

Nondestructive Strength and Toughness Testing Applied to Additive Manufacturing

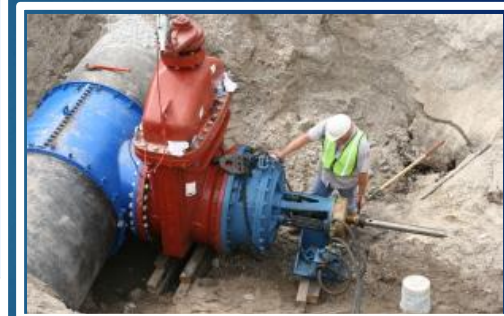
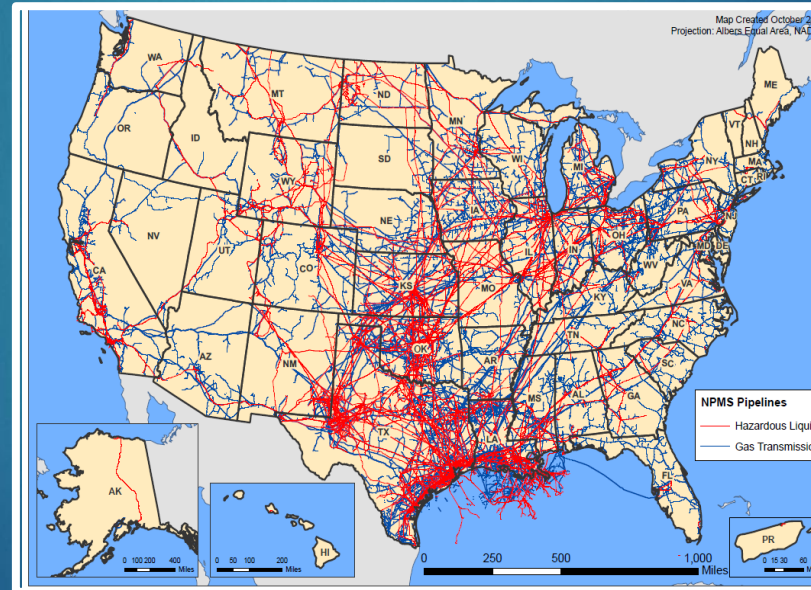
S. C. Bellemare, PhD, PE



Massachusetts Materials Technologies LLC



Metals that are relied on for strength and toughness



Material verification and quality control / quality assurance is in need of nondestructive methods for strength and toughness evaluation.

Current Strength Testing

Destructive
Cut-Outs
(samples removed)

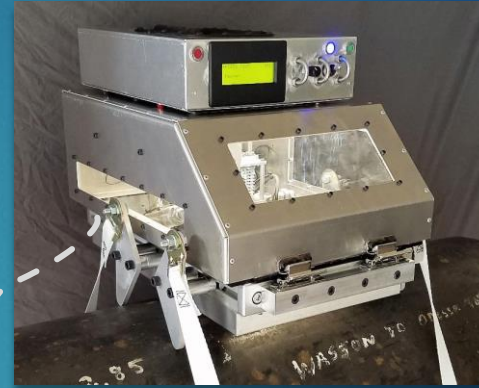


Nondestructive
Hardness Tests
(Limited accuracy)



MMT's Portable Instruments

Nondestructive & Accurate



Laboratory-level accuracy at reduced time and cost

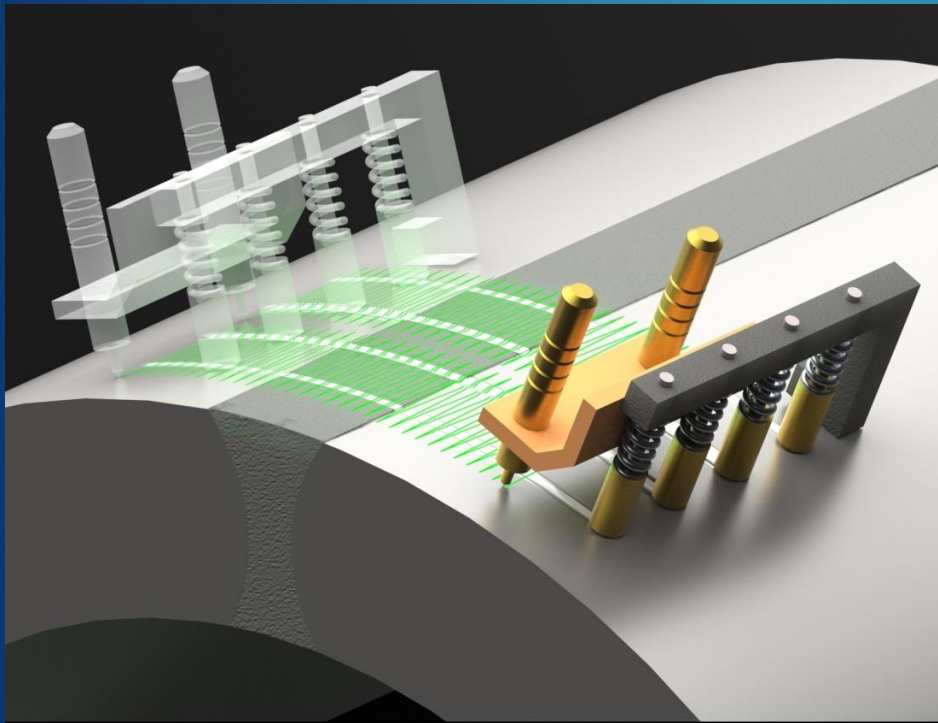


Two New Instruments for Nondestructive Evaluation

In-Field NDE Testing:

Hardness, Strength and Ductility (HSD)

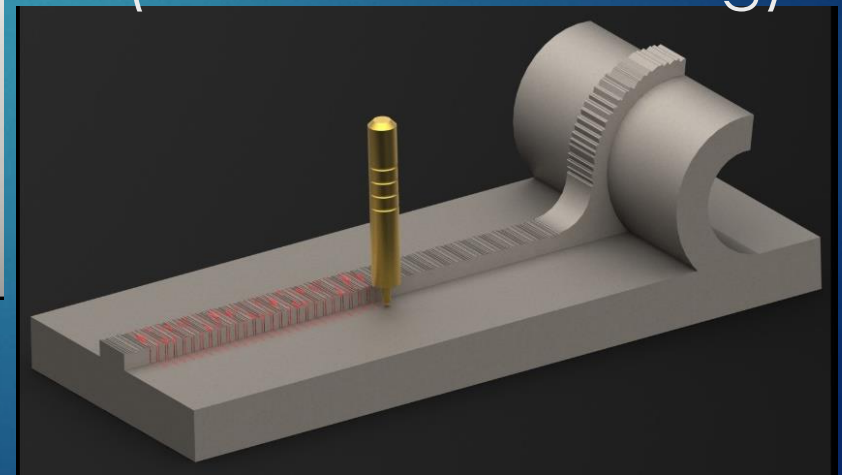
(via frictional sliding)



Laboratory NDE Testing:

**Non-Destructive
Toughness Testing (NDTT)**

(via micromachining)



Massachusetts Materials Technologies LLC (MMT)

2014

Year
company
founded

11

Employees
(8 Full-time
equivalent)

2

Non-
Destructive
Testing (NDT)
technologies

1

Mission:
Improve
safety
through cost-
effective NDE



Major Sponsor: **National Science Foundation (NSF)** Small Business Innovative Research (SBIR) Grants: Phases I and II
(Grants for **\$1,050,000** through March 2019)



Other Nondestructive Applications



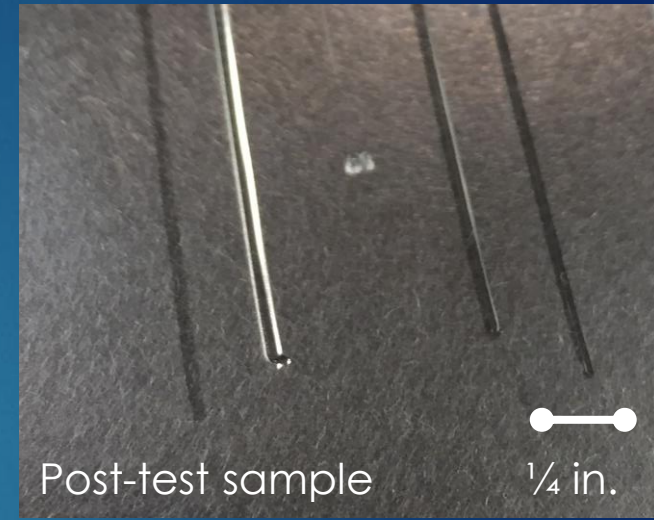
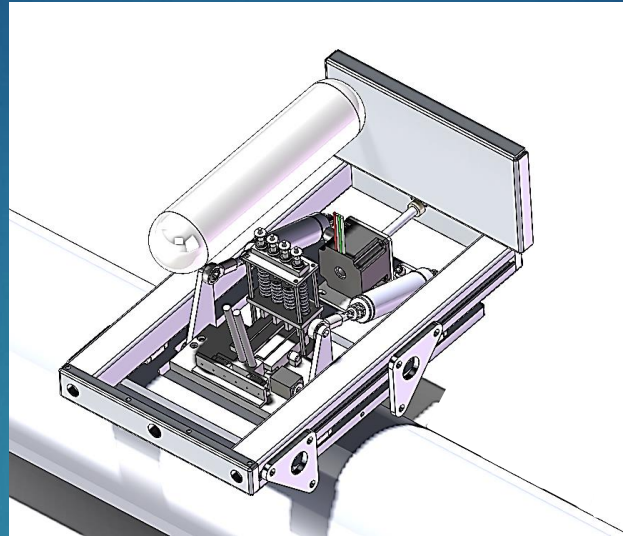
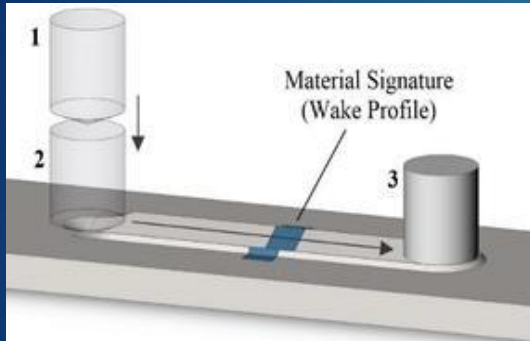
Energy • Defense • Aerospace • Infrastructure



Where materials and welding processes are relied upon for their strength and toughness.

MMT's 30 months of committed effort:

HSD: Innovative Breakthrough

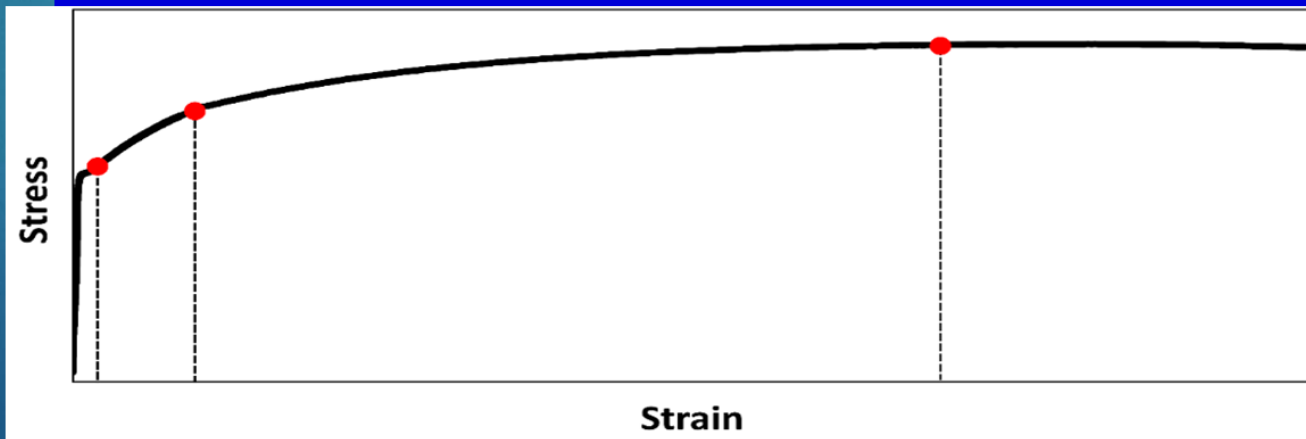
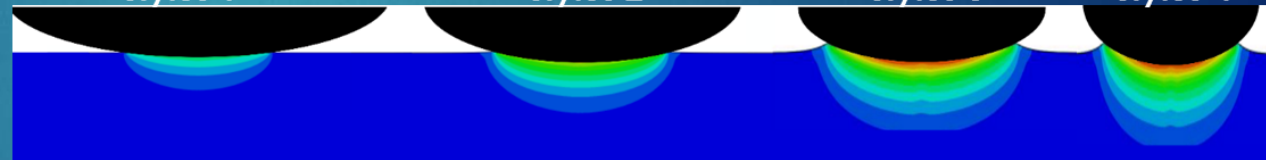


Stylus 1

Stylus 2

Stylus 3

Stylus 4

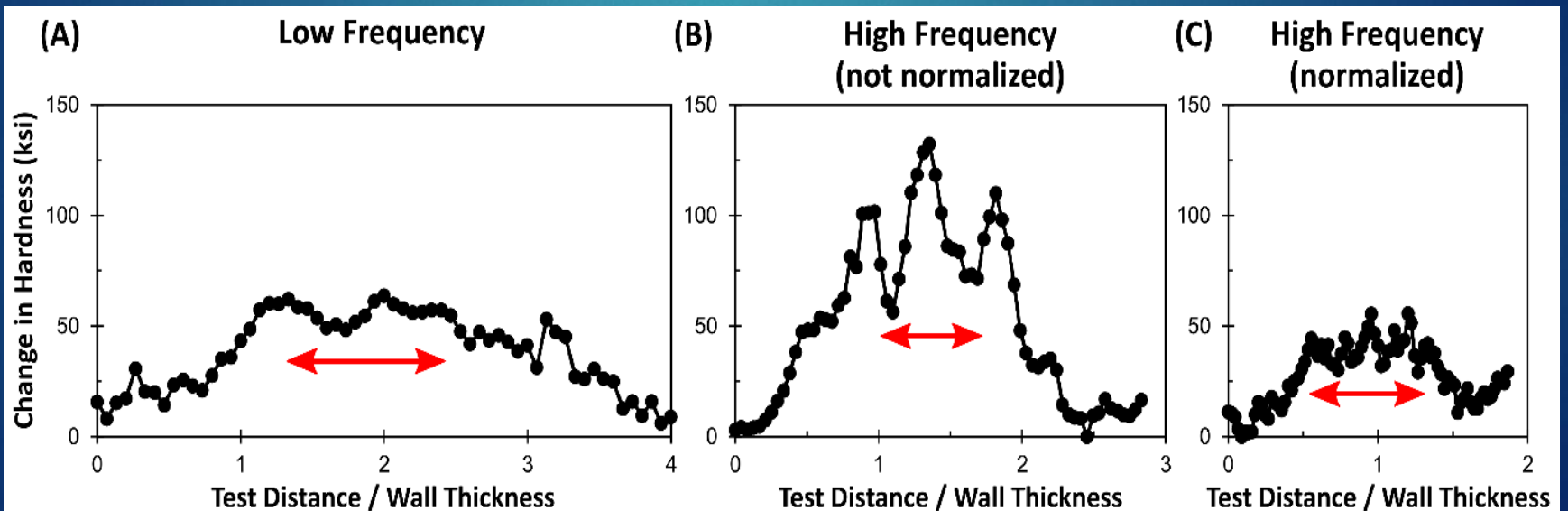
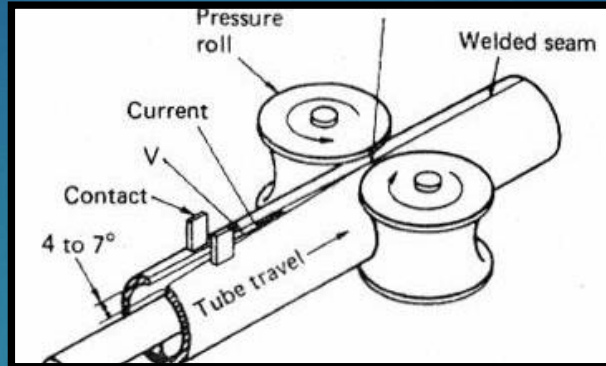


- ▶ Bellemare, PhD thesis, MIT, 2006
- ▶ Three peer-reviewed journal articles (2008-2010):
 - ▶ Acta Materialia,
 - ▶ International Journal of Solids and Structures,
 - ▶ Mechanics of Materials.

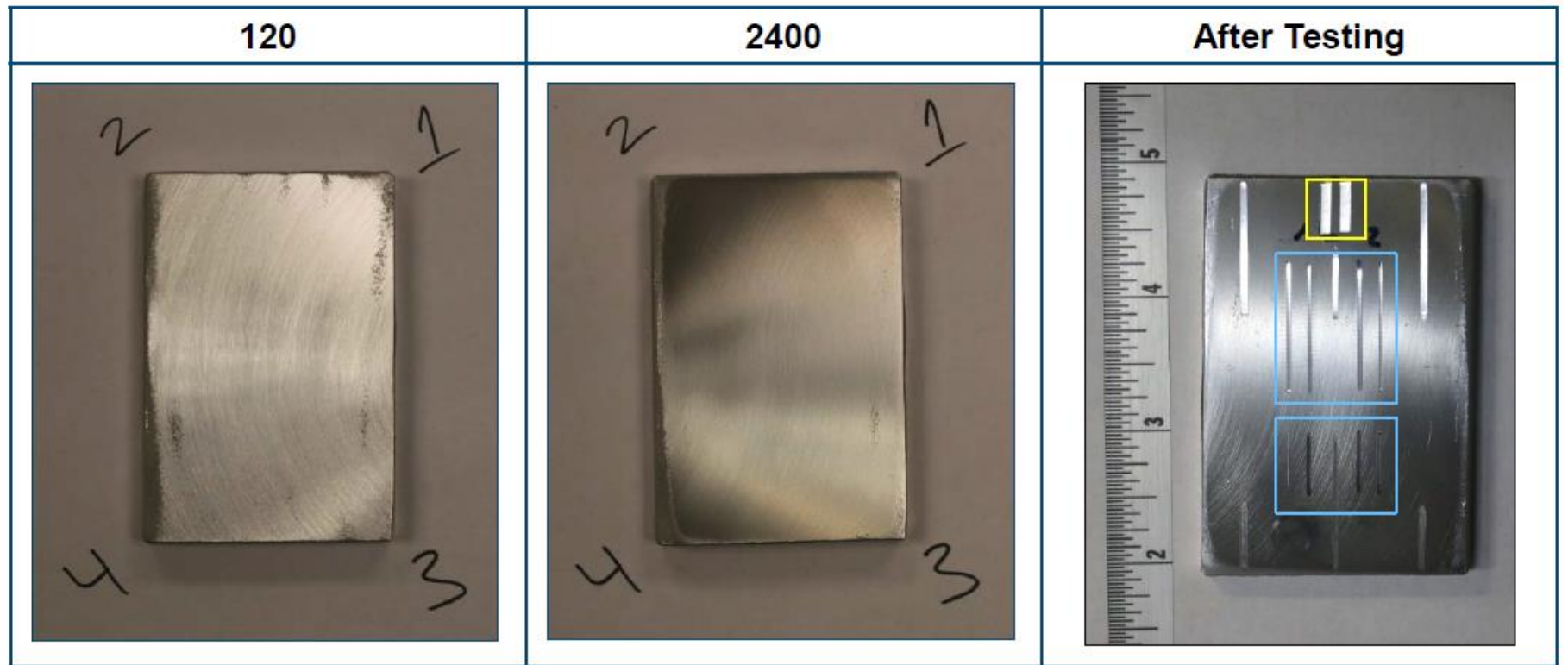
Steel – HSD versus Laboratory Testing

Sample	Type	Tensile Test 0.5% YS [ksi]			HSD Prediction 0.5% YS [ksi]			Range of Difference	Average Difference
		Min.	Max.	Avg.	Test 1	Test 2	Avg.		
08T2	Midwall	34.4	40.3	37.0	38.3	35.8	37.0	0.0%	0.0%
F004	Flat	43.3	43.5	43.4	40.1	41.9	41.0	-5.3%	-5.6%
24T2	Midwall	43.4	44.5	44.0	45.8	46.7	46.2	3.9%	5.2%
12SLF	Midwall	43.3	47.7	45.5	46.0	45.9	46.0	0.0%	1.0%
14GRB	Midwall	42.8	51.7	47.3	50.7	48.0	49.4	0.0%	4.4%
12Y64	Midwall	49.4	50.5	50.3	51.8	50.3	51.1	1.1%	1.6%
18GRB-B	Midwall	50.6	53.7	52.2	51.5	52.0	51.8	0.0%	-0.8%
F001	Flat	53.5	54.0	53.8	53.8	55.5	54.6	1.1%	1.6%
16X42	Midwall	54.1	58.0	55.7	58.0	57.0	57.5	0.0%	3.2%
F015	Flat	56.1	56.9	56.5	59.8	58.5	59.1	3.9%	4.6%
10SHF	Midwall	64.1	66.0	65.0	60.8	63.0	61.9	-3.4%	-4.8%
16GRB	Midwall	69.8	70.2	70.0	72.1	69.9	71.0	1.1%	1.4%
F005	Flat	70.6	72.7	71.7	68.9	71.3	70.1	-0.7%	-2.2%
T3011	Midwall	72.5	73.0	72.7	69.6	70.0	69.8	-3.7%	-4.0%
F028A	Flat	53.8	55.8	54.8	52.1	52.8	52.5	-2.4%	-4.2%
F041	Flat	64.9	65.8	65.4	67.3	67.8	67.6	2.7%	3.4%
F030A	Flat	65.7	68.4	67.5	70.5	64.7	67.6	0.0%	0.1%

Long. Seam Determination with HSD Tester



Aluminum 6061 Cold Sprayed



■ NDTT ■ HSD

Aluminum 6061 Cold Sprayed (HSD blind test results)

Sample	Yield Strength EUL @ 0.5% [ksi]			Ultimate Tensile Strength [ksi]			Work Hardening Exponent		
	Test 1	Test 2	Average	Test 1	Test 2	Average	Test 1	Test 2	Average
V1	36.8	36.0	36.4	38.9	42.5	40.7	0.043	0.087	0.065
V3	29.3	30.0	29.7	39.6	41.0	40.3	0.130	0.134	0.132
W1	32.9	36.6	34.7	50.8	50.1	50.5	0.170	0.135	0.153
W2	33.0	31.4	32.2	45.0	41.5	43.2	0.134	0.124	0.129
M1	36.6	37.4	37.0	43.7	44.3	44.0	0.091	0.088	0.090
M2	37.4	38.7	38.1	37.4	46.5	42.0	0.128	0.092	0.110
M3	43.8	--	43.8	43.9	--	43.9	0.001	--	0.001
M4	36.5	--	36.5	46.7	--	46.7	0.236	--	0.236

Unprocessed

Processed

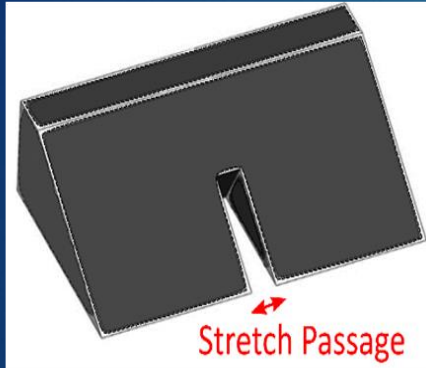
Unprocessed

Processed

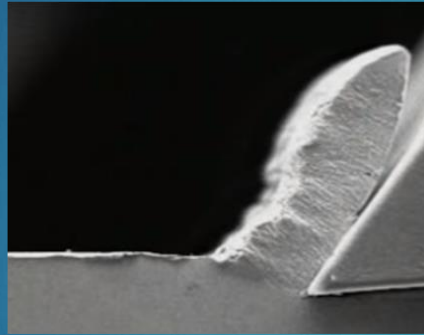
V3 (UTRC) expected SY **33.8 ksi** & UTS **40.5 ksi**

Upcoming: Fracture Toughness via MMT's NDTT

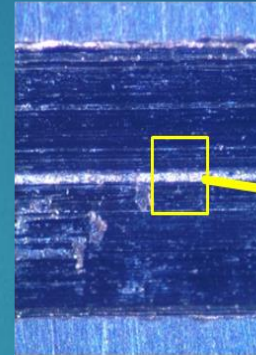
How it works:



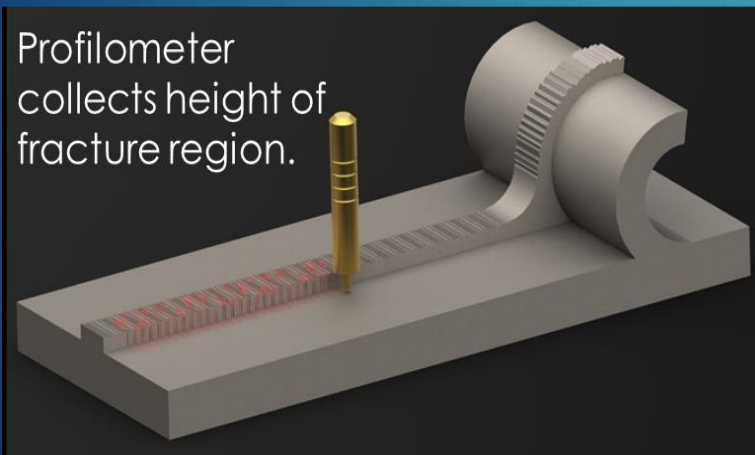
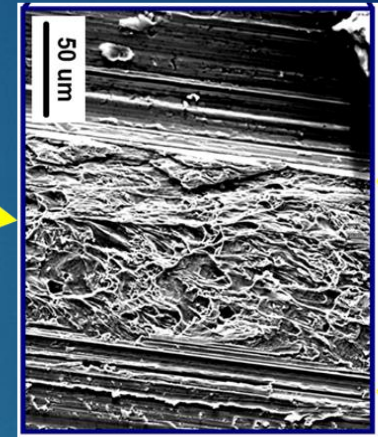
FTT Wedge Stylus



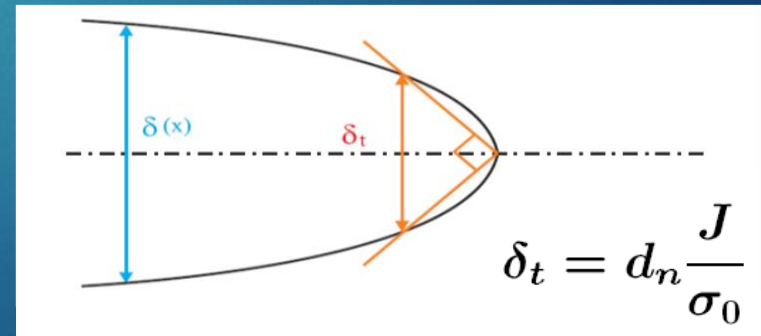
Machines off a thin (2-3) mil layer



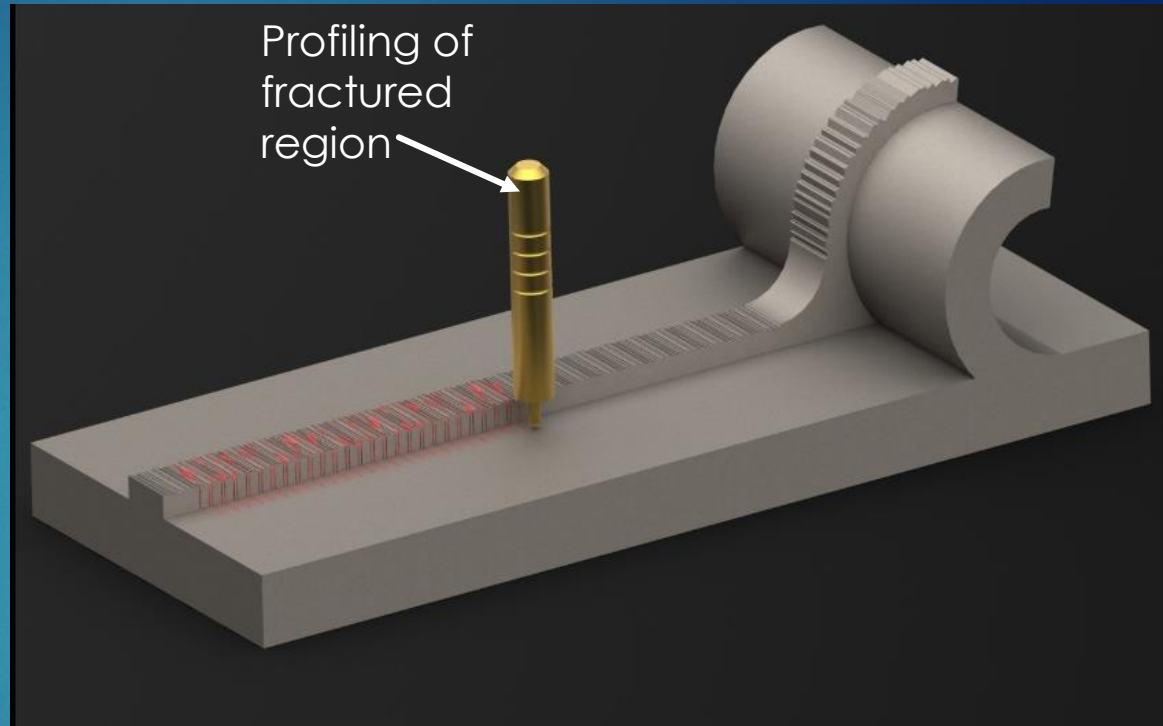
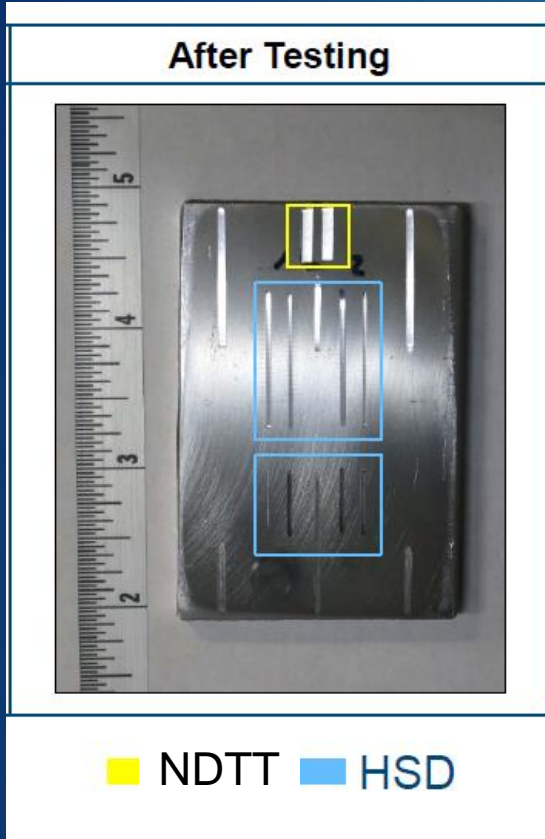
Wedge creates fracture region



From fracture mechanics, toughness is proportional to the crack tip opening



Aluminum 6061 Cold Sprayed

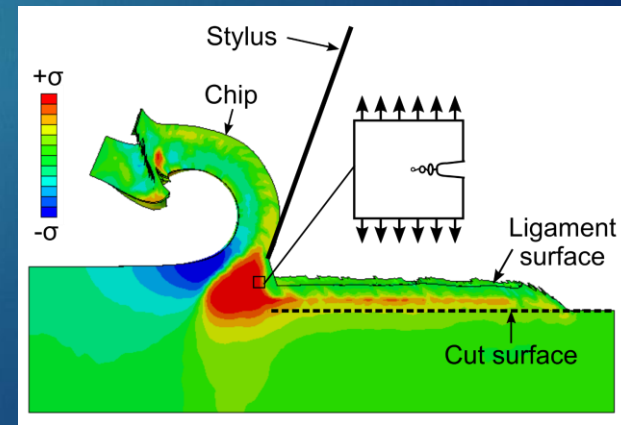
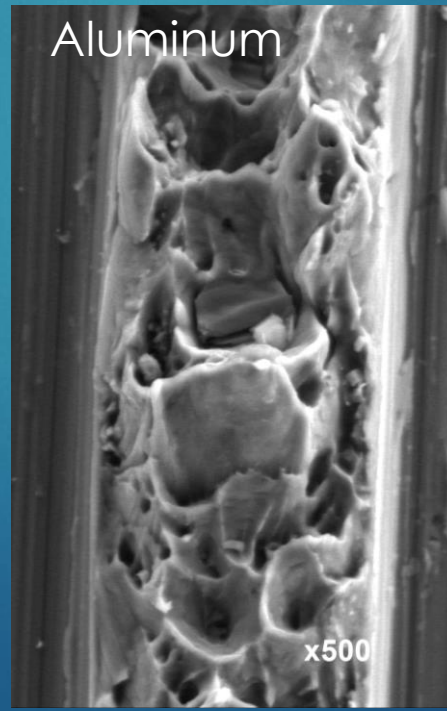
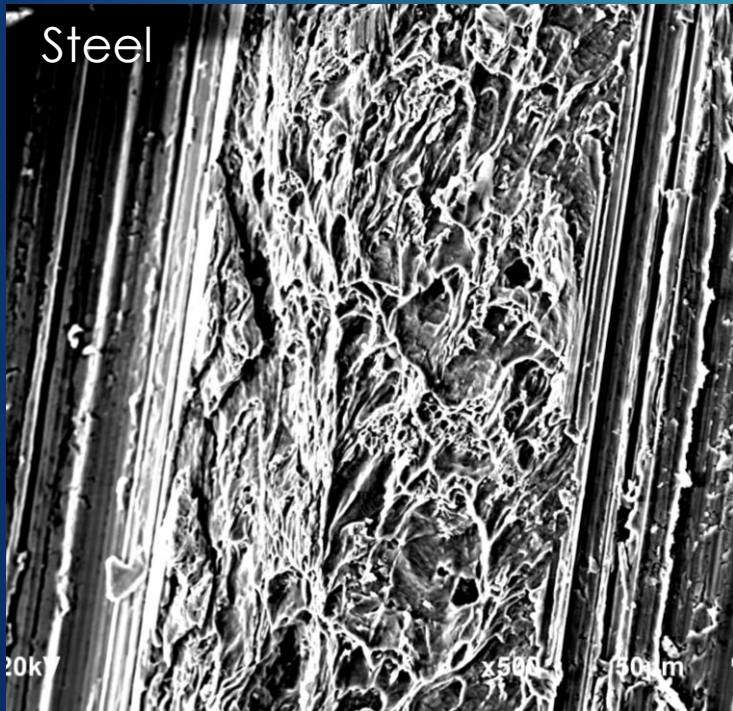
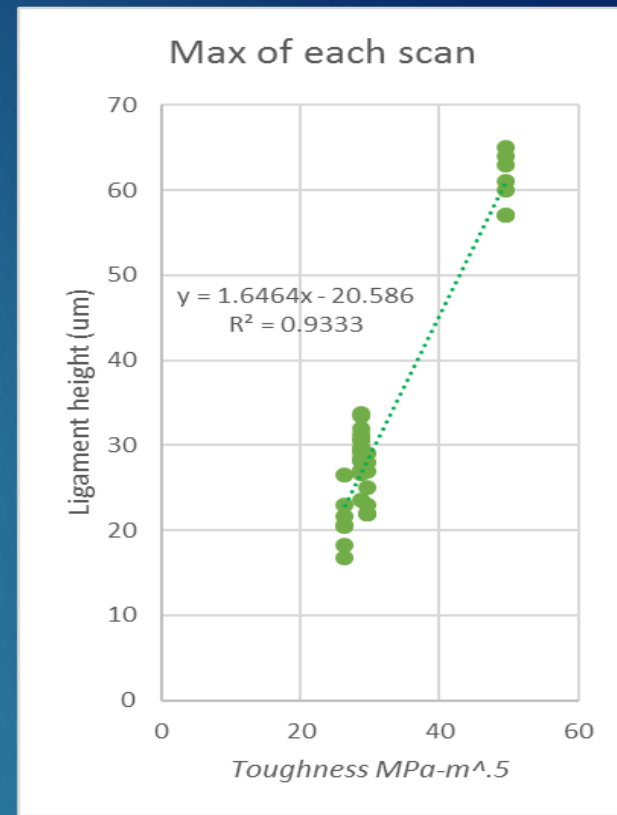
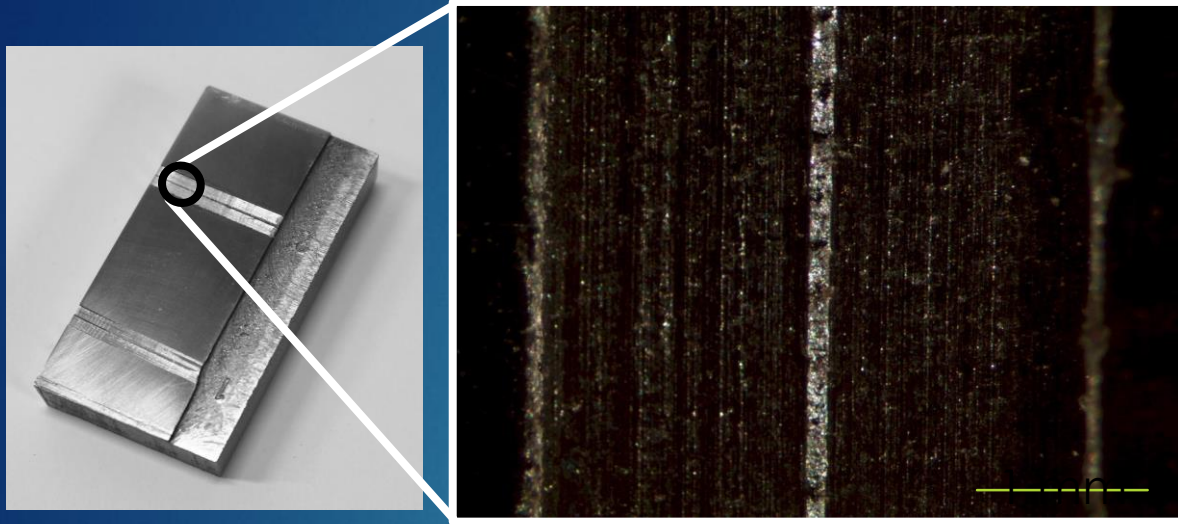


Sample	Max. Ligament Height [um]			
	Test 1	Test 2	Test 3	Avg.
V1	18.7	18.8	14.9	17.5
V3	23.8	37.7	34.2	31.9

% Difference (V1/V3)

-45.2%

Validation of MMT's NDTT





Steps Forward

1. Potential user discussion / feedback
2. Proof of concept studies
3. Generate tool / procedure for specific applications
4. Enhance / make NDE effective for material properties determining performance

Nondestructive Metal Strength and Toughness Testing Solutions

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