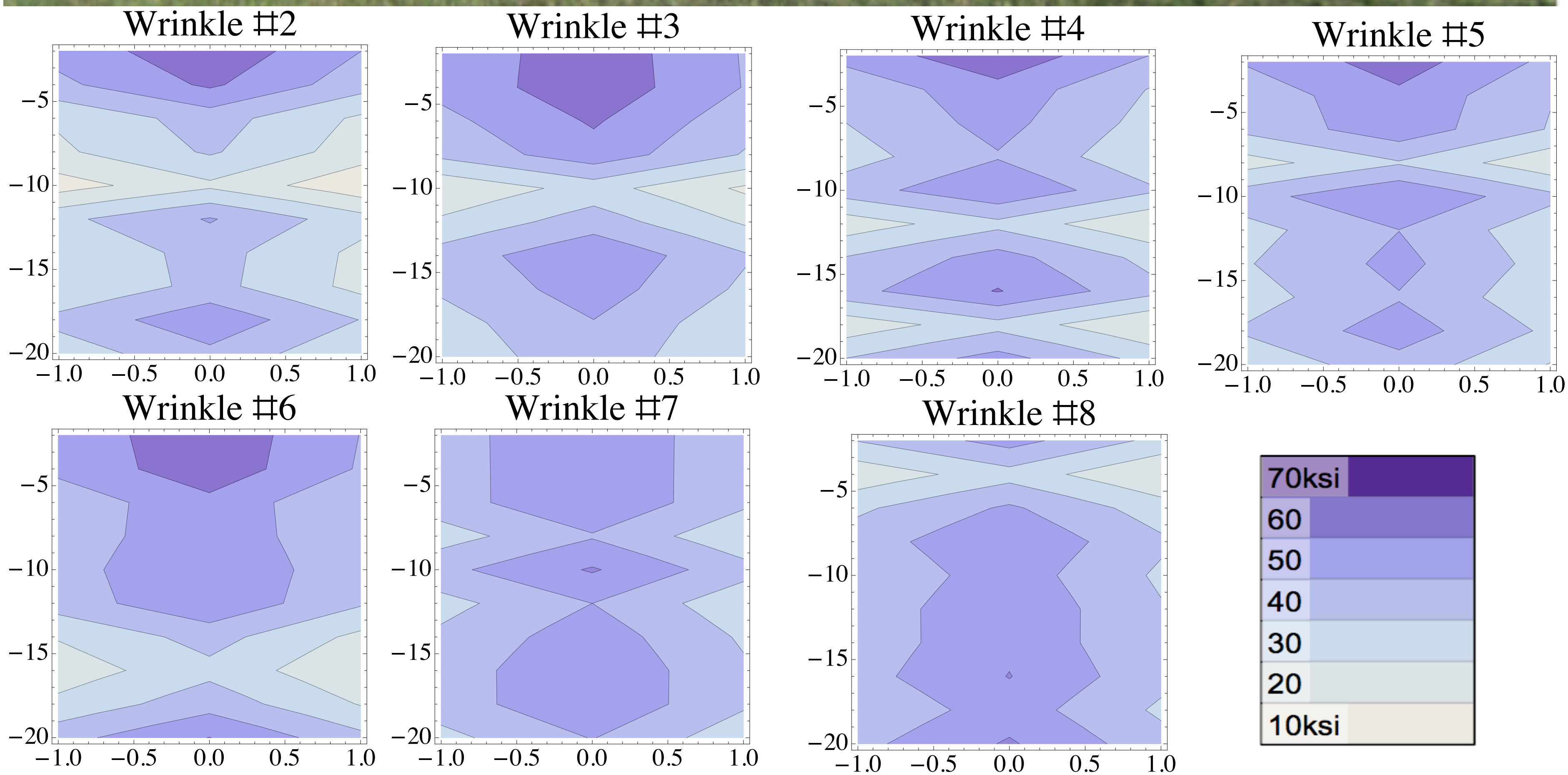
WRINKLE BEND RESULTS

Residual Stress Map of Cross Section of Wrinkle Bend #5

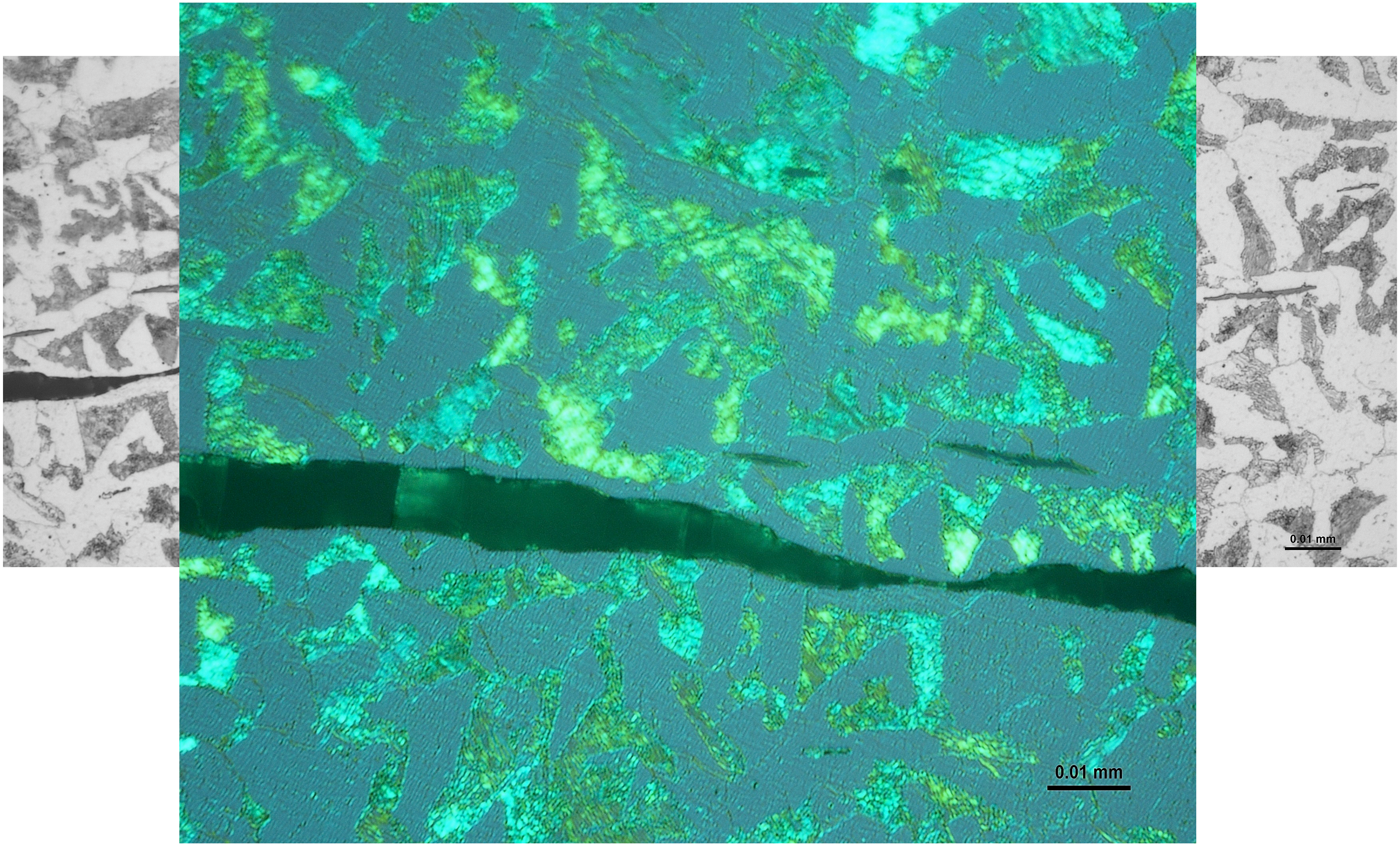




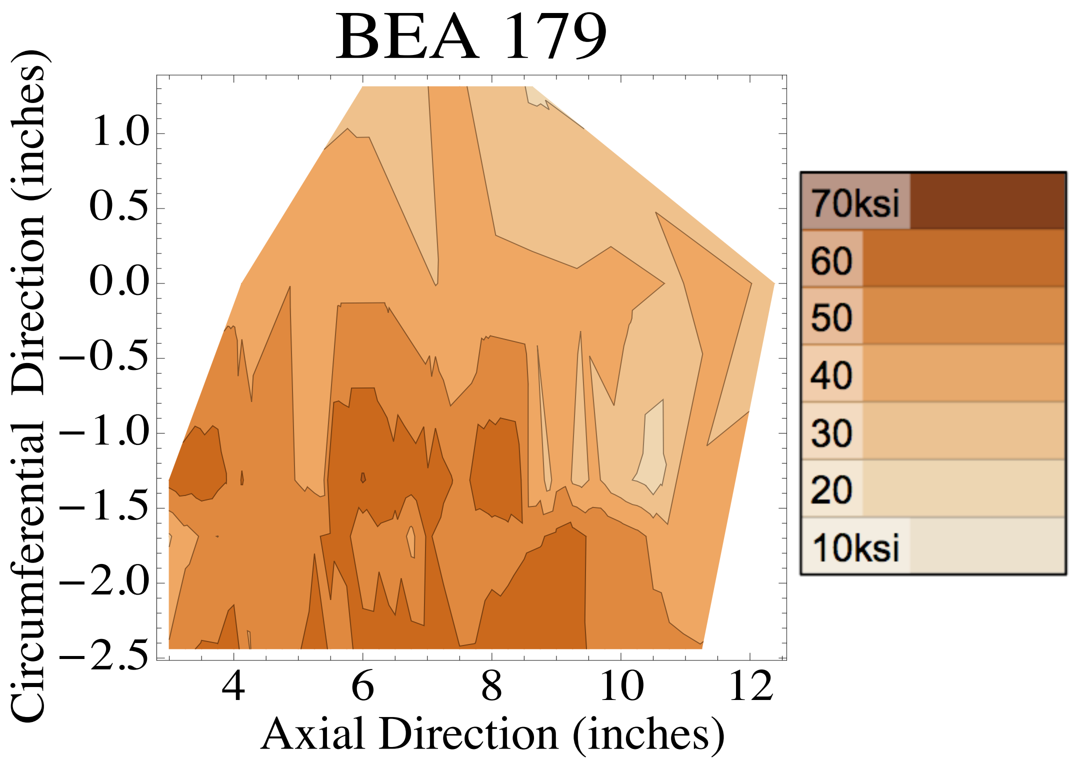
WRINKLE BEND RESULTS



WRINKLE BEND RESULTS



PIPELINE GOUGE RESULTS



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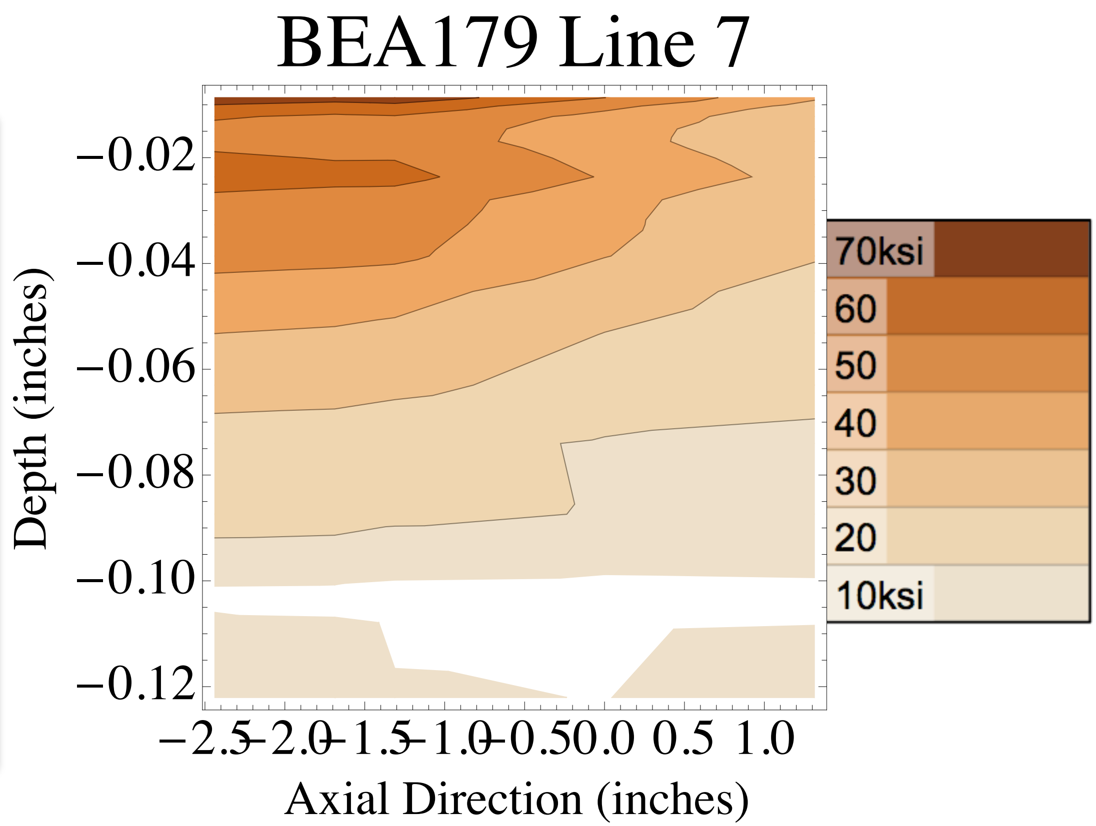

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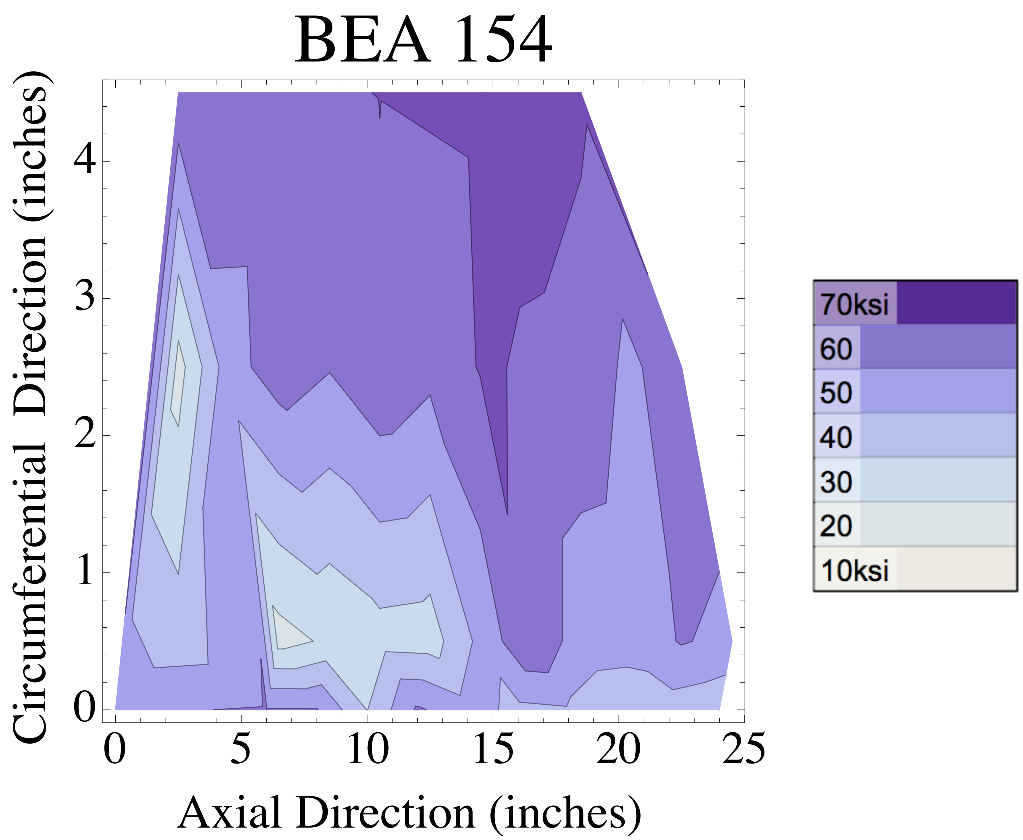

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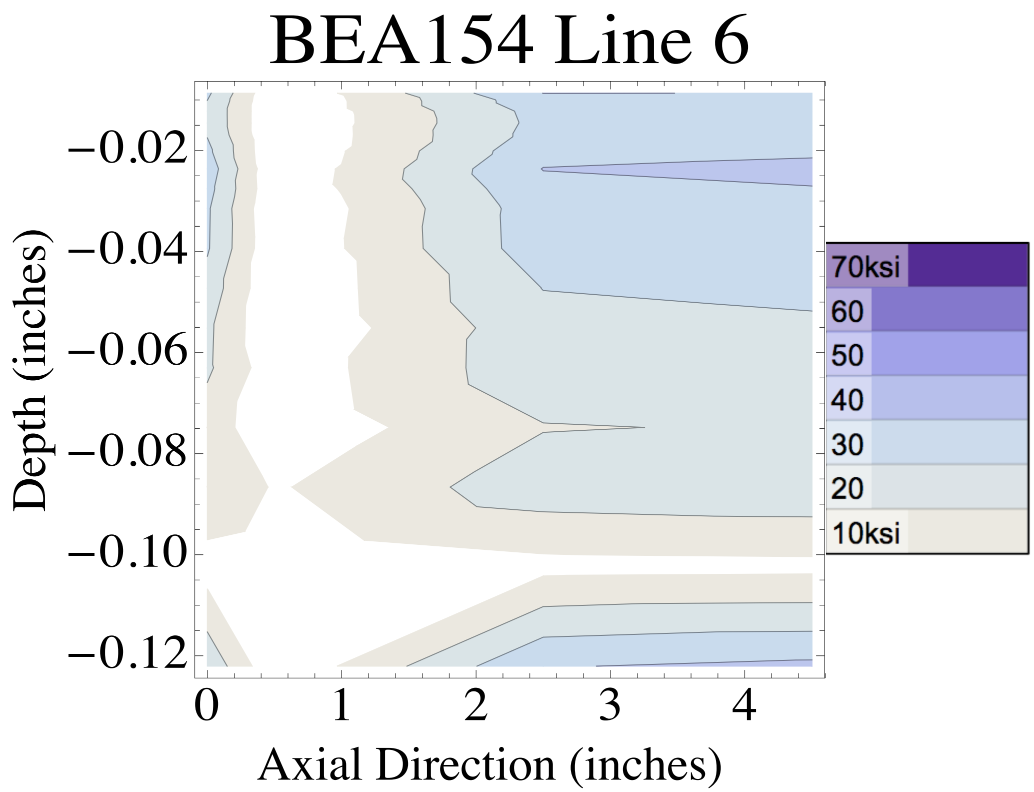

DISCUSSION OF RESULTS

- Comparison of the residual stress results for seven different wrinkle bends indicated that:
  - There is a large residual stress gradient along all of the wrinkle bends.
  - There is a significant difference in maximum residual stress levels between the seven geometrically identical wrinkle bends.
  - The difference in residual stress levels can be used to determine the criticality of the mechanical damage.
  - The presence of hydrogen (coming from inner diameter) dramatically increased the impedance towards the inner diameter of the pipe.
  - Geometric and shape based measurements would predict the same criticality for all seven wrinkle bends which differs dramatically from residual stress measurements.

DISCUSSION OF RESULTS

- The gouges exhibited large residual stress gradients as a function of position and depth.
- Electromagnetic measurements can successfully measure changes in residual stress regardless of the shape or size of the damage.
- The large differences in residual stress levels of the mechanical damage region compared to an undamaged region allows for an easy method to pinpoint mechanical damage that is not visible or geometrically measurable.

INDUSTRY INTERESTS AND DESIRES

- The pipeline industry has assisted G2MT in:
  - Obtaining pipeline samples
  - Obtaining residual stress measurements
  - Obtaining comparison models
- Other industries are very interested in residual stress sensors for various applications
- G2MT has developed partnerships with servicing companies to help advance the sensors commercialization and entrance to market
- The Canadian Neutron Beam Centre and G2MT are establishing a relationship to run in-situ residual stress testing to calibrate and validate electromagnetic sensors with neutron diffraction for multiple applications.

EXPECTED OUTCOME

- To provide the pipeline inspection industry with a new paradigm of pipeline inspection tools based on material properties.
  - Effective management of damage and deformation.
- To provide multiple industries with a new paradigm of inspection tools for various materials and applications.
  - A strain gauge and x-ray diffraction are only surface measurements.

RECOMMENDED ADDITIONAL WORK

- Additional work for variable separation
  - Hydrogen: To be able to properly measure the hydrogen concentration existing in the pipe which further alters the residual stress properties.
- In-situ residual stress measurements while performing neutron diffraction and electromagnetic measurements.
  - To provide characterization never been seen before.
  - To increase the accuracy of the electromagnetic sensors to residual stress.
- Development of wireless system to deliver instantaneous analyzed results to customer as well as RBI companies.
- Increase ruggedness of instrumentation.

FUTURE PHASES II AND III WOULD INVOLVE?

- **Phase II**
  - Prototype developed and packaged
  - First portable system for in-situ characterization of damage severity due to dents and wrinkle bends in pipelines used in field testing of operating pipes
- **Phase III**
  - Multiple sensor and probe designs and other options will be in the market or in development.
  - Working on increased acceptance based on DOT and industrial testing
  - Increase market share and development of testing standards.

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- Brian Olson and Brett Harwell from Premier Mechanical Integrity Associates.