Nondestructive Measurement of Strength, Ductility, and Toughness

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Presentation Outline

- Background on MMT
- Hardness Strength and Ductility (HSD) Tester
- Nondestructive Toughness Tester (NDTT)
- Future perspectives

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Massachusetts Materials Technologies LLC (MMT)

- **2014** MMT Founded
- **2** Nondestructive Testing (NDT) Technologies
- **1** Mission: To improve safety through cost-effective NDE

Initial Sponsor: National Science Foundation (NSF)

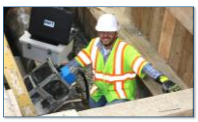
Strong team:

Customers: Exxon, Dow, GE, TCPL, National Grid

Building Experience in Oil and Gas Pipeline Testing

- $800K+ in Revenues from Testing Services
- 12+ Customers

2016 → 2018



Two Years of Progress

- Improve Pipeline Safety
- Enable Life Extension
- Prioritize Inspection and Repairs
- Meet Regulatory Requirements

Accelerating Growth through New Markets

- Oil & Gas
- Defense
- Power
- Process Facilities
- Bridges
- Aerospace

MMT's Complementary Nondestructive Testing Solutions

Hardness, Strength, and Ductility (HSD) Tester
Measures Strength

Nondestructive

Accurate

Cost Efficient

Time Saving

Nondestructive Toughness Tester (NDTT)
Measures Toughness

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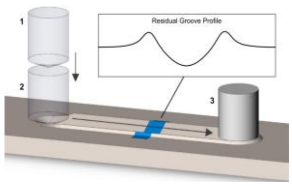
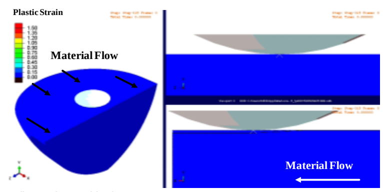
Fundamentals of Frictional Sliding

1. Contact mechanics test using a hard stylus (e.g. diamond)
2. Press stylus into softer material causing local deformation
3. Slide stylus across the surface of the material creating a permanent groove (depth < 0.002 inches)



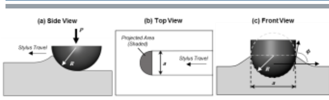
Finite Element Analysis (FEA) of Frictional Sliding



Bellemare et al., *Int. J. Solids and Structures*, 2007
Bellemare et al., *Journal of Applied Mechanics*, 2008
Bellemare et al., *Acta Materialia*, 2010

Steady state simulations
- Material properties
- Stylus geometries
- Friction coefficients

Dimensional Analysis



Frictional Sliding Measurements

Stylus sliding hardness, $H = \frac{8P}{\pi a^2}$

Stylus attack angle, $\phi = \frac{\pi}{2} - \text{acos}\left(\frac{a}{2R}\right)$

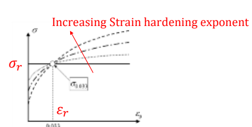
Representative Stress-Strain Functions

Representative strain, $\varepsilon_r = f(\phi)$

Representative stress, $\sigma_r = f(\phi, H, E_n)$

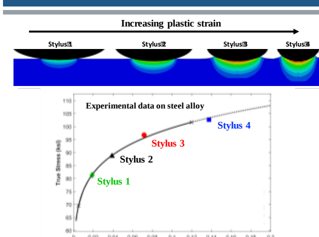
Reduced modulus, $E_n = \left[\frac{1-v_i^2}{E_i} + \frac{1-v^2}{E}\right]^{-1}$

Stylus Elastic Constants — Substrate Elastic Constants



Dao et al., *Acta Materialia*, 2001

Relating Frictional Sliding to Tensile Testing



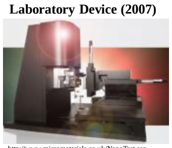
1. Dissimilar styluses used to measure material response at different strain magnitudes
   Chollacoop et al., *Acta Materialia*, 2003.
2. Complete stress-strain curve obtained by power-law fit to independent measurements
3. Determine yield and ultimate tensile strength from stress-strain curve

Hardness, Strength, and Ductility (HSD) Tester

Background

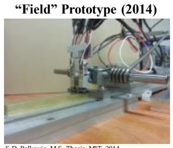
- Scientific basis established through academic research at MIT (2004 – 2014)
- Portable technology designed and implemented by MMT (2014 – present)

Laboratory Device (2007)



http://www.micromaterials.co.uk/NanoTest.asp

"Field" Prototype (2014)



S.D. Palkovic, M.S. Thesis, MIT, 2014

Commercial Unit (2017)

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HSD Hardware

Tests plates, curves, and irregular surfaces

Load and groove geometry measured continuously

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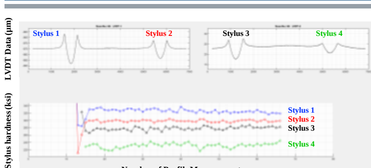
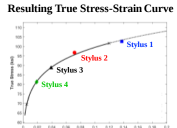
Typical Test Output



Resulting True Stress-Strain Curve



Typical test is ~35 mm long and takes 10 minutes (60-80 measurements)

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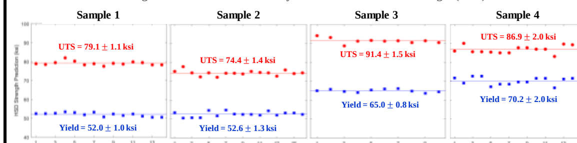
Repeatability on the Same Material

- Results combined from two HSD units on four homogeneous steel samples (collected over 3 months)
  - Plots show average and standard deviation of yield and ultimate tensile strength (UTS)



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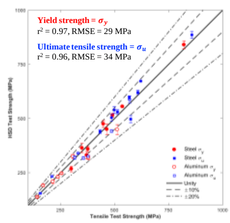
Comparison with Laboratory Tensile Test



Steel			Aluminum		
Alloy	Yield (MPa)	UTS (MPa)	Alloy	Yield (MPa)	UTS (MPa)
1020	300	432	3003	143	156
X42	371	574	5052	170	210
4130	377	499	5086	215	315
4140	448	608	5083	238	356
A572	464	513	5456	255	377
A656	537	621	6061	315	331
A514	821	858	7075	512	570

- Additional published validation data on steel pipes, copper, brass, aluminum and nickel alloys

Palkovic et al., *CORROSION 2018*, 2018; Palkovic et al., *PPIM 2018*, 2018.
Palkovic et al., *Journal of Pipeline Engineering*, 14(2), 2015. Bellemare et al., Acta Materialia, 2010

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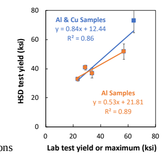
Applications with Cold Spray Samples

Influence of powder processing on HSD measurements (2017)

Sample ID	Material	T (°C)	P (Bar)	Comments	HSD Yield (ksi)	HSD UTS (ksi)	HSD Strain Hardening (n)
M2-U	6061 Al	230	35	No processing	38.6	44.4	0.067
M4-P	6061 Al	230	35	Preheated @ 230°C for 75 min	31.2	44.3	0.127
V1-U	6061 Al	230	35	No processing	38.0	39.3	0.024
V3-P	6061 Al	230	35	Preheated @ 230°C for 75 min	29.9	37.1	0.089

Comparison of Laboratory Tensile tests with HSD measurements

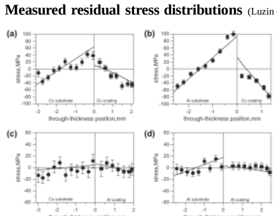
Sample ID	Material	T (°C)	P (Bar)	Tensile Elongation	Tensile yield or Max (ksi)	HSD Yield (ksi)
CS-18-043	6061 Al	450	35	7.6%	33.8	37.0
CS-18-044	6061 Al	300	20	1.9%	29.1*	40.9
CS-18-047	3003 Al	400	---	3.2%	23.6	32.8
Valmet 7050	7050 Al	430	35	Could not test	57**	53.3
AcuPowder 155A	Cu	400	25	2.1%	64.2*	73.2



*Tensile sample failed prior to 0.2% offset yield strength
**Using literature values from Rokni et al.(2017) for 7050 Al w/ similar spray conditions

Residual Stresses in Cold Spray Deposits

Measured residual stress distributions (Luzin et al., Acta Materialia, 2011.)



Yield strength (σ_y) considered:

- CP Cu = 60 MPa
- CP Al = 30 MPa

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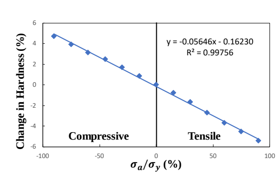
Influence of Residual Stresses on HSD Test

Numerical Study

- FEA with external stress applied σ_a



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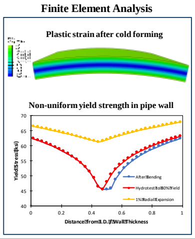
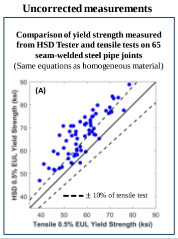
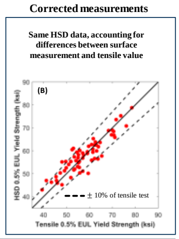
Past Experience: Correcting Pipe Surface Measurements

Finite Element Analysis | **Uncorrected measurements** | **Corrected measurements**







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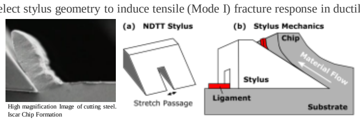
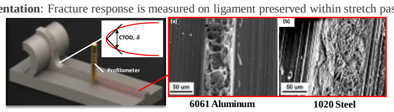
Nondestructive Toughness Tester (NDTT)

- **Concept**: Select stylus geometry to induce tensile (Mode I) fracture response in ductile metals



- **Implementation**: Fracture response is measured on ligament preserved within stretch passage

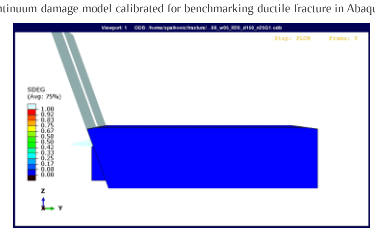


6061 Aluminum | 1020 Steel

Numerical Studies of Crack-Tip Location

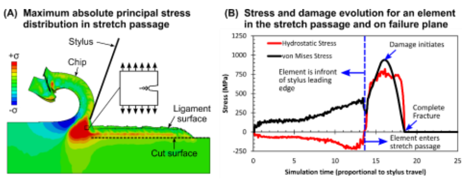
- 3D FEA with continuum damage model calibrated for benchmarking ductile fracture in Abaqus

Finite element colored by local damage criteria



Numerical Studies of Crack-Tip Stress Fields

- Results shows significant hydrostatic tension, a critical parameter for fracture of metals and polymers



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NDTT Prototype

Laboratory prototype

Portable prototype

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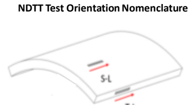
Proof-of-concept for Pipeline Steel

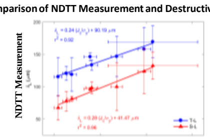
- Tests conducted on 8 pipeline steel samples Palkovic et al., IPC 2018 (accepted)

NDTT Test Orientation Nomenclature



S-L: Accessible in field
T-L: Direction of laboratory CT test, and lowest capacity for modern pipelines (Xu and Tyson, 2015)

Comparison of NDTT Measurement and Destructive Lab Tests



Fracture Mechanics Theory: $\delta_{CTOD} \propto \frac{J_c}{\sigma_y}$

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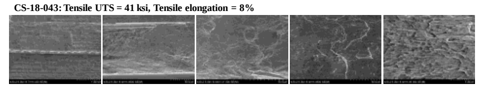
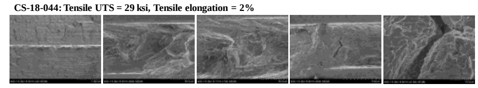
Applications on Cold Spray Samples

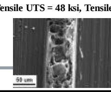
CS-18-043: Tensile UTS = 41 ksi, Tensile elongation = 8%



CS-18-044: Tensile UTS = 29 ksi, Tensile elongation = 2%



Bulk 6061: Tensile UTS = 48 ksi, Tensile elongation = 15%



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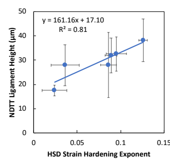
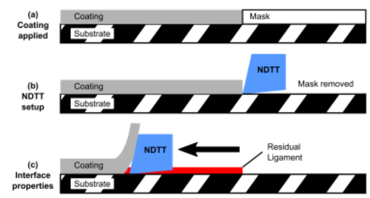
Applications on Cold Spray Samples

Sample ID	Material	T (°C)	P (Bar)	Comments	HSD Strain Hardening (n)	NDTT ligament height (um)
CS-18-043	6061 Al	450	35	Tensile Strain = 7.6%	0.126	38.2 ± 8.7
CS-18-044	6061 Al	300	20	Tensile Strain = 1.9%	0.095	32.6 ± 7.1
CS-18-047	3003 Al	400		Tensile Strain = 3.2%	0.036	27.9 ± 8.5
Valmet 7050	7050 Al	430	35	Rokni et al.(2017); Tensile Strain = 3%	0.086	27.9 ± 13.4
V1-U	6061 Al	230	35	No processing	0.024	17.5 ± 2.2
V3-P	6061 Al	230	35	Preheated @ 230°C for 75 min	0.089	31.9 ± 7.2



Future Work – Cold Spray Bond Strength



Summary of HSD & NDTT Findings

- **Hardness Strength and Ductility (HSD) Tester**
  - Accurate and repeatable for power-law hardening metals
  - Correlates with strength and ductility from laboratory tensile tests
  - Identify influence of different processing parameters
- **Nondestructive Toughness Tester (NDTT)**
  - Correlates with ductility of cold spray coatings
  - Future work should investigate toughness, fatigue, and bond strength correlations

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Aging Infrastructure and Fleet is a Global Problem

MMT Delivers Performance Testing

Characteristic Analysis
Many technologies available
Data such as:
- Geometry
- Porosity
- Microstructure

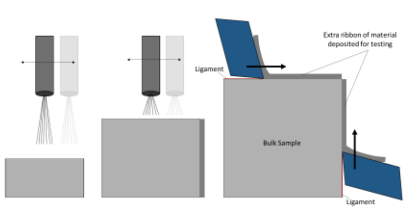
Performance Testing
MMT technologies
Critical and hard to get data such as:
- Strength
- Toughness
- Interface integrity

BOTH ARE NEEDED

Complete performance verification ensuring safety and component/repair longevity.

NDTT Application to Additive Manufacturing

The NDTT can quantify anisotropic properties by testing in different configurations.



Material Evaluation is Necessary

- Evaluate Manufacturing Methods
- Prioritize Maintenance and Repairs
  $9B Navy
  $12B Air Force
- Minimize Costs
- Improve Safety
- Enable Life Extension

Anticipated Roadmap

- Continue process performance testing and refine the specific attributes to be tested (yield, ductility, toughness, large porosities, bond strength)
- Complete the adaptation of the tools to test both cold spray samples and repaired parts for the specific attributes selected
- Standardize the testing method, procedure and quality assurance

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Acknowledgements

- Army Research Laboratory, Northeastern University, HF Webster
- Vic Champagne, Prof. Sinan Muftu, Tricia Schwartz, Aaron Nardi, and Matt Siopis
- NSF SBIR Phase I and Phase II program, MassVentures

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