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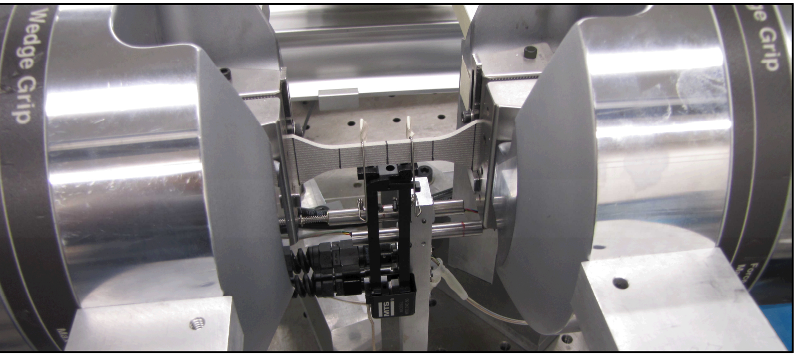

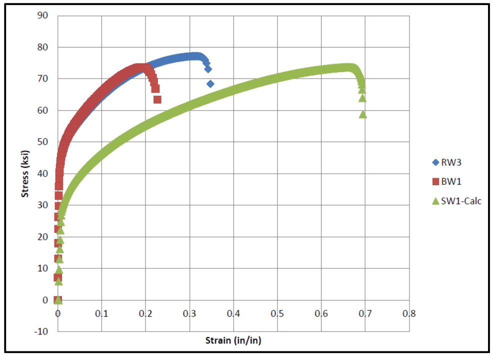

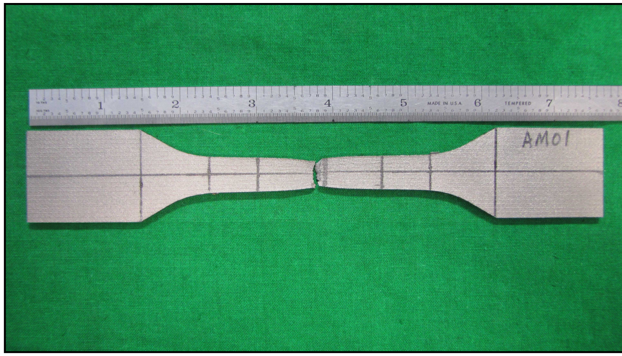

Weld Replacement with Additive Manufacturing

Blake Reece , Cody Kirk

Acknowledgements: Kim Haulenbeek , Kurt Metzinger , Andrea Dorado

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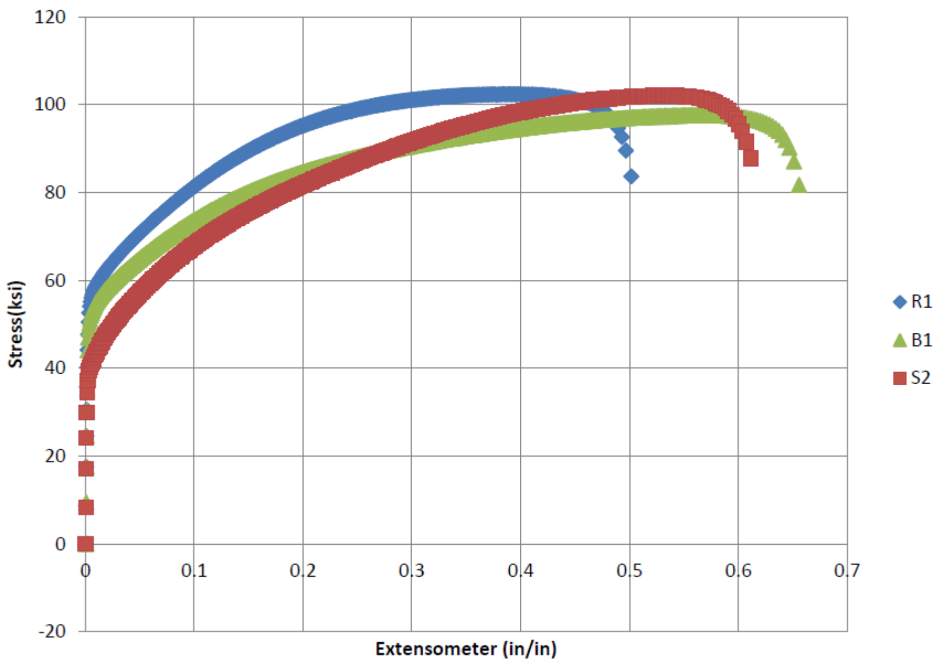
Overview

- Issues with stainless steels & traditional manufacturing
- Current state of metal AM technology
- Identifying potential entry points for metal AM use
- Performance comparison of AM and welded joints
- Future work

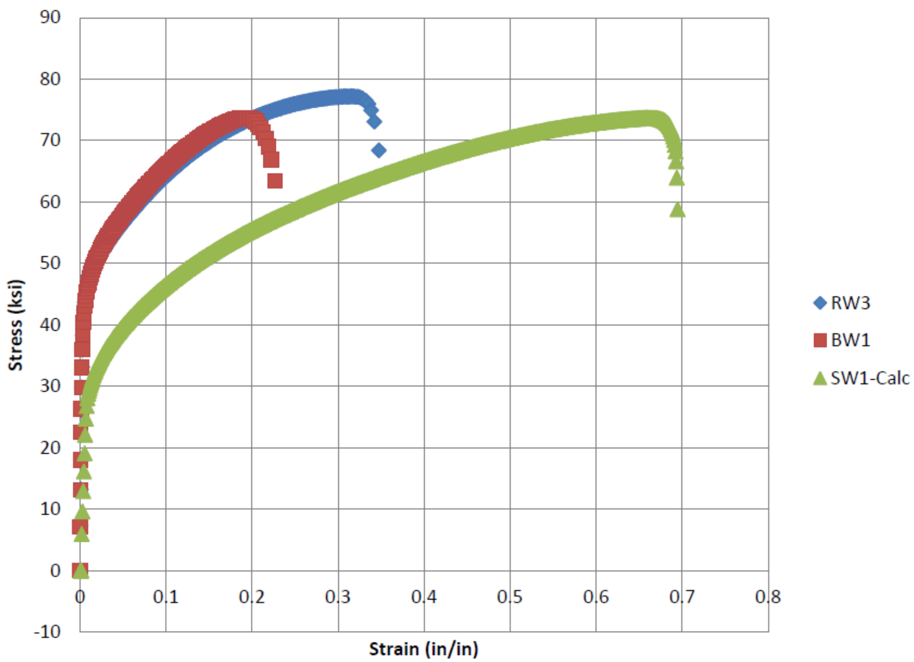
Manufacturing Issues with Stainless

- Large variance in material properties from different suppliers
- Welds and other joints create "weak" points in a structural design
  - Welds have lower strength, less ductility, leading to crack propagation as a common failure mode
  - Assembly geometry can also force the selection of lower-performing welds & joints, further reducing joint performance
- Weld performance is highly variable
  - Extensive quality control and inspection needed to verify the quality of welds
  - Performance of a weld still varies based on a # of inputs (heat, filler material, welder, etc.)

Material and Weld Inconsistency



Wrought SS 304L Comparison



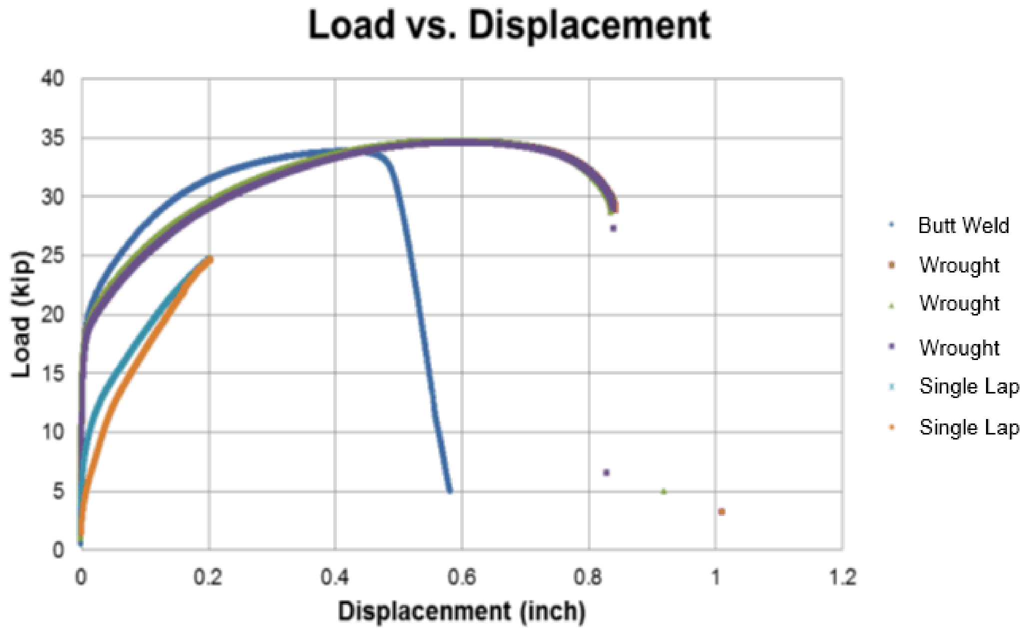
Welded SS 304L Comparison

- 23% variance in yield strength & elongation in wrought samples
- 66% variance in elongation in welded samples!

Reference: Gorman, Jhana. “SML0293 – Tensile Test Two”, internal memorandum, November 7, 2013.

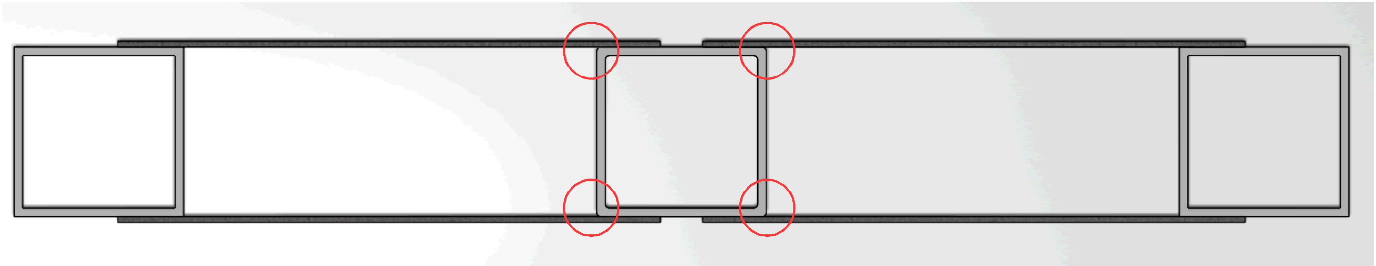
Weld Performance Issues

- Weld material loses ductility of the parent material
  - Elongation can be reduced as much as 64% from parent properties
  - Yield and tensile strengths reduced as much as 25%
  - Heat affects parent material as well



Reference: Dorado, Andrea and Lusher, Daniel. "Weld Configuration Tensile Testing", internal memorandum, December 1, 2014.

- Non-ideal welds can reduce strength and ductility even further
  - Only 2 of the 4 circled joints can be welded in the wall-section below, leading to single lap joints



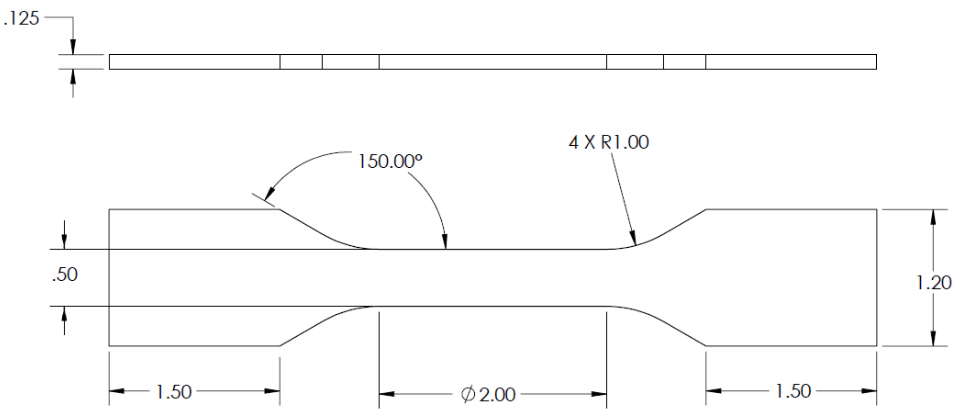
Can AM Really Help?

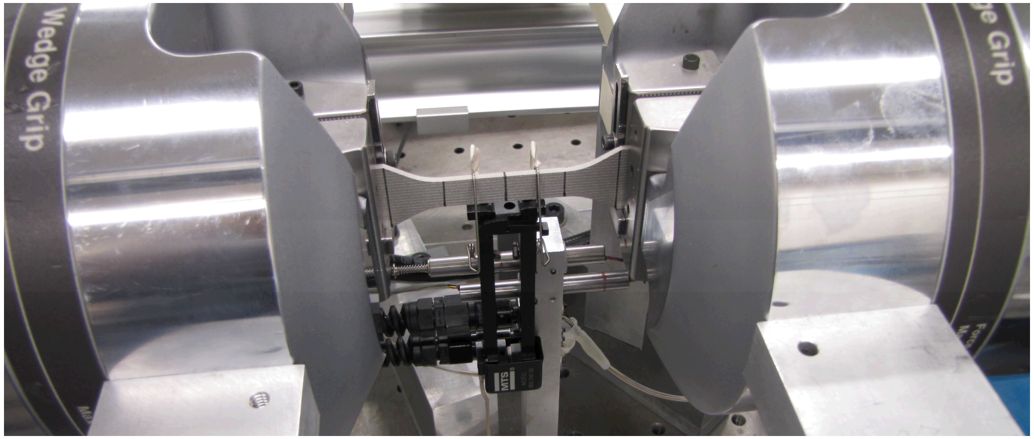
- Printed metals have significant variability in material properties
  - Elongation & strength values can vary up to 20% between parts
    - This is still within the tolerance seen in wrought samples, and controlling printer environments and powders could reduce variability
    - Much less variability than weld properties
- Printed metals lose ductility
  - Many processes essentially “weld” powders, so ductility is lost; however, strength is gained with AM, unlike in welded stainless steels
  - Heat treatments on AM materials an option to regain ductility
- AM can reduce multi-component assemblies to a single part, reducing the amount of welds/joints in an assembly

Metal AM Technologies

Name	Description	Common Metals	Comments
Selective Laser Melting/Direct Metal Laser Sintering (SLM/DMLS)	Fiber optic laser melts and bonds metal powder grains together to form a solid component through full melt (homogeneous structure); a micro-welded component	Stainless Steels: 17-4, 15-5, 316, 304 Other metals: Inconel, Titanium, Martensitic carbon steels, CoCr, Aluminum	Most common process, smaller build areas, density varies, embrittlement common, anisotropic, grainy finish
Electron Beam Melting (EBM)	Electron beam is used to melt and bond metal powder (or metal wire) grains together to form a solid component through full melt (homogeneous structure). Wire-feed or powder-bed options.	Stainless Steels: Not recommended because of large resultant grain size (mm-cm range) Other metals: Inconel, Titanium, Martensitic carbon steels, CoCr, Aluminum, Copper	Fully-dense components, isotropic, requires high level of vacuum, larger build sizes, great for titanium, uncommon process and expensive (KCP does have this capability)
Laser Engineered Net Shaping (LENS)	Fiber optic laser melts powder grains as they are propelled through a nozzle to form a solid component through melting	Stainless Steels: 17-4, 15-5, 13-8, 316, 304/304L, 309 Other metals: Inconel, Titanium, Martensitic carbon steels, CoCr, Aluminum 4047	Fast deposition, very dense components, larger build sizes, very few vendors and expensive, very grainy finish, mostly in academia/R&D

Materials Testing

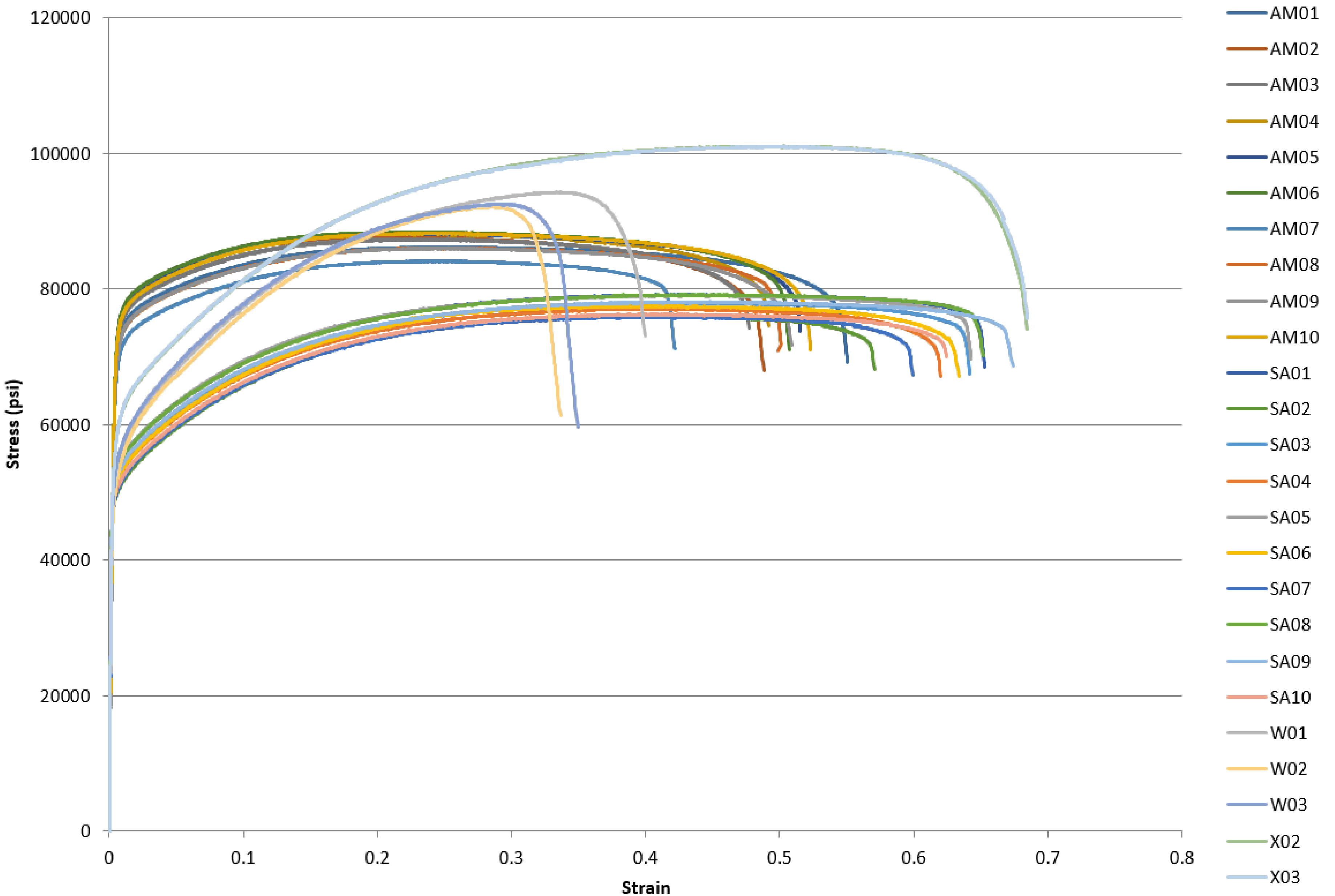




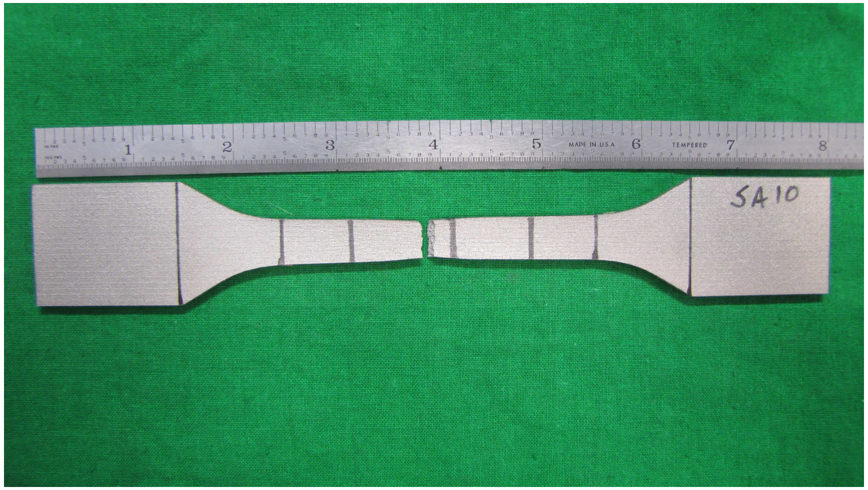
316L samples pulled in standard, quasi-static tensile tests

- 3 wrought samples, 3 welded samples (v-groove, ground flush)
- 20 additively manufactured by ProtoLabs
  - 10 without heat treatment, 10 with solution anneal treatment
  - Build orientation in the z-direction on all samples

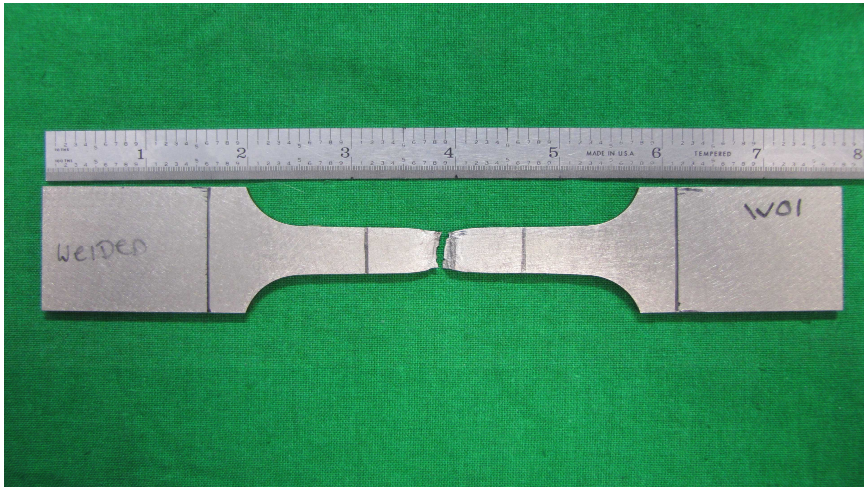
Stress-Strain Curves - All Test Samples



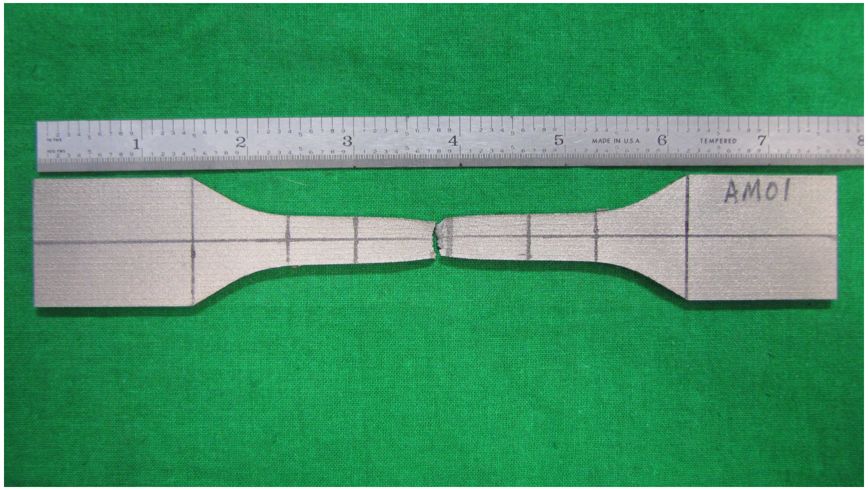
Test Results, Cont.



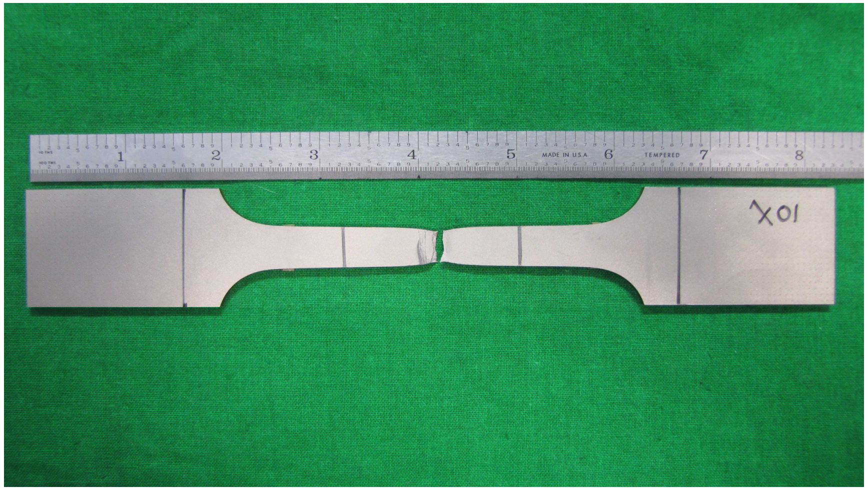
Printed 316L w/Solution Anneal



Welded 316L



Printed 316L



Wrought 316L

Material Property Evaluation

	AM	AM w/Solution Anneal	Wrought	Welded	Published 316L Values
Peak Stress, psi	87092	77641	101100	93038	75000
Tensile Elongation at Break, %	49.8	63.1	68.5	36.2	40-60%
Yield Stress, psi	69999	50278	55747	50523	30000
Tensile Elongation at Yield, %	0.57	0.41	0.44	0.42	n/a
Modulus of Elasticity, psi	1.92E+07	2.38E+07	2.33E+07	2.35E+07	2.8E+07
Toughness (in. lbf. in^{-3})	41959	50764	64193	30700	n/a

- All AM samples exceed the minimum published values for wrought 316L
- Solution anneal approaches wrought performance for both elongation and toughness

Summary and Future Work

- AM stainless steel components have the potential to outperform traditionally manufacturing parts through elimination of welds and joints
  - Solution annealed AM parts exhibit similar ductility and toughness to wrought material
  - Further work being done to understand rate effects on AM parts
  - Topology optimization would lead to further performance advantages
- Cost, build size, and quality control remain issues with AM parts
  - LENS and EBM development could have more long-term promise for larger-scale metal parts
  - Cost becomes more tolerable on small production runs. Savings could be achieved through elimination of weld inspection and testing.