Theoretical Understanding of Materials Science and Mechanics

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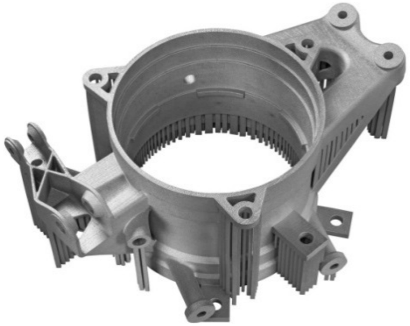
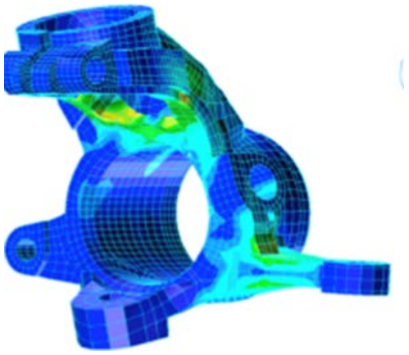


USNC/TAM Workshop

Session 5

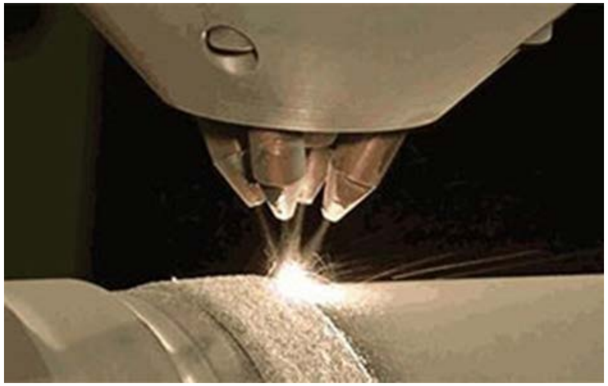
08 Oct 2015

Questions

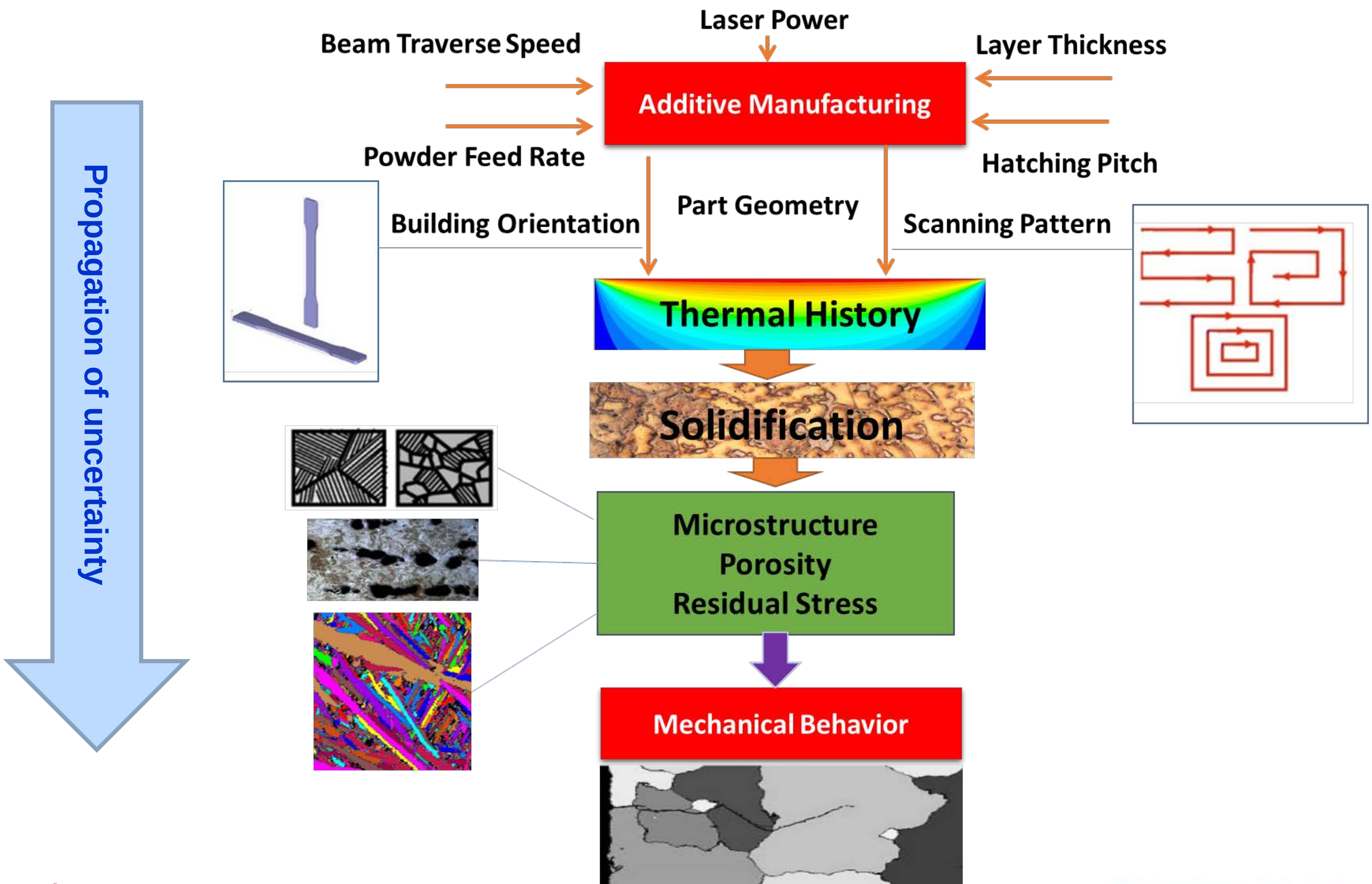


What multidisciplinary and related materials and mechanical sciences are needed for AM?

Do materials standards change with a theoretical and computational approach to materials development and implementation?



Additive Manufacturing Process



Multidisciplinary Science Needs

Powder-heat source interactions

Microstructure evolution under non-equilibrium conditions

Heat transfer in melt pool and HAZ

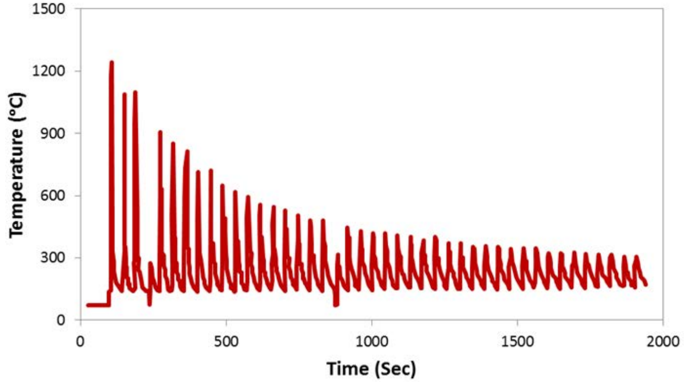
Origins of metallographic texture

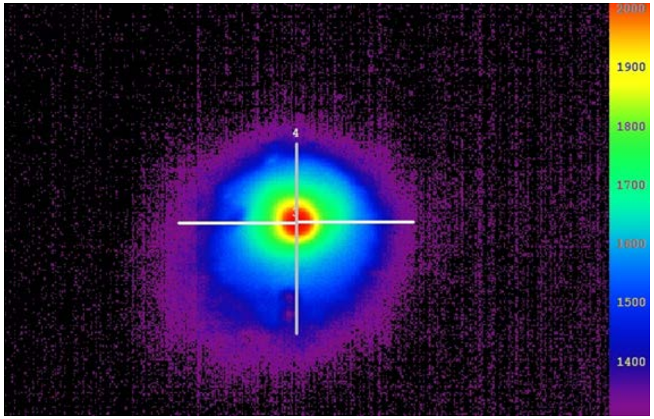
Elastic-plastic constitutive relationships

Residual stress and distortion prediction

Melt pool solidification

Physics of porosity development





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Microstructure Evolution is Key

Process Parameters

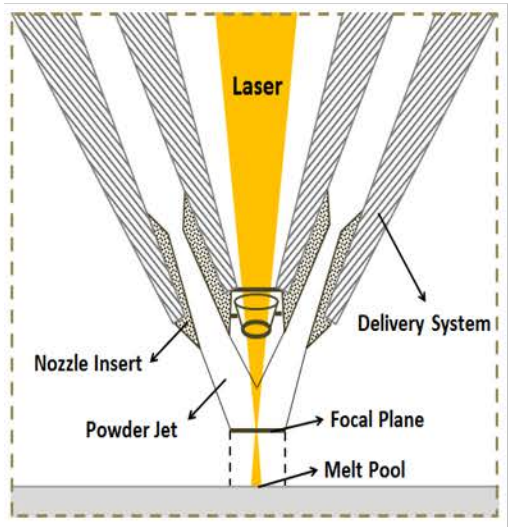
- Material
- Tool path
- Laser
- Scan speed
- Etc.

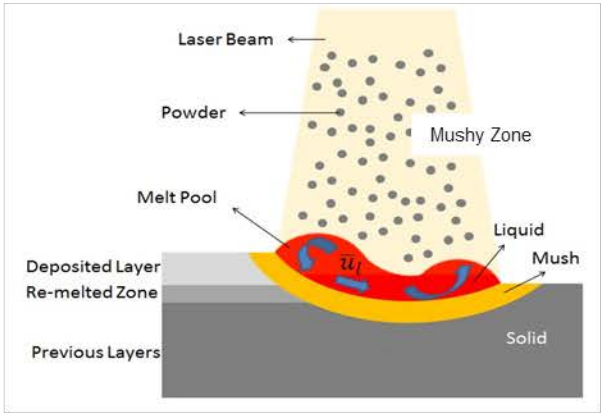
→ ***Heat Transfer***

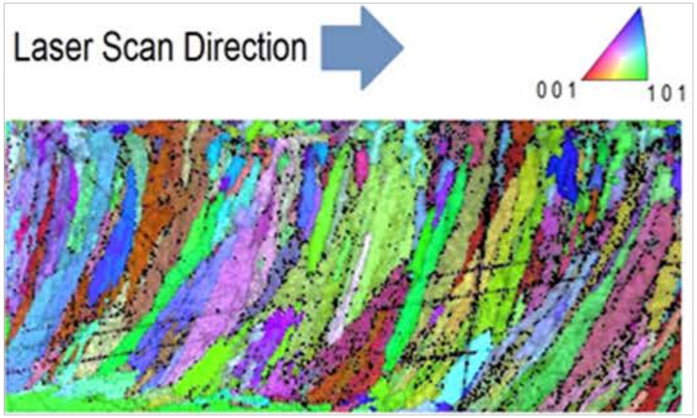
Cooling rate
Thermal history
Thermal cycling

→ ***Microstructure*** → ***Mechanical Properties***

Temperature Measurement → Process Control and Model Validation







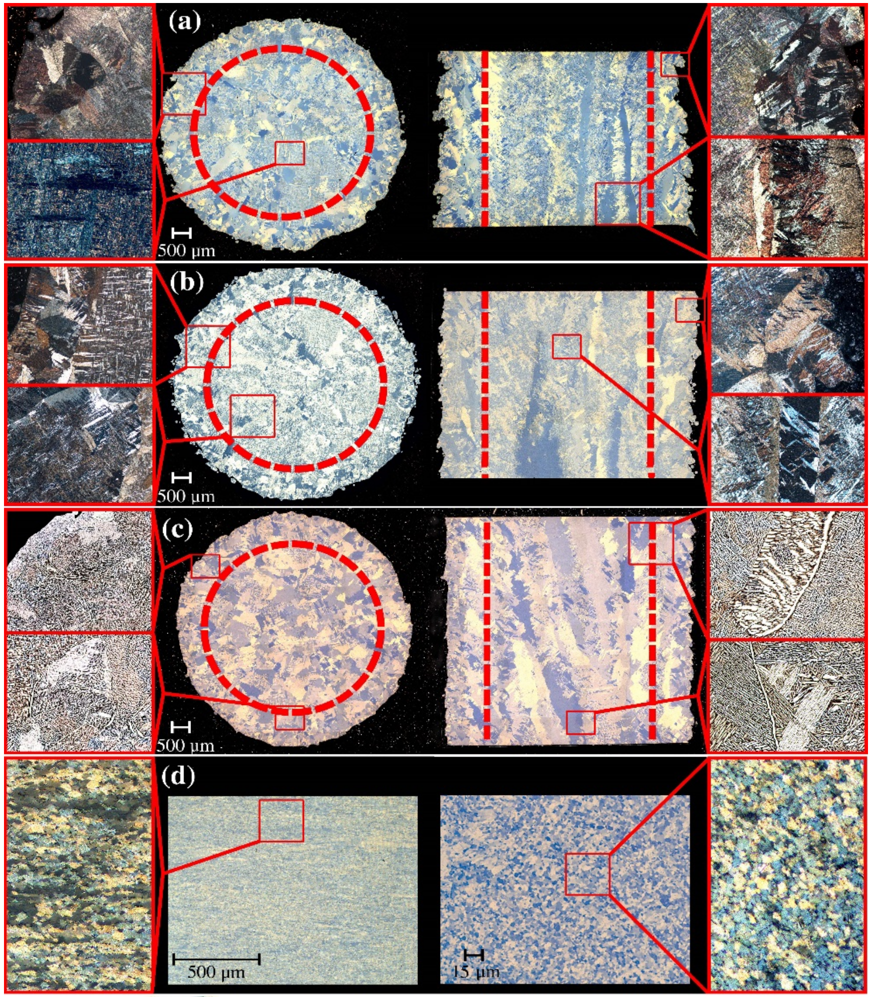
Effect of Heat Treatment on AM Ti-6Al-4V

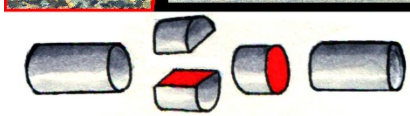
As-built

Annealed below β-transus temperature

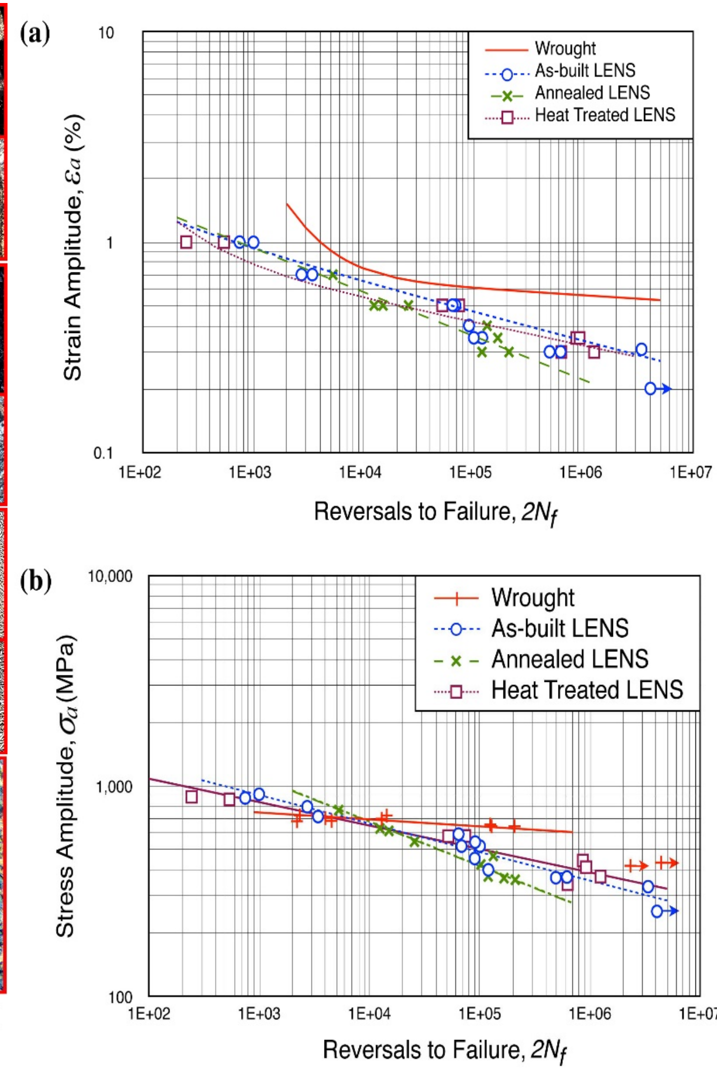
Heat treated above β-transus temperature

Wrought



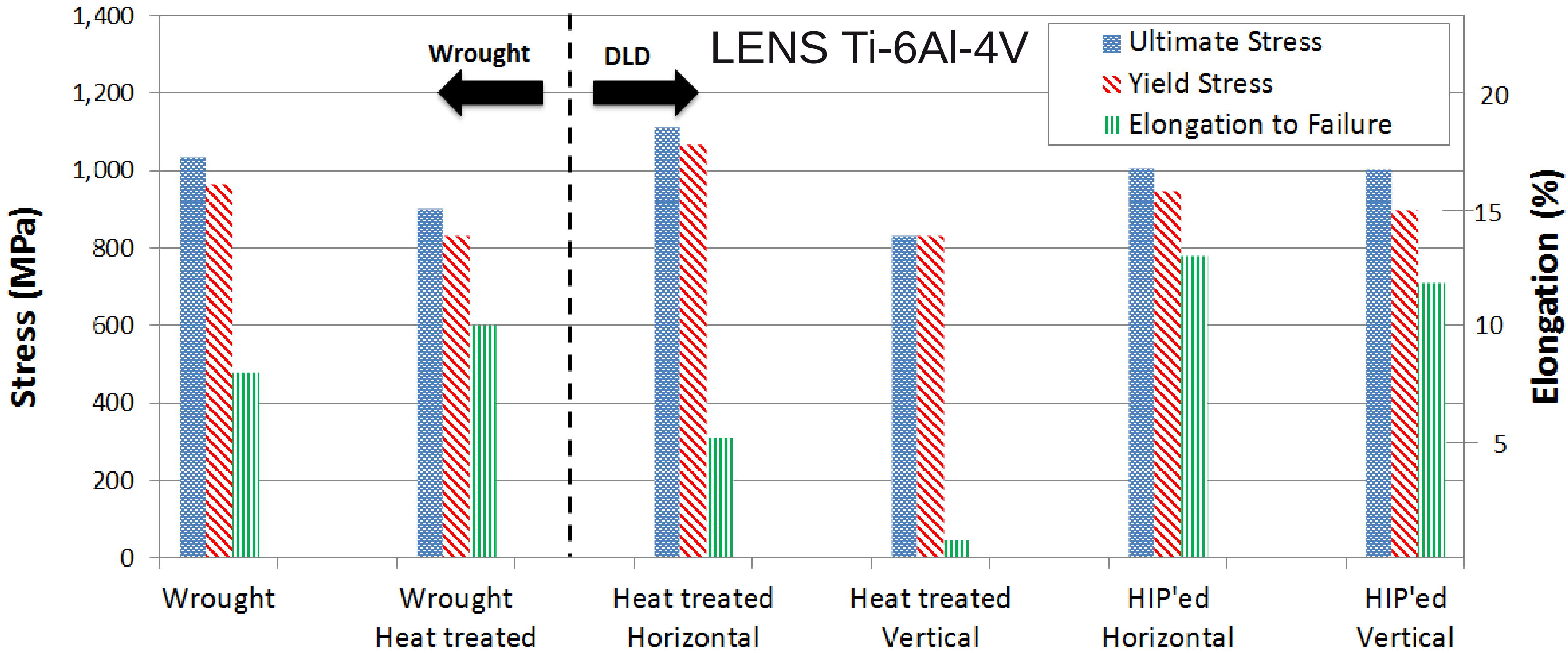


Both the radial cross-section and longitudinal cross-section were cut from the gage area.



Sterling, A.J., Torries, B., Lugo, M., Shamsaei, N., Thompson, S.M., 2015, “Fatigue Behavior of Ti-6Al-4V Alloy Additively Manufactured by Laser Engineered Net Shaping,” <u>*56th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*</u> Kissimmee, FL.

Tensile Behavior: Wrought vs. AM

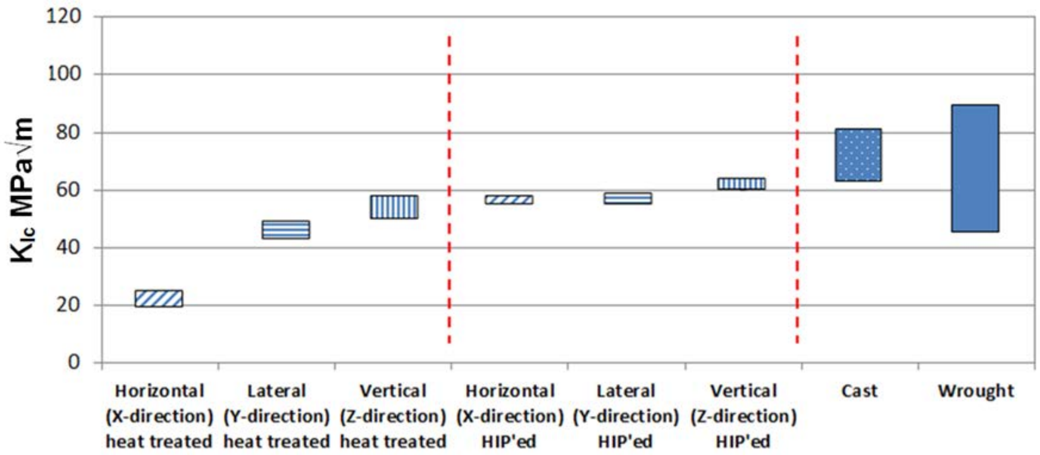


- Higher strength and less ductility/elongation compared to wrought

P.A. Kobryn, S.L. Semiatin, Mechanical properties of laser-deposited Ti-6Al-4V, Solid Free. Fabr. Proceedings. Austin. (2001) 179–186.

Fracture Toughness

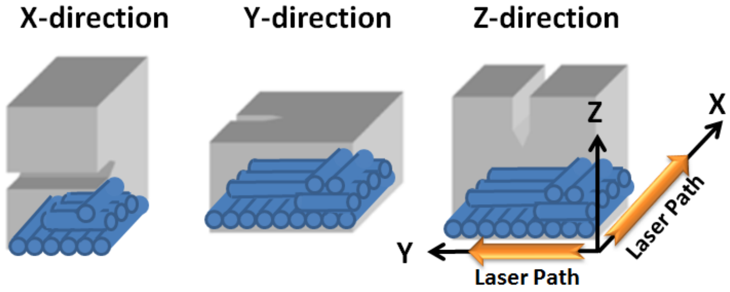
LENS Ti-6Al-4V



Significant anisotropy

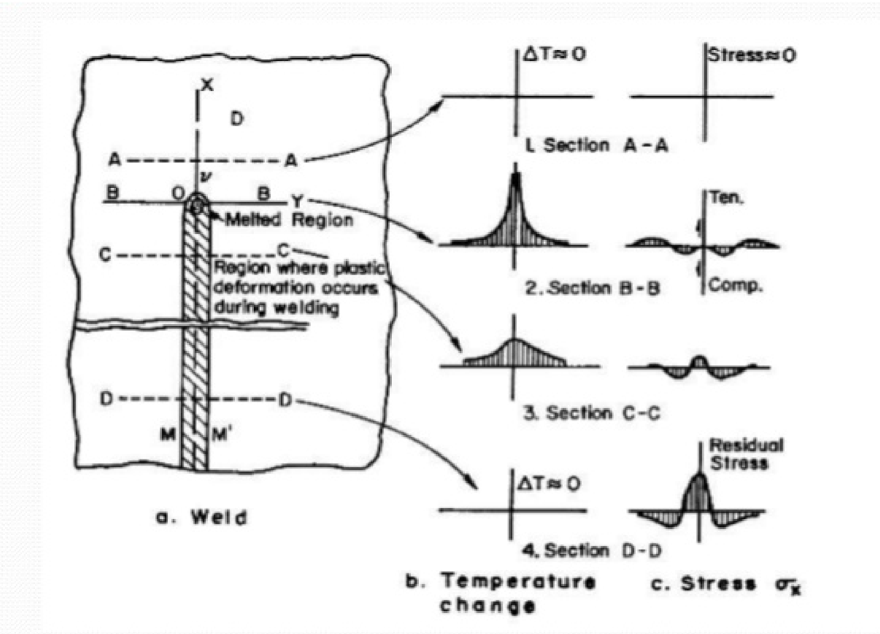
HIP process can:

- reduce anisotropy
- improve fracture toughness



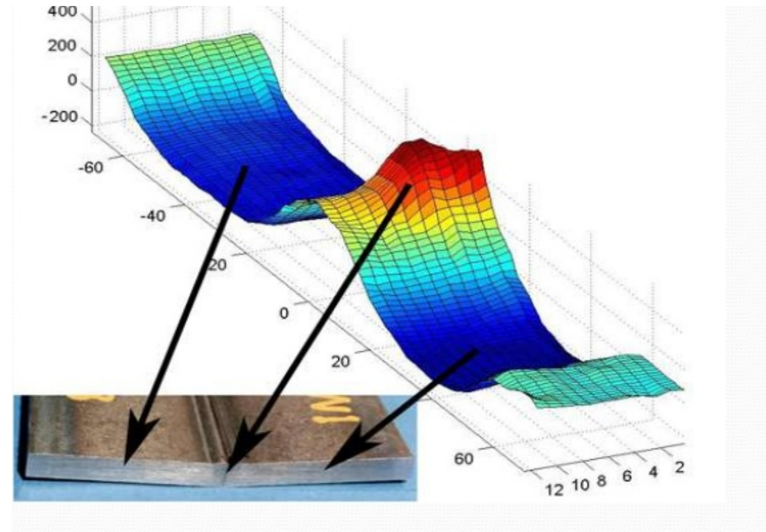
P.A. Kobryn, S.L. Semiatin, Mechanical Properties of Laser-Deposited Ti-6Al-4V, Solid Free. Fabr. Proceedings. Austin. (2001) 179–186.

Residual Stress

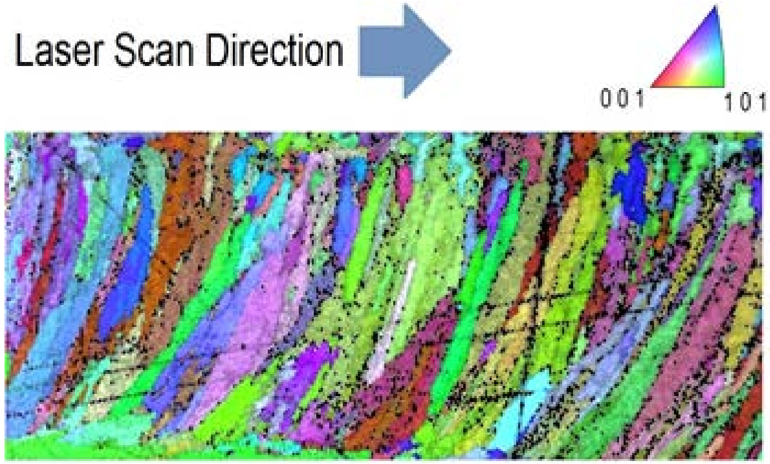


Analysis of Welded Structures, K. Masubuchi, 1980

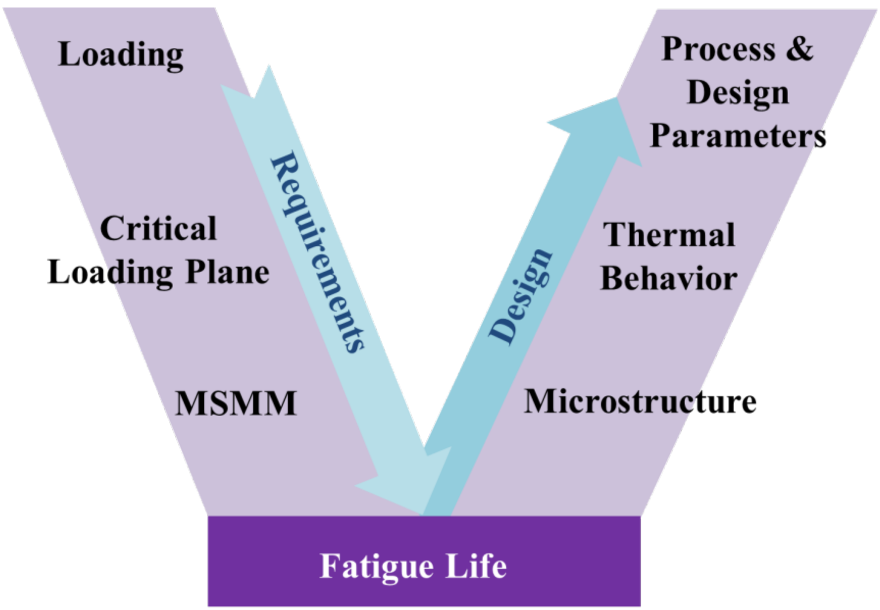
Thermal gradients produce residual stresses and subsequent distortion



Using AM for "Tailoring" Materials for Application



EBSD image of a single layer from LENS Ti-6Al-4V



Premise:

HPC

- Quantify service environment and potential loading
- Use a microstructurally-sensitive mechanical model (MSMM) to predict part performance virtually
- Optimize microstructure and determine a target thermal history
- Determine process/design parameters to produce parts via additive manufacturing

- **Build actual part for service**

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Mechanical and Materials Science Key Issues

Short Term
- Nonlinear elastic-plastic constitutive relationships
- Material properties at elevated temperatures
- Residual stress and distortion

Intermediate Term
- Microstructure evolution under non-equilibrium conditions

Long term
- Thermal monitoring and control to optimize builds and exploit unique microstructure

Materials Standards

- Strong need for standards
- Variability and uncertainty and reproducibility
- ASTM Committee F42 on Additive manufacturing
- ASTM Committee E08 on Fatigue and Fracture
- ASTM Committee E07 on Nondestructive Testing

- **Virtual prototyping can *accelerate* standards development**

Materials Standards Key Issues

Short Term

- Existing standards are in their infancy

Intermediate Term

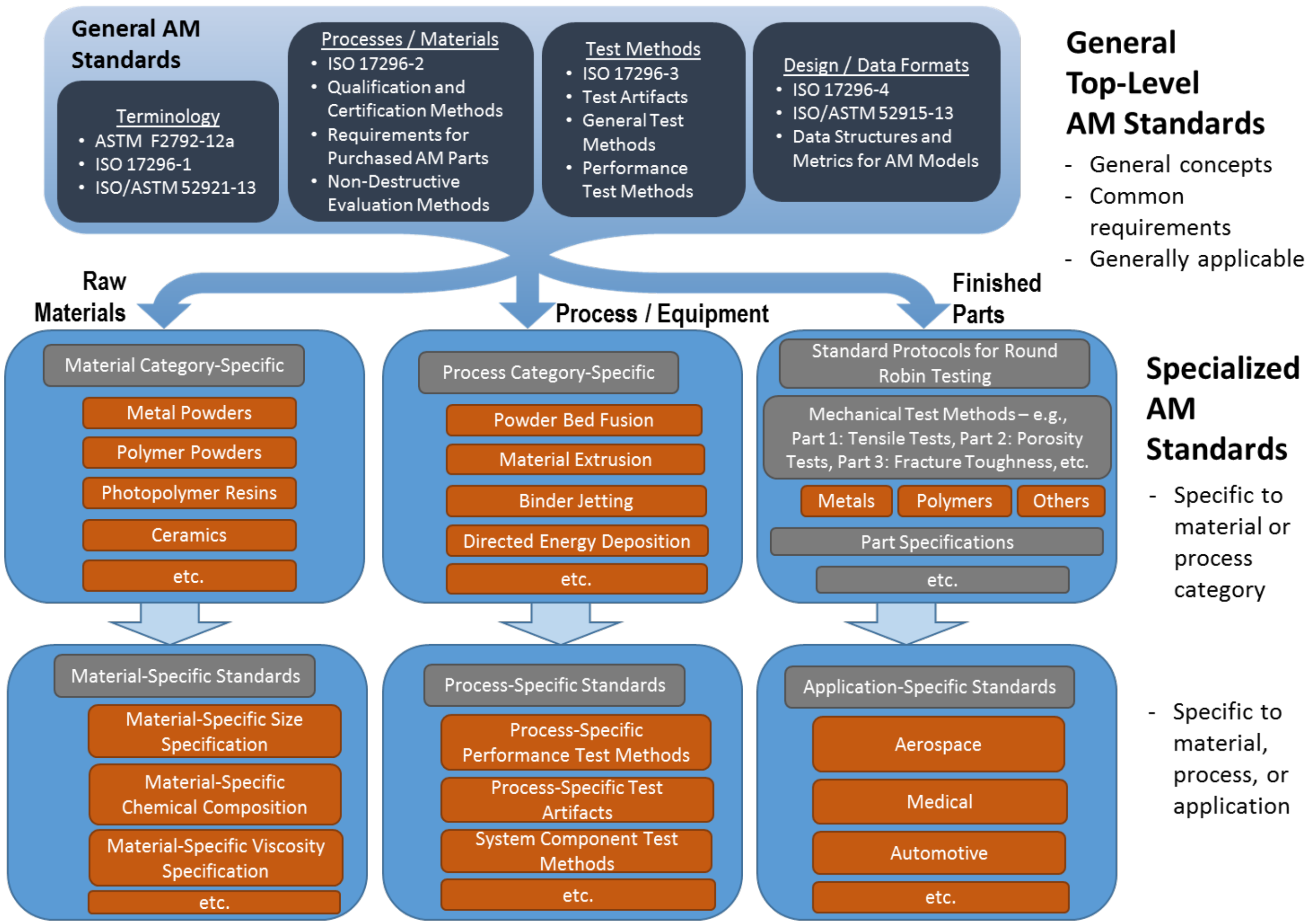
- Understand difference between coupons and components

Long term

- Virtual prototyping can accelerate standards development

F42 Activity

Proposed Structure of AM Standards



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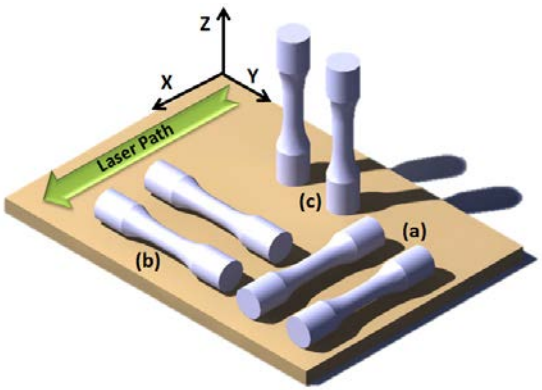
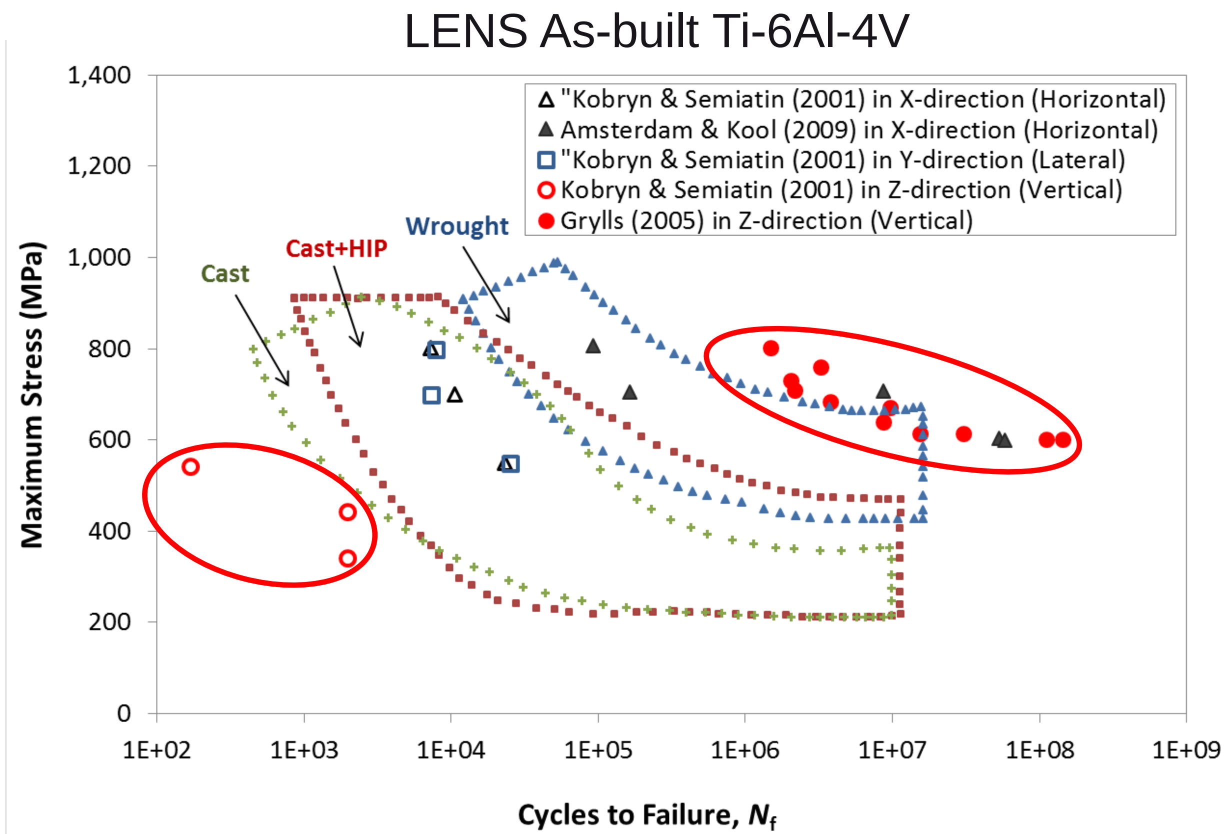
Anisotropy Effect on Fatigue Behavior of AM Parts





- Significant anisotropy effects
- Different process parameters results in different mechanical behavior
- Lack of process/testing standardization causes variability in results

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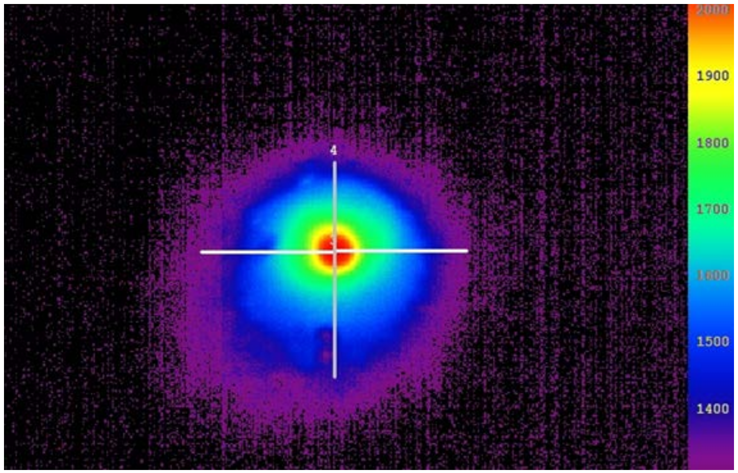
Back Up Slides

Transport Phenomena



Laser

- type, power, frequency
- beam profile, diameter and offset
- substrate/laser relative speed
- scanning pattern, idle time
- laser-induced plasma & pressure

Blown Powder Dynamics

- nozzle specifications
- particle feed rate, frequency, efficiency, idle time
- particle/carrier-gas interaction (drag)
- particle/particle interaction (collisions)
- particle/melt pool interaction (mass reflection/absorption)
- body force interaction

Blown Powder Energy Transfer

- laser/powder interaction
  - attenuation, scattering, absorption
- mid-flight pre-heating, melting and evaporation

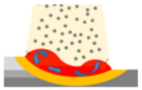
Melting (Useful Energy Utilization)

- melt pool initiation (melting of submerged powder)
- melt pool/laser interaction (absorption)

Melt Pool Heat Loss

- convection to shielding/carrier gas
- radiation/reflection to surroundings
  - variant emissivity, reflectivity
- melt pool evaporation

Melt Pool Dynamics



- melt pool/powder interaction (splashing, mass addition)
- temperature distribution (superheat)
- radiation transmission
- wetting behavior with pre-deposited layers and gas (surface tension, contact angle variation, oxidization)
- profile stability (boiling, vapor re-coil)
- fluid dynamics (Marangoni convection, density-driven flows, body forces)

Conduction

- Heat Affected Zone (HAZ) volume/depth
- high heat flux transport
- sensible heating / thermal cycling
- substrate interaction (heat sinking effects)

Part Heat Loss

- convection to inert gas
- radiation to surroundings
  - emission, absorption

Solidification

- enthalpy of fusion (melt pool dissolution)
- re-melting of previous layers
- porosity / inert gas entrapment
- heterogeneous nucleation of solid participate
- mushy zone thermo/fluidics

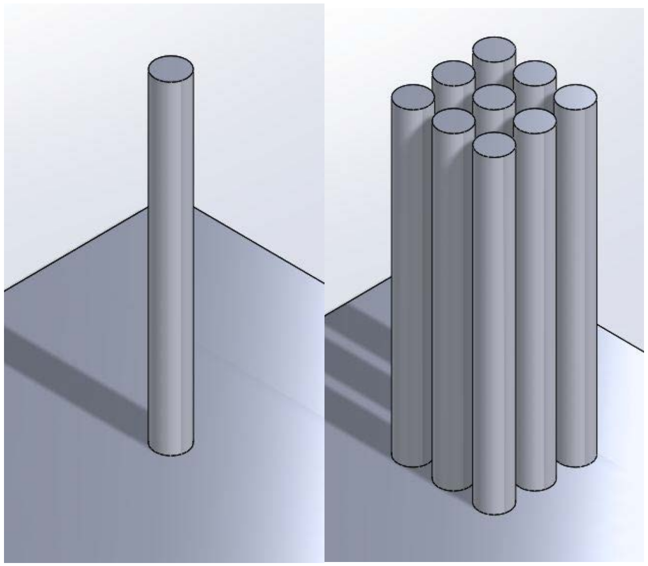
Microstructural Evolution

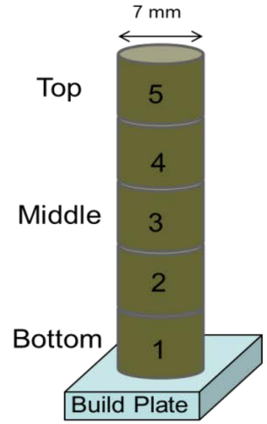
- dendritic solidification/growth
- dilution of chemical constituents
- mass transfer

Mechanical Analysis

- stress modeling , residual stress
- elastic, plastic and thermal strain
- warping, epitaxy

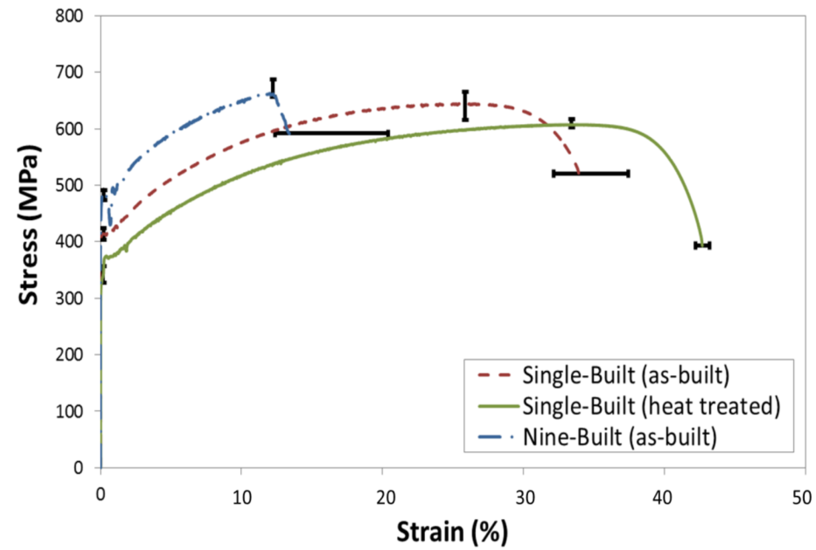
Effect of Size and Geometry





Yield Stress (MPa)		
Single-Built (as-built)	Single-Built (heat treated)	Nine-Built (as-built)
408	307	480
384	306	477
350	301	475
390	321	485
410	322	487

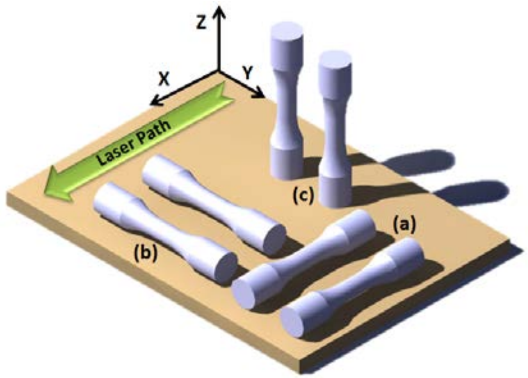
LENS 316L SS

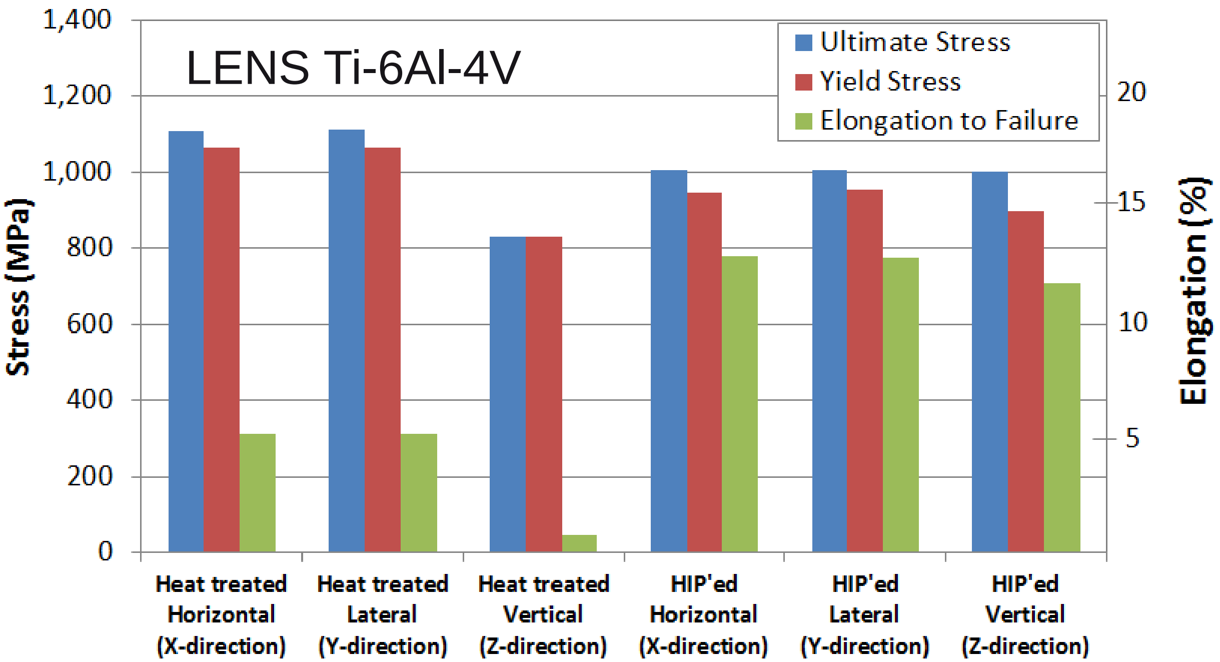


- Process and design parameters should be adjusted depending on part's dimensions/geometry
- Mechanical properties vary within the parts

Yadollahi, A., Shamsaei, N., Thompson, S.M., Seely, D., 2015, "Effects of Time Interval and Heat Treatment on the Mechanical and Microstructural Properties of Direct Laser Deposited 316L Stainless Steel," *Materials Science and Engineering A*, **644**, pp. 171-183.

Tensile Behavior: Building Orientation





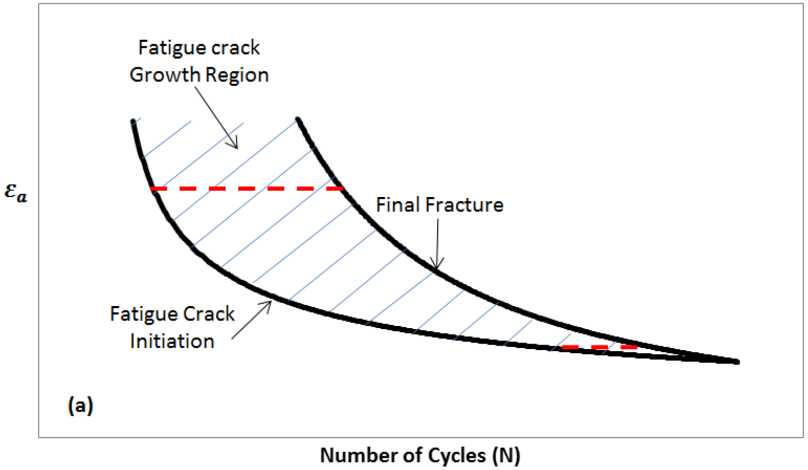
- No difference between X and Y specimens as the tool path rotated 90° between each layer
- Significant anisotropy between vertical and horizontal builds
- Post build heat treatment did not help
- Hot isostatic pressing (HIP) removed anisotropy and increased elongation, but reduced strength

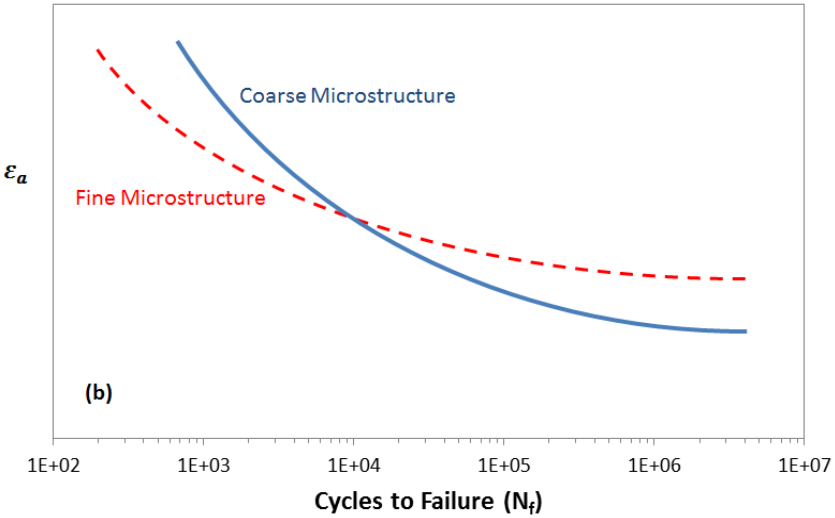
P.A. Kobryn, S.L. Semiatin, Mechanical properties of laser-deposited Ti-6Al-4V, Solid Free. Fabr. Proceedings. Austin. (2001) 179–186.

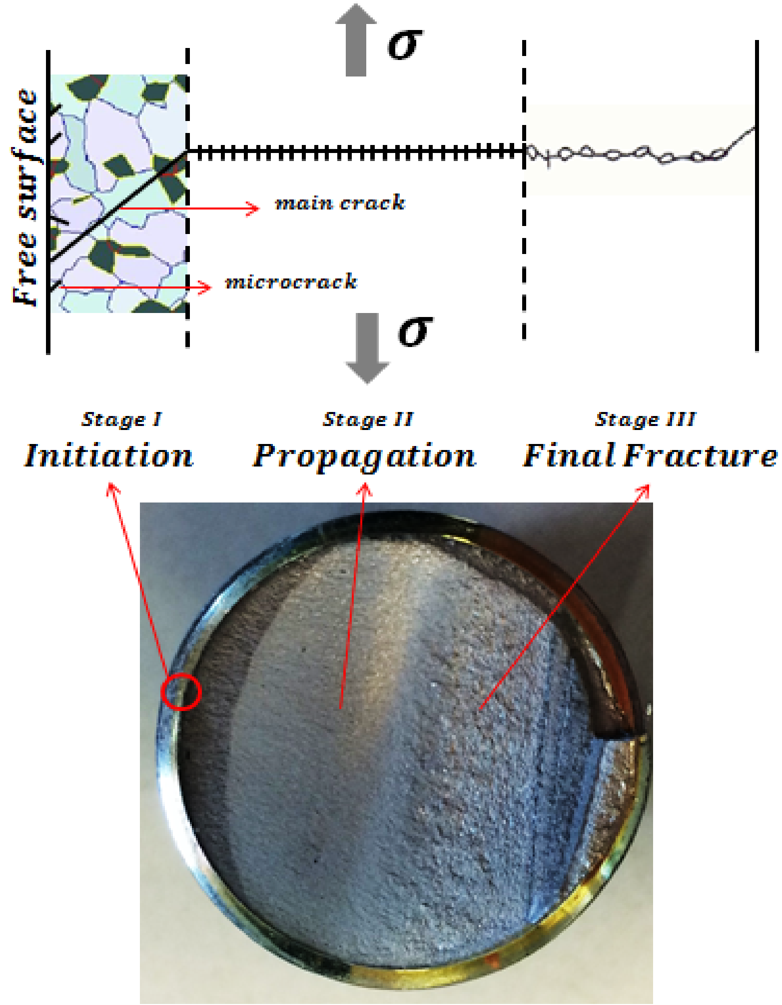
Monotonic Tensile Behavior: Summary

- Significant directionality (anisotropy) in strength
- AM parts have higher strength but lower ductility
- Post build processes (e.g. machining, heat treatment) can be used to increase ductility and reduce directionality
- Process parameters should change with part size and number
- AM parts are not homogeneous; as microstructure and mechanical properties vary within part

Fatigue: Background

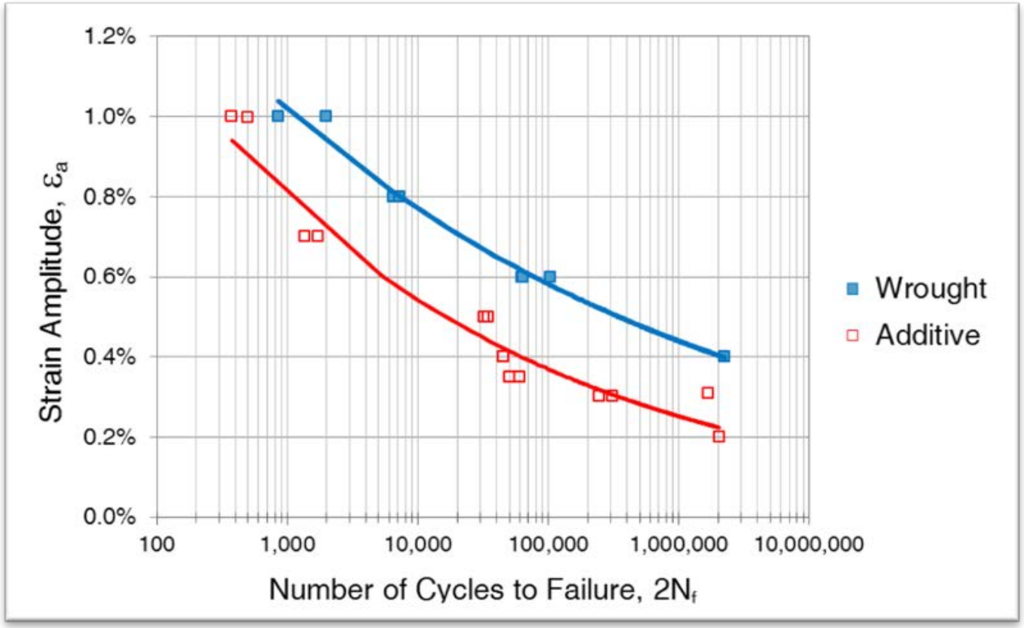


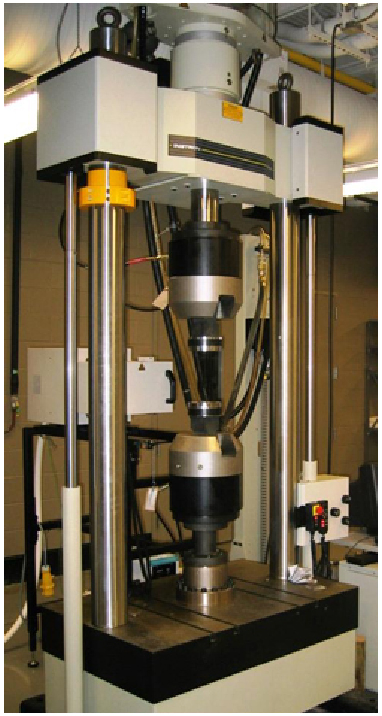




Fatigue of AM Ti-6Al-4V

Strain Life Curve: Wrought & LENS Ti-6Al-4V





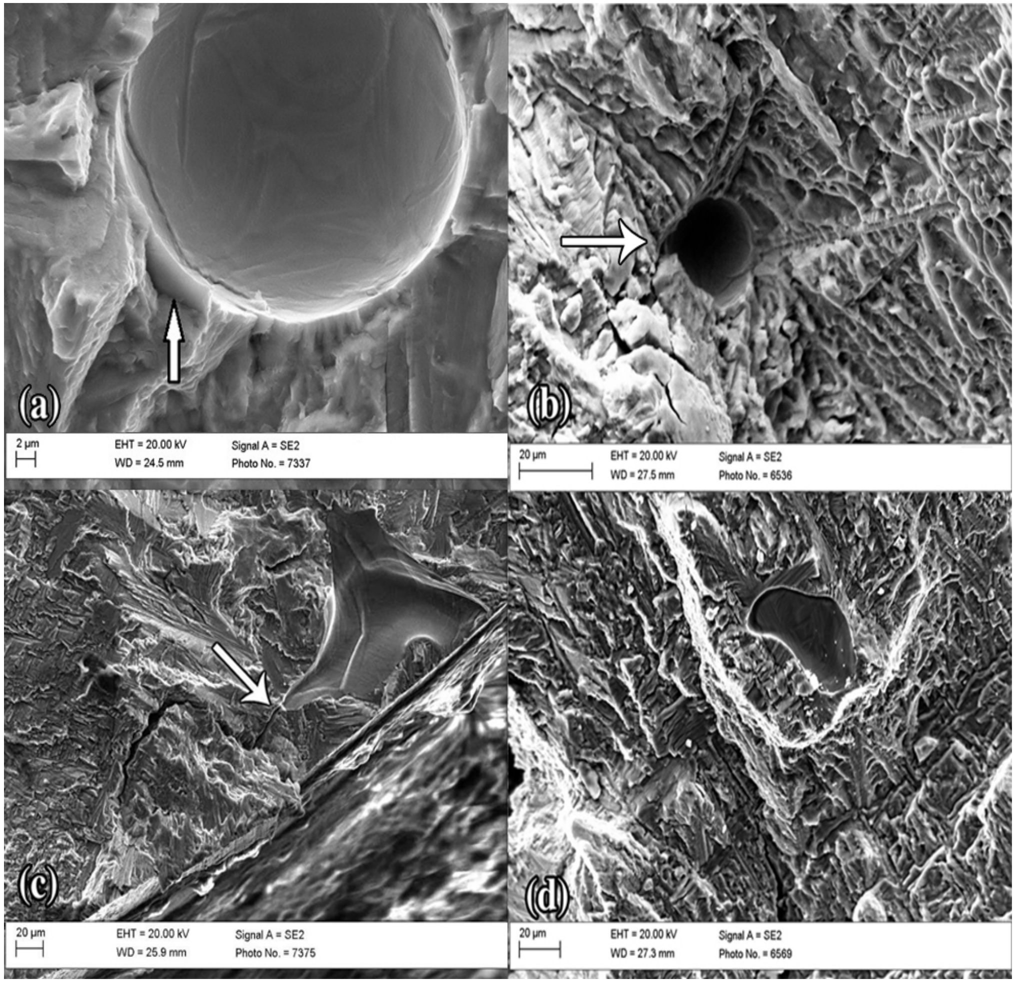
- **An order of magnitude** shorter fatigue lives for AM samples as compared to wrought samples.
- Such shorter fatigue lives may be related to the lack of ductility as well as presence of defects in AM samples.

Sterling, A.J., Torries, B., Lugo, M., Shamsaei, N., Thompson, S.M., 2015, “Fatigue Behavior of Ti-6Al-4V Alloy Additively Manufactured by Laser Engineered Net Shaping,” _56th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference_ Kissimmee, FL.

Porosity in AM Ti-6Al-4V

Fatigue life decreases with presence of:

- Larger pores
- Near-surface pores
- Closely-packed pores (pore density)
- More irregularly-shaped pores



- Some porosity introduced by partially melted (un-melted) particles
- Very little correlation was found between the number of pores and fatigue life of specimens

Sterling, A.J., Torries, B., Lugo, M., Shamsaei, N., Thompson, S.M., 2015, "Fatigue Behavior of Ti-6Al-4V Alloy Additively Manufactured by Laser Engineered Net Shaping," _56th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference_ Kissimmee, FL.

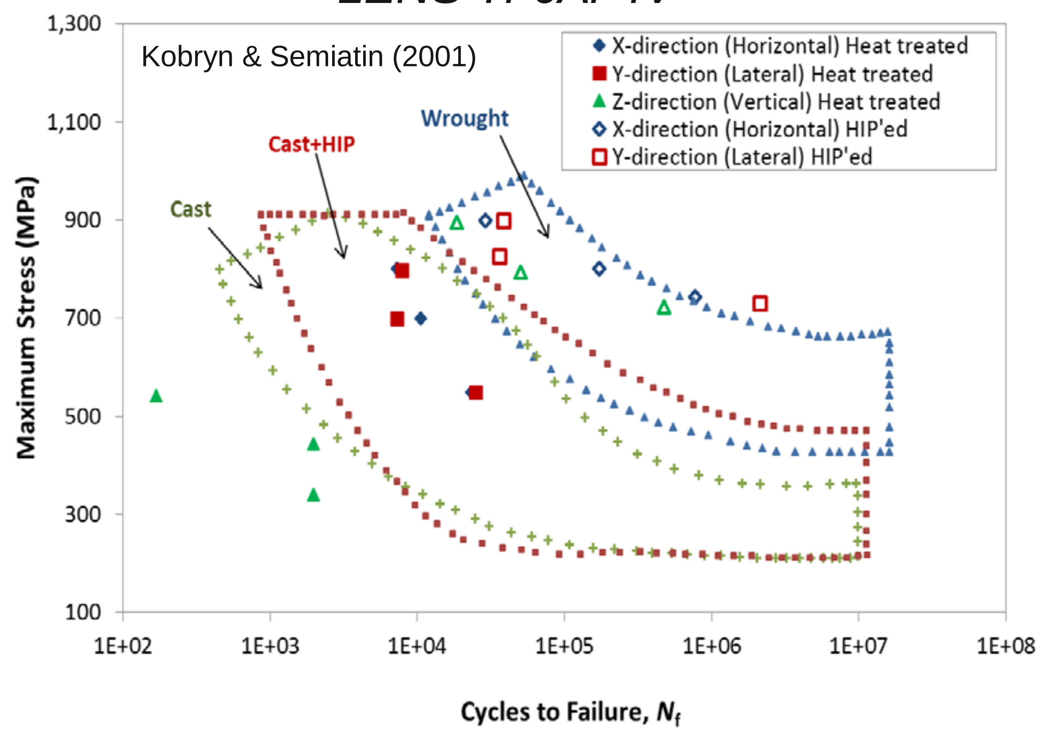
Post-Processing via HIP

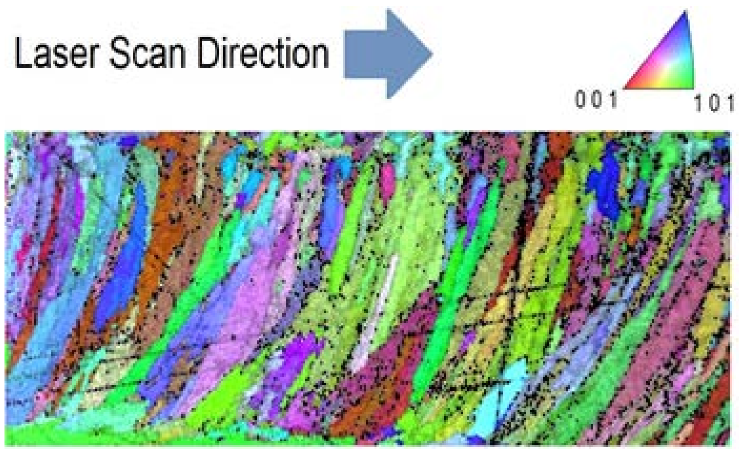
Hot Isostatic Pressing (HIP)

- reduce anisotropy
- improve fatigue resistance

However, any targeted microstructural features (a known benefit of AM) are removed

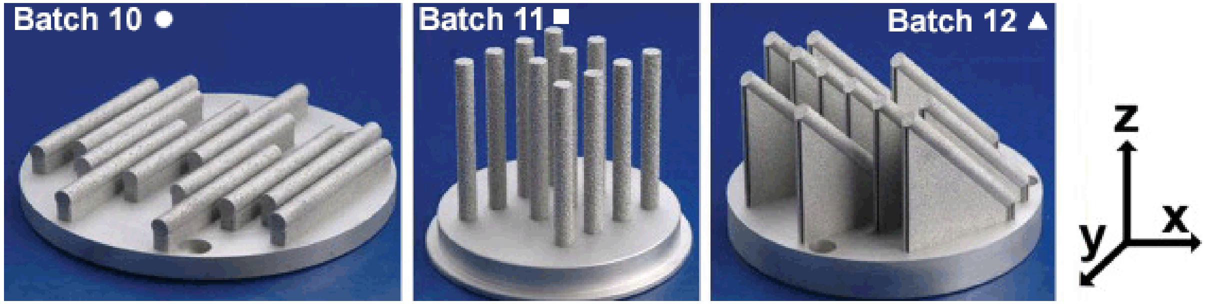
LENS Ti-6Al-4V



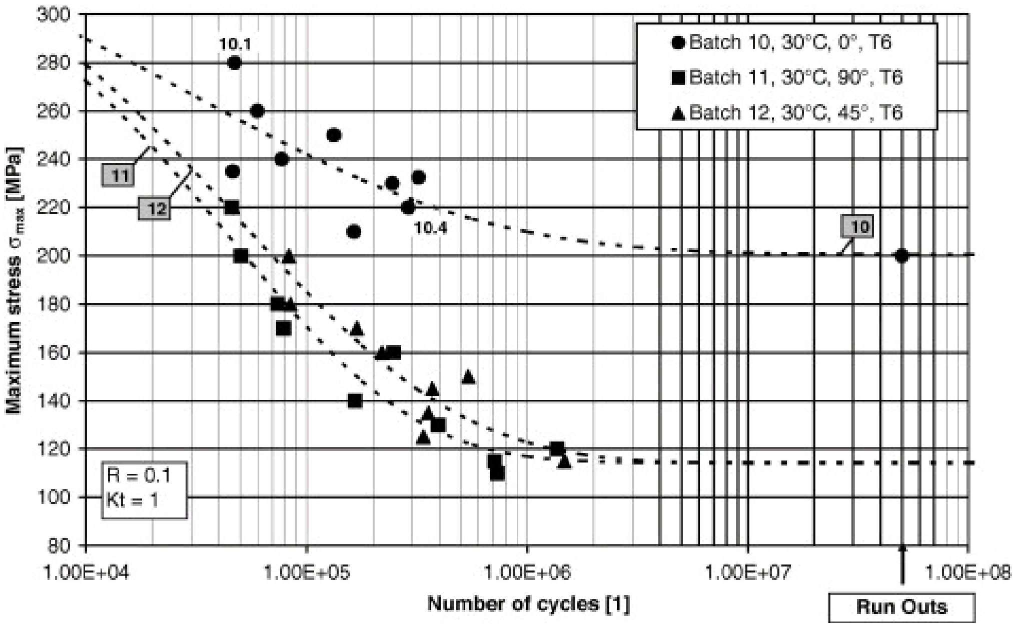


- EBSD image of a single layer deposited by LENS
- Microstructural tailoring for enhancing structural integrity

Anisotropy in SLM Parts

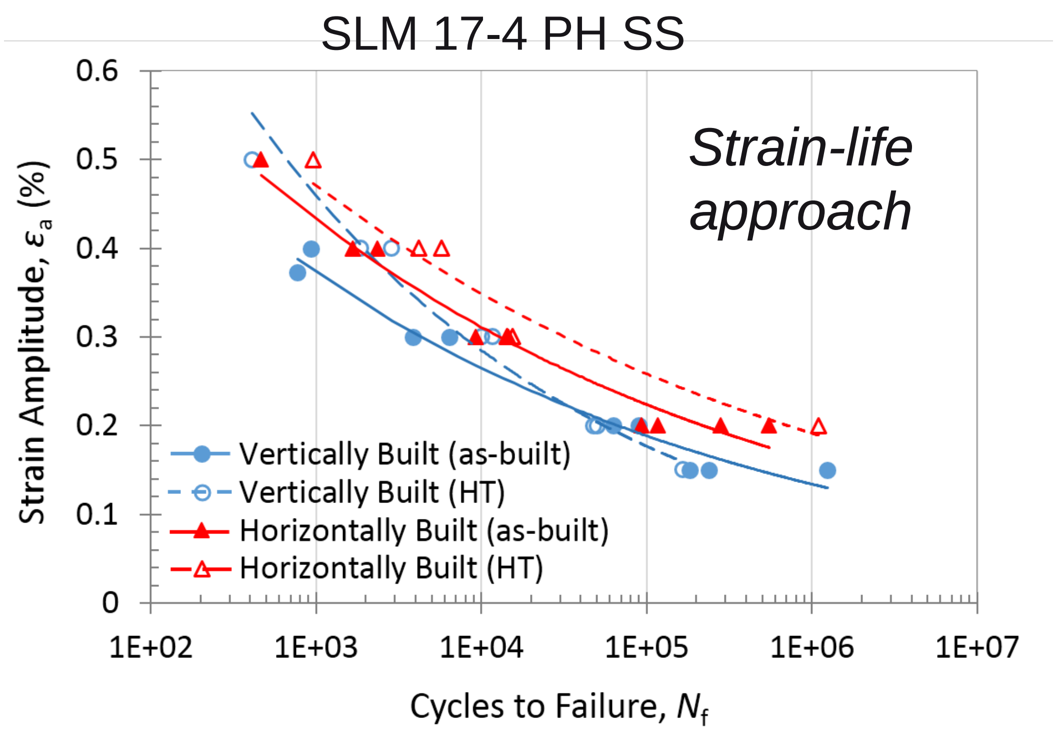


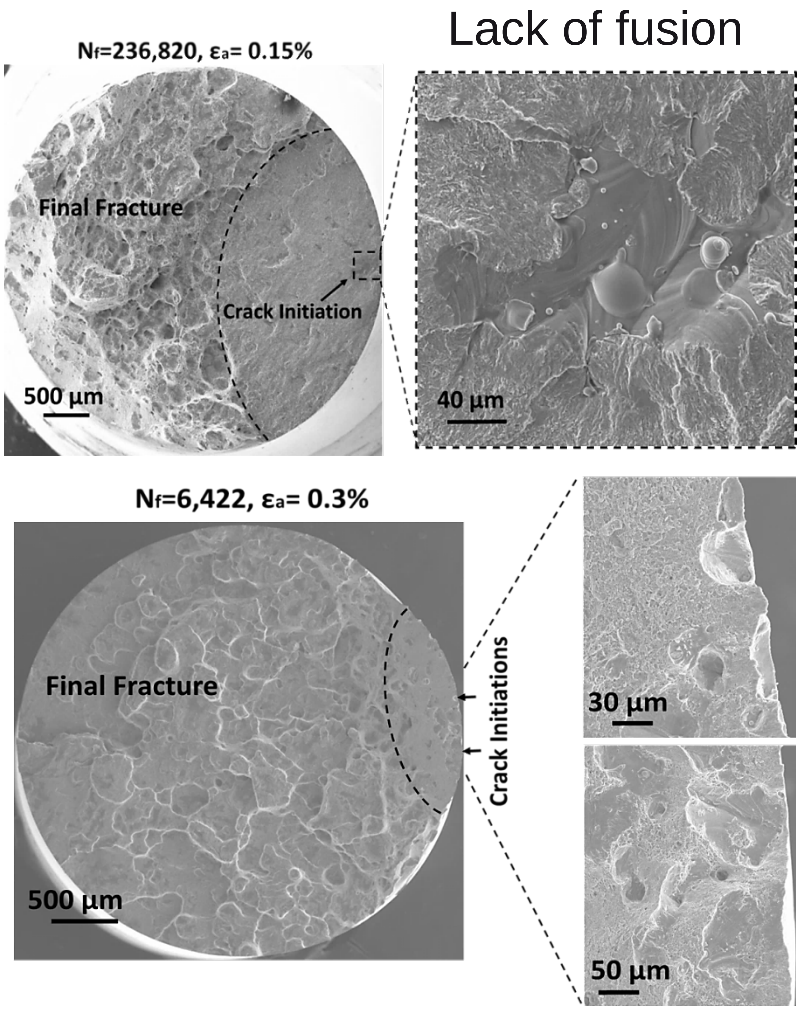
Stress-life approach



Brandl, E., Heckenberger, U., Holzinger, V., & Buchbinder, D. (2012). Additive manufactured AlSi10Mg samples using Selective Laser Melting (SLM): Microstructure, high cycle fatigue, and fracture behavior. Materials & Design, 34, 159-169.

Effects of Post-Processing on SLM Parts

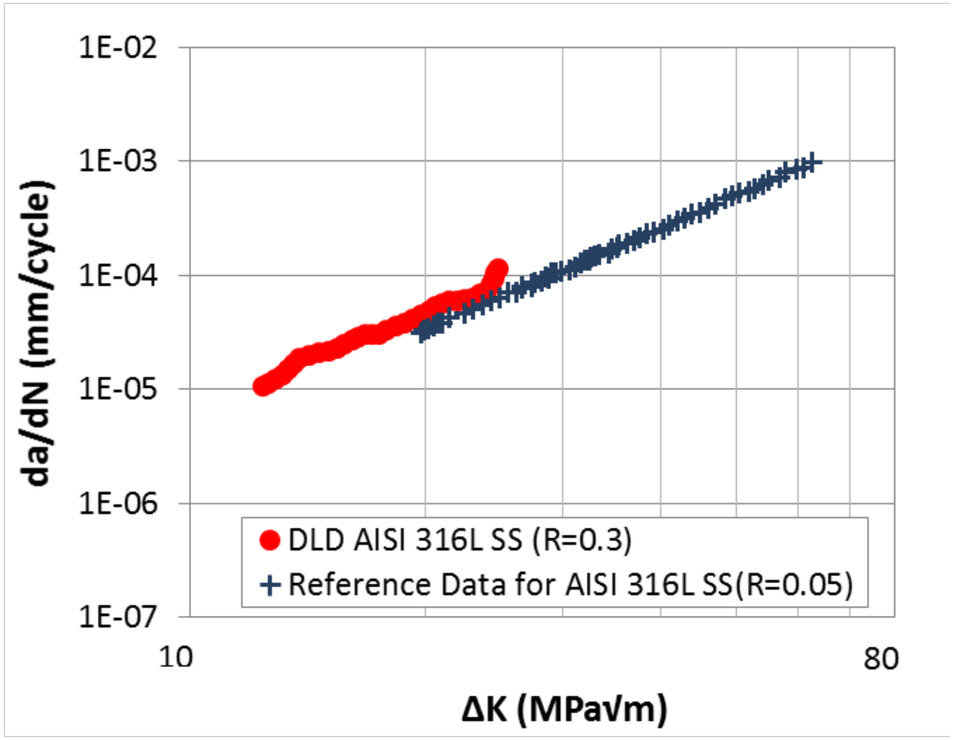




- **Significant anisotropy**
- **Cracks initiate from near surface defects**
- **Heat treatment:**
  - **did not reduce anisotropy**
  - **but, improved fatigue resistance**

Aref Yadollahi, Nima Shamsaei, Scott M. Thompson, Alaa Elwany, Linkan Bian, Fatigue Behavior of Selective Laser Melted 17-4 PH Stainless Steel, Solid Free. Fabr. Proceedings. Austin. (2015).

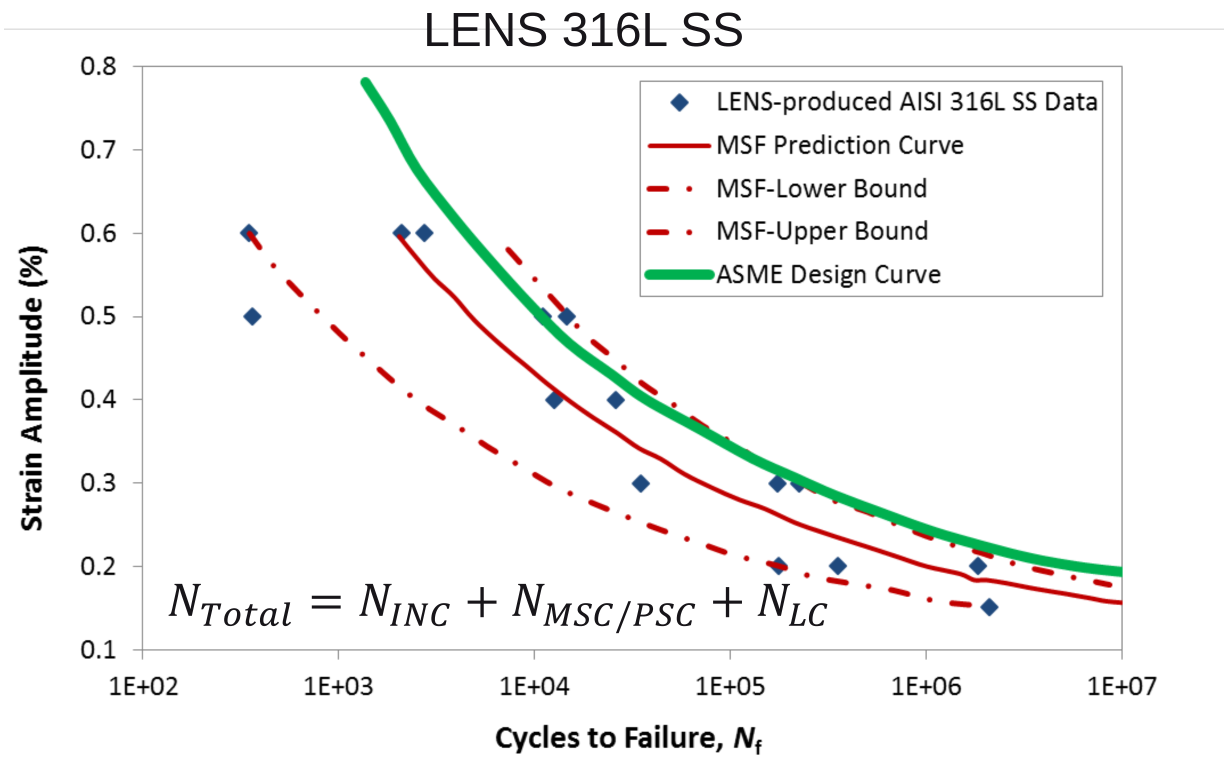
Fatigue Crack Growth Behavior in AM Parts

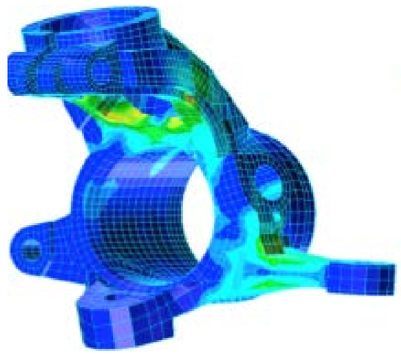


- Crack growth resistance of AM parts may be superior to wrought materials if appropriate process and design parameters are utilized
- In general, fatigue crack growth resistance of AM parts is not well understood

P. Ganesh, R. Kaul, G. Sasikala, H. Kumar, S. Venugopal, P. Tiwari, et al., Fatigue Crack Propagation and Fracture Toughness of Laser Rapid Manufactured Structures of AISI 316L Stainless Steel, Metallogr. Microstruct. Anal. 3 (2014) 36–45.

Microstructure-Sensitive Fatigue Model





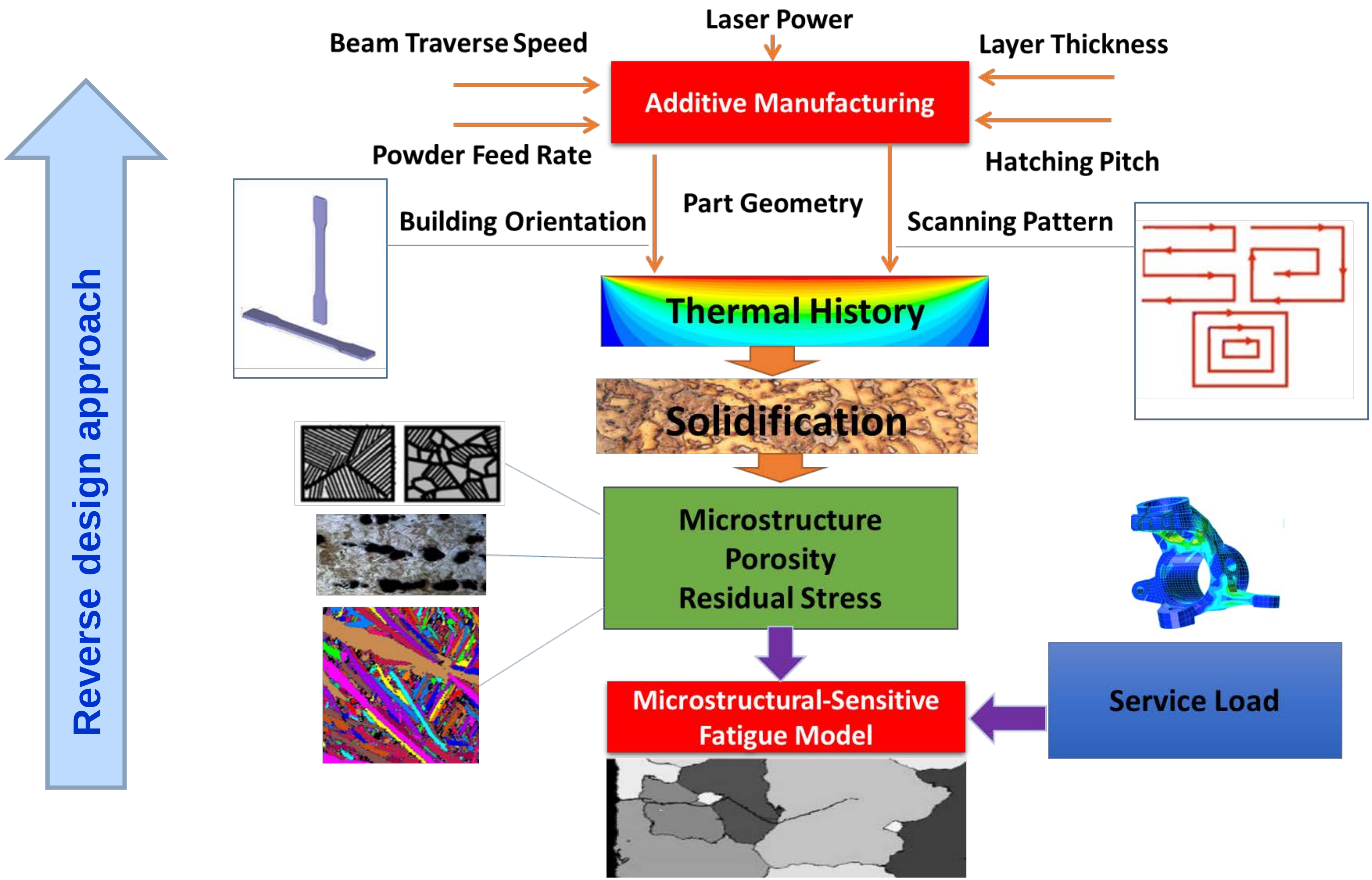
- Fatigue behavior of AM parts mainly depends on the microstructure resulting from processing and design parameters
- A **microstructure-sensitive fatigue model** that can incorporate microstructural features may be appropriate for modeling the fatigue behavior of AM parts
- ***Both*** stress and strength vary within the AM part

Y. Xue, A. Pascu, M.F. Horstemeyer, L. Wang, P.T. Wang, Microporosity effects on cyclic plasticity and fatigue of LENS-processed steel, Acta Mater. 58 (2010) 4029–4038.

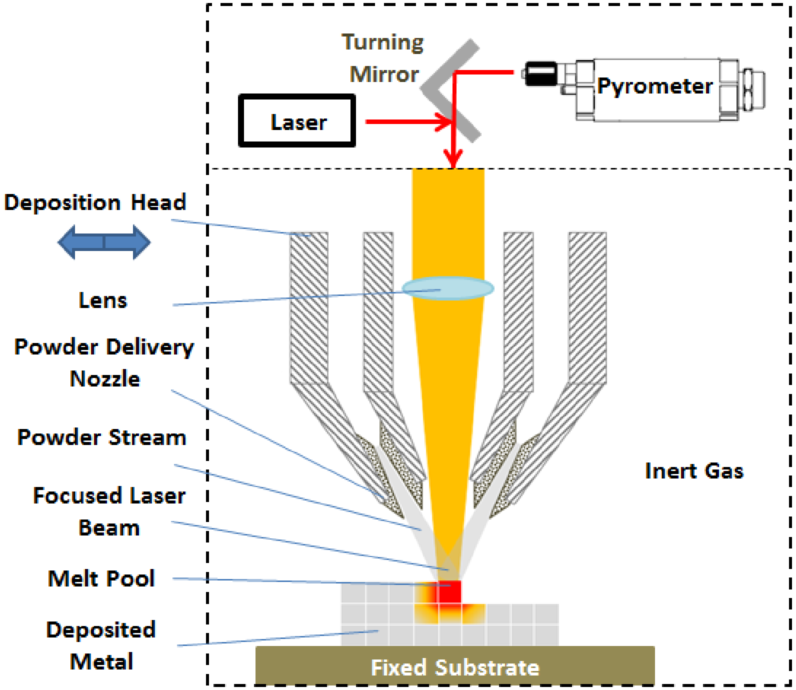
Fatigue Behavior: Summary

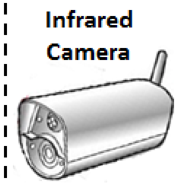
- Significant directionality
- Cracks initiate from pores, un-melted powder particles, and at regions with lack of fusion
- Post build treatments can reduce anisotropy and improve fatigue resistance; however, it removes any benefits gained from anisotropy
- Microstructure-sensitive fatigue models can be developed and calibrated for AM parts – reflecting the microstructural effects on fatigue behavior
- Depending on manufacturing and post-manufacturing process parameters, fatigue of AM parts can be superior or inferior to traditionally-manufactured parts
- Extensive research needed to better understand process-property-performance relationships for AM materials

Application Driven Design for Additive Manufacturing

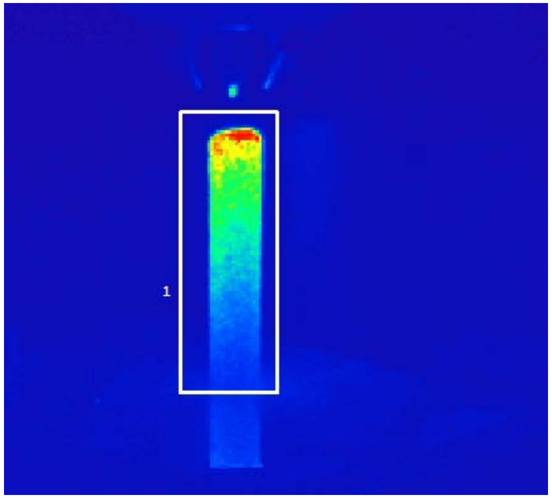


In-Situ Thermal Monitoring and Control

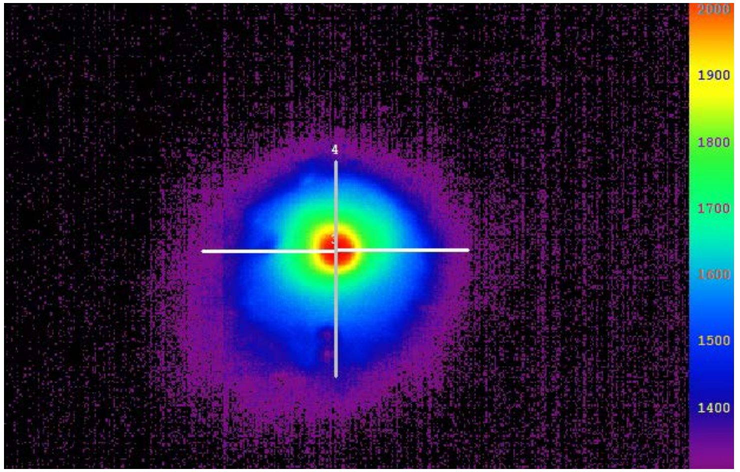




Thermal profile of part



Molten pool temperature distribution



Thermography Benefits

- Quantify cooling rates, thermal history
- Real-time part quality/features control

Ongoing Challenges

- Residual stresses and distortion
- Surface finish
- Is there an endurance limit for AM materials?
- Quantification of uncertainty in AM processes
- Certification/Standards
- In-situ- and post-quality control
- Fatigue behavior under torsion and multi-axial loading (possible benefits of directional properties)
  - Should we use HIP for all products? Post-processing?
  - Process/design optimization may be a better approach in minimizing defects

Questions?

Please contact:

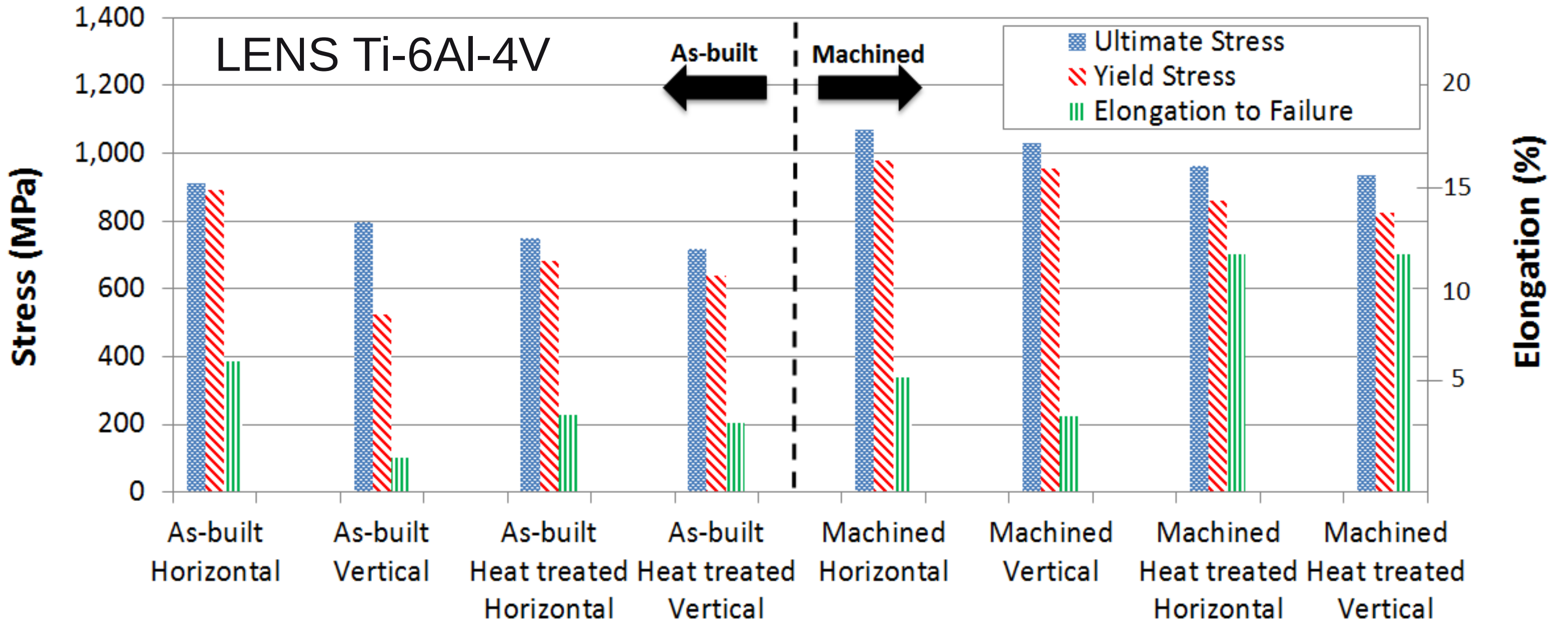
Steve R. Daniewicz
daniewicz@me.msstate.edu

<u>**This presentation has been based on the following articles:**</u>

Scott M Thompson, Linkan Bian, Nima Shamsaei, Aref Yadollahi. **An overview of Direct Laser Deposition for additive manufacturing; Part I: Transport phenomena, modeling and diagnostics.** Additive Manufacturing. Vol. 8, pp. 36-62.

Nima Shamsaei, Aref Yadollahi, Linkan Bian, Scott M Thompson. **An overview of Direct Laser Deposition for additive manufacturing; Part II: Mechanical behavior, process parameter optimization and control**. Additive Manufacturing. Vol. 8, pp. 12-35.

Tensile Behavior: Effect of Machining



- Machining removes the outer surface and improves strength and ductility
- Specimen core has mostly columnar microstructure parallel to loading direction
- Residual stresses can be removed by the post build machining
- Machining also reduces the effects of building orientation

Alcisto, J. et al. Tensile Properties and Microstructures of Laser-Formed Ti-6Al-4V. *Journal of Materials Engineering and Performance*, 20, (2010) 203–212.

Tensile Behavior: Common Trends

Alloys	Ultimate Stress (MPa)		Yield Stress (MPa)		Elongation to failure (%)		AM Process
	Wrought	DLD	Wrought	DLD	Wrought	DLD	
316 SS	586[1]	758[1]	234[1]	434[1]	50[1]	46[1]	LENS
316L SS	480[*2]	540-560[3]	170[*2]	330-345[3]	40[*2]	35-43[3]	Laser consolidation
404L SS	…	655[1]	276[1]	324[1]	55[1]	70[1]	LENS
AISI H-13	1,725[1]	1,703[1]	1,448[1]	1,462[1]	12[1]	1-3[1]	LENS
CPM-9V	…	1,315[3]	…	821[3]	…	>2[3]	Laser consolidation
Ti-6Al-4V	931[‡1]	896-1,000[‡1]	855[‡1]	827-965[‡1]	10[‡1]	1-16[‡1]	LENS
TC-18	1,157[‡5]	1,147-1,188[‡5,6]	1,119[‡5]	1,095[‡5,6]	14[‡5]	4.5-5.75[‡5,6]	Laser melting deposition
IN-718[3]	1,379[†1]	1,400[†1]	1,158[†1]	1,117[†1]	20[†1]	16[†1]	LENS
IN-625	834[1]	931[1]	400[1]	614[1]	37[1]	38[1]	LENS
IN-600	660[‡1]	731[1]	285[‡1]	427[1]	45[‡1]	40[1]	LENS
IN-690	725[4]	665[3]	348[4]	450[3]	41[4]	49[3]	DLF
IN-738	1,095[4]	1,200[3]	950	870[3]	6.5[4]	18[3]	Laser consolidation

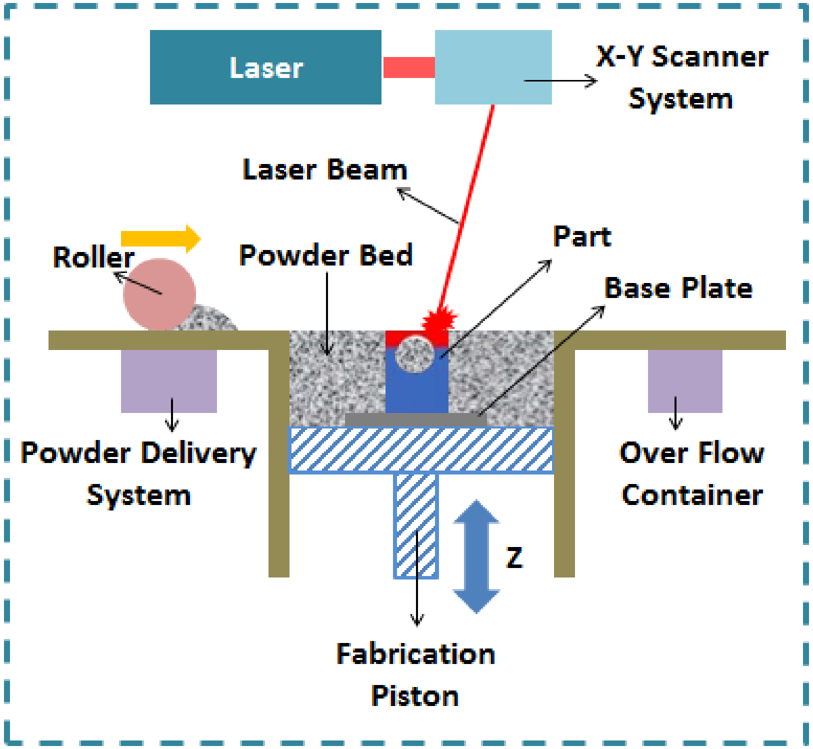
[*] Hot finished-annealed.
[‡] Annealed.
[†] Solution treated and annealed.

[1] C. Selcuk, Laser metal deposition for powder metallurgy parts, Powder Metall. 54 (2011) 94–99.
[2] ASM Handbook, ASM Handbook Volume 3, Alloy Phase Diagrams., Mater. Park. OH ASM Int. (1992).
[3] L. Costa, R. Vilar, Laser powder deposition, Rapid Prototyp. J. 15 (2009) 264–279.
[4] Nickel, Cobalt, and Their Alloys, ASM International, 2000.
[5] Y. Wang, S. Zhang, X. Tian, H. Wang, High-cycle fatigue crack initiation and propagation in laser melting deposited TC18 titanium alloy, Int. J. Miner. Metall. Mater. 20 (2013) 665–670.
[6] Z. Li, X. Tian, H. Tang, H. Wang, Low cycle fatigue behavior of laser melting deposited TC18 titanium alloy, Trans. Nonferrous Met. Soc. China. 23 (2013) 2591–2597

Laser Based Additive Manufacturing

Powder Bed Fusion

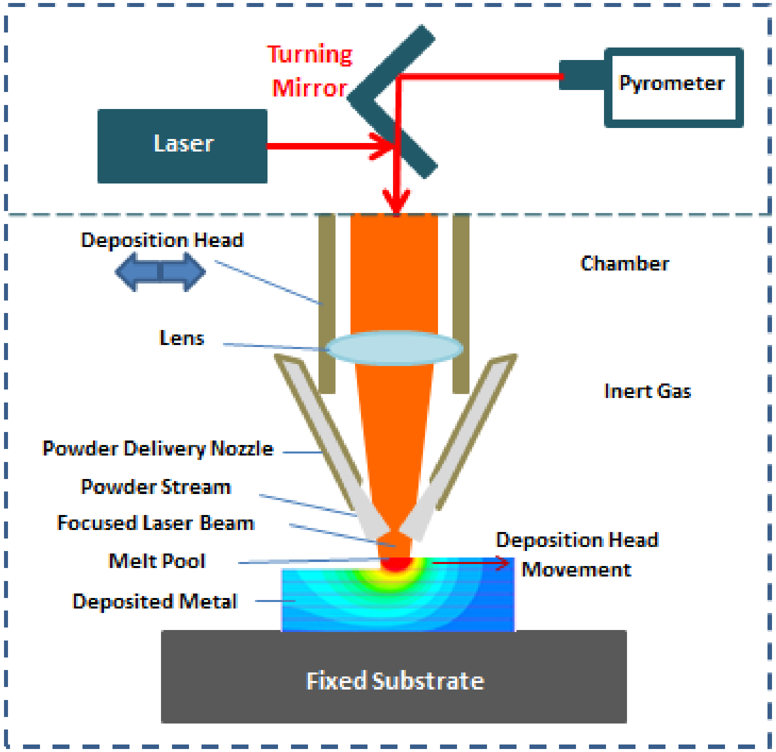
Selective Laser Melting (SLM)



- ***Good surface finish***
- ***High precision***
- ***Very complex geometries***

Direct Laser Deposition

Laser Engineered Net Shaping (LENS)



- ***Multi material feeding***
- ***High build rates***
- ***Parts repair***

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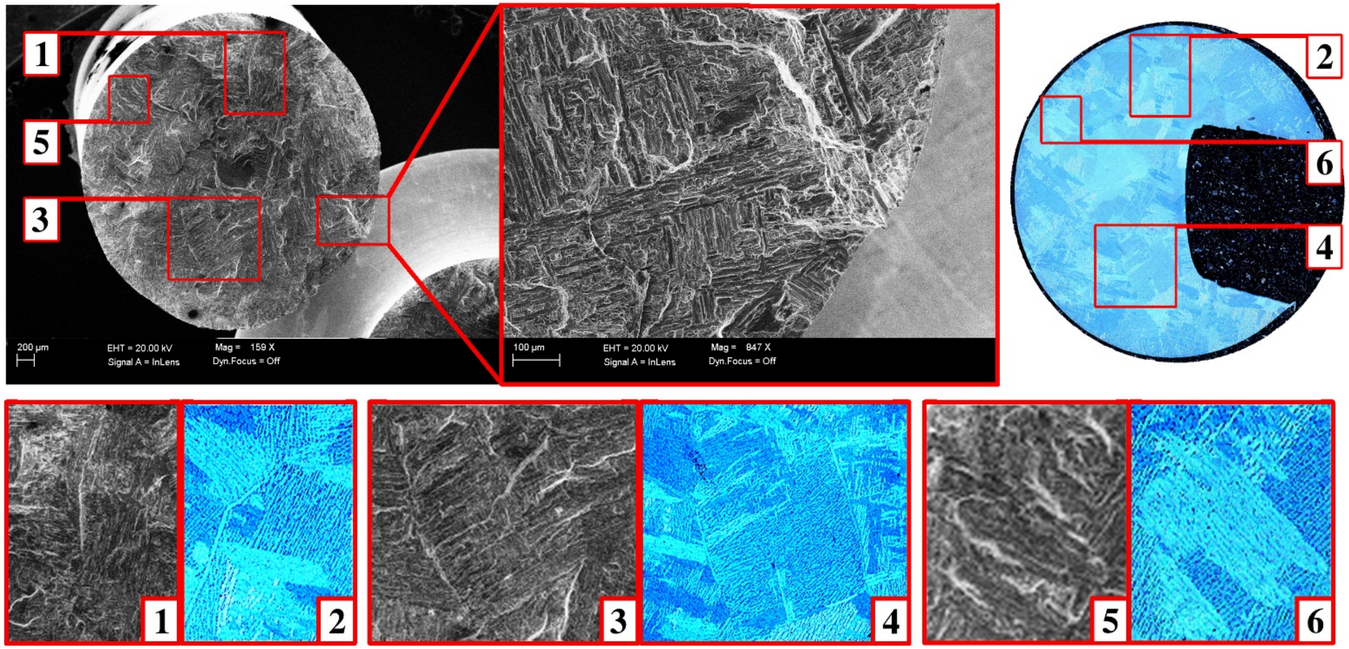
Failure Mechanisms of Heat Treated AM Ti-6Al-4V



No porosity was found on the fracture surface

Currently under investigation to find the underlying microstructure on crack initiation and propagation sites

Sterling, A.J., Torries, B., Lugo, M., Shamsaei, N., Thompson, S.M., 2015, "Fatigue Behavior of Ti-6Al-4V Alloy Additively Manufactured by Laser Engineered Net Shaping," <u>*56th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*</u> Kissimmee, FL.

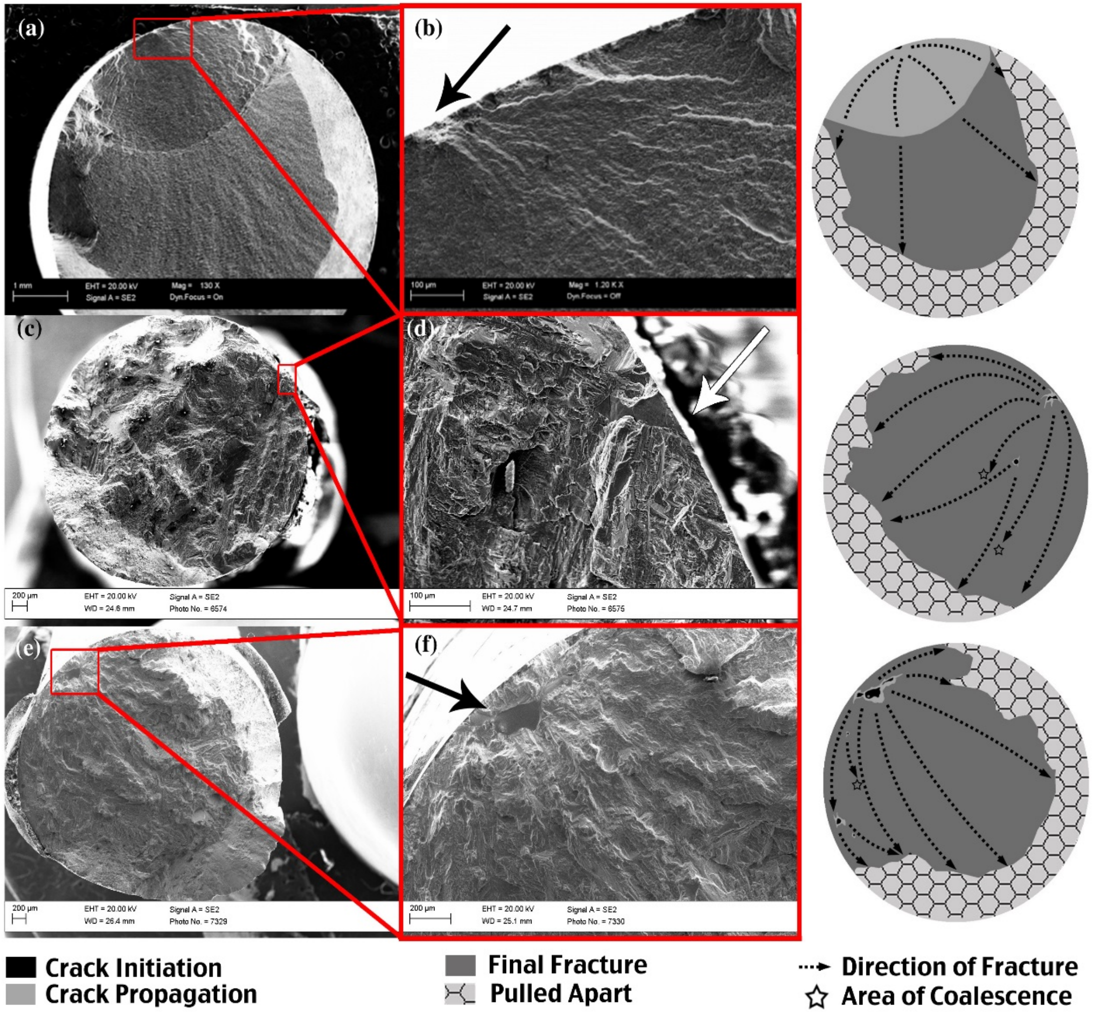
Failure Mechanisms of Wrought and AM Ti-6Al-4V

Wrought Ti-6Al-4V

As-built LENS

Annealed LENS

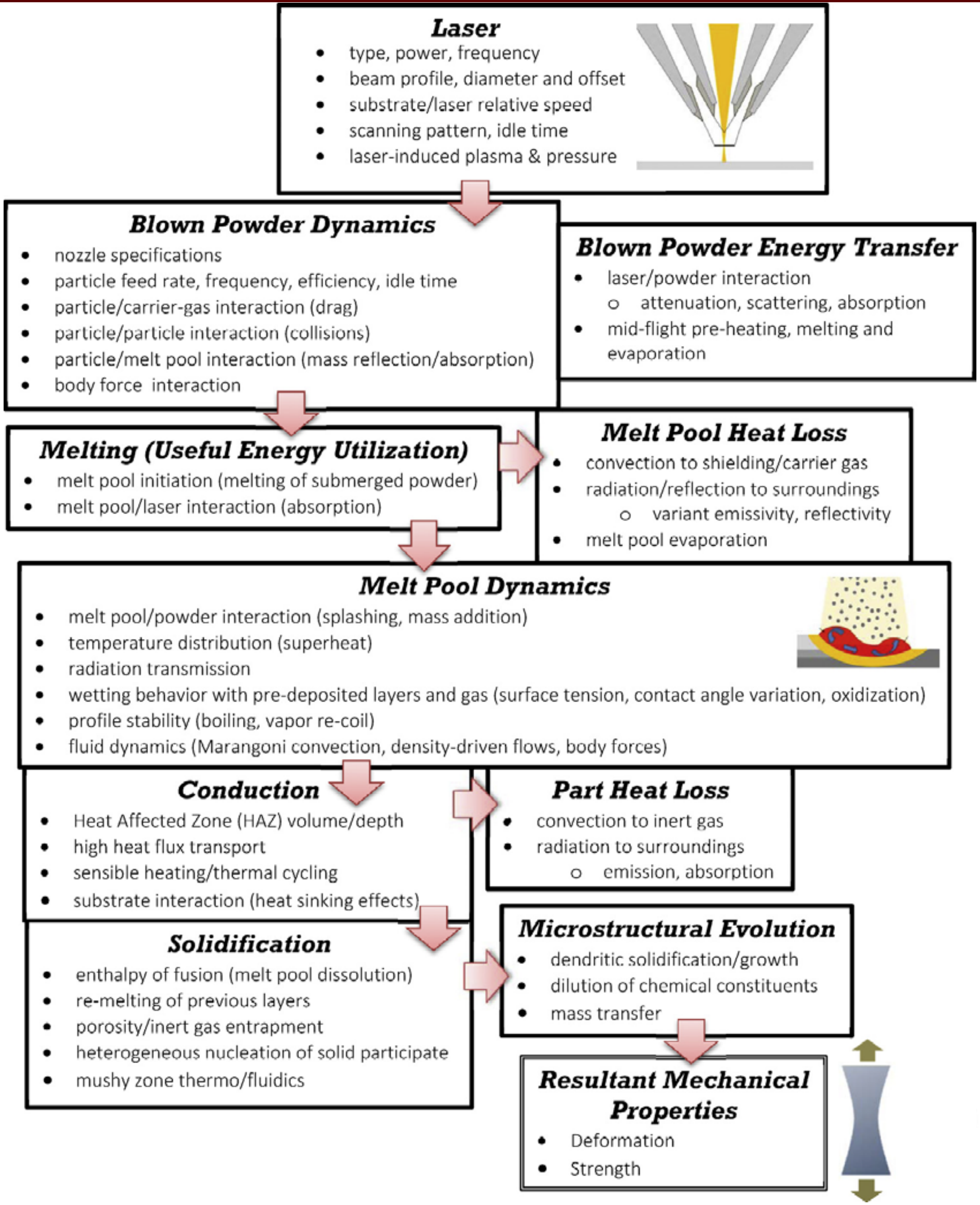
No difference between LENS as-built and annealed



Sterling, A.J., Torries, B., Lugo, M., Shamsaei, N., Thompson, S.M., 2015, "Fatigue Behavior of Ti-6Al-4V Alloy Additively Manufactured by Laser Engineered Net Shaping," *56th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference* Kissimmee, FL.

Physical Events During Direct Laser Deposition (DLD)

Add discussion



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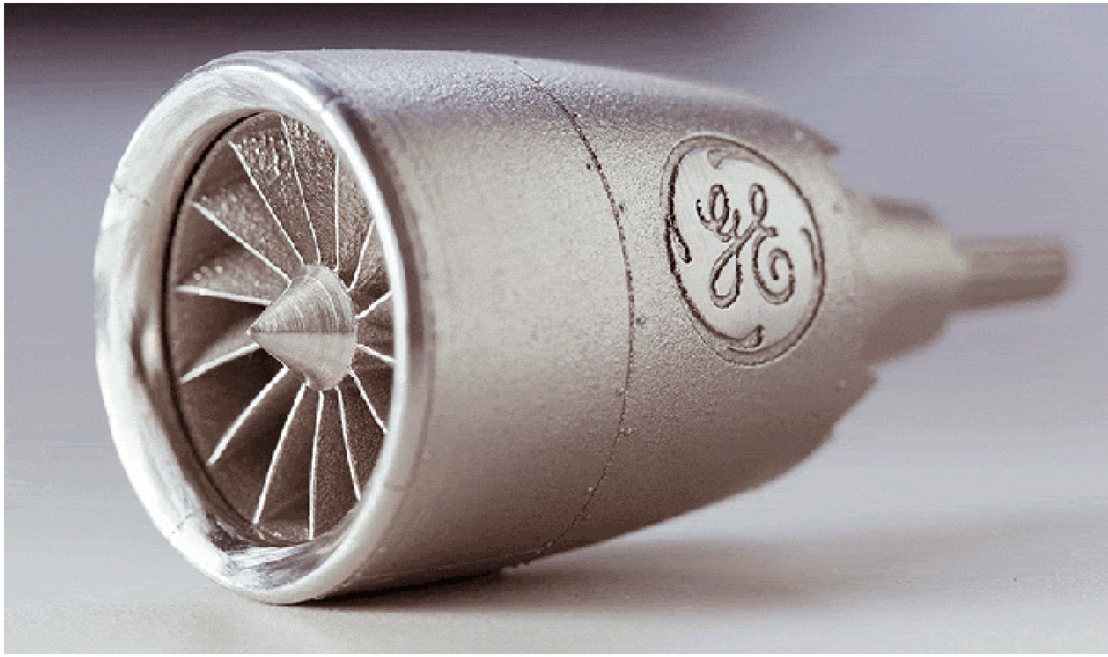
Additive Manufacturing: Large Potential



- Actual parts are now being manufacturing
- **Don't fly with them yet!**

Facilities at Mississippi State

Direct Laser Deposition (DLD)

- OPTOMEC LENS 750 w/ 1 kW laser and multi-camera thermal monitoring
- Multi-powder feeder for functional-grading

Laser Powder Bed Fusion

- 400 W system to-be-installed at CAVS
- Thermal monitoring system to-be-installed

Materials characterization equipment

- Mechanical testing (fatigue, tension, etc.)
- Microstructural characterization
  - EBSD, Microscopy, X-Ray tomography

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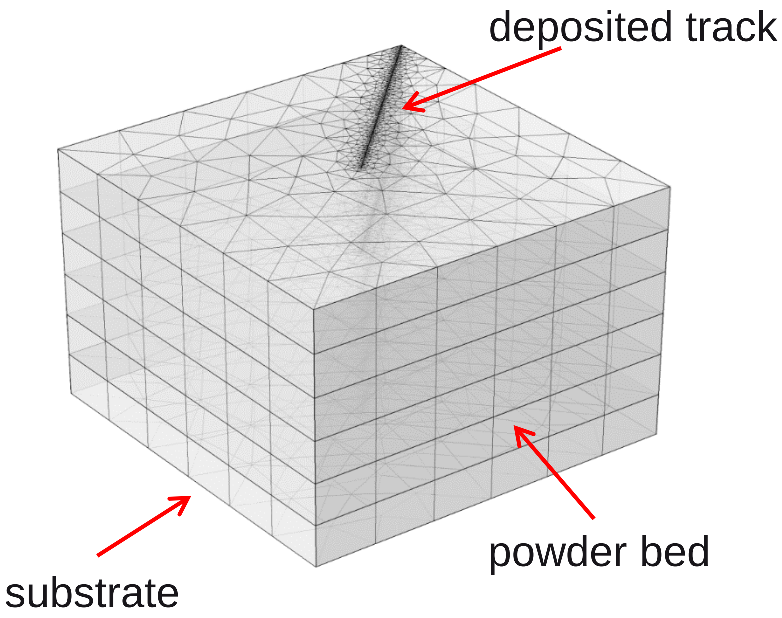
Simulation of SLM Process (Thin Wall Build)

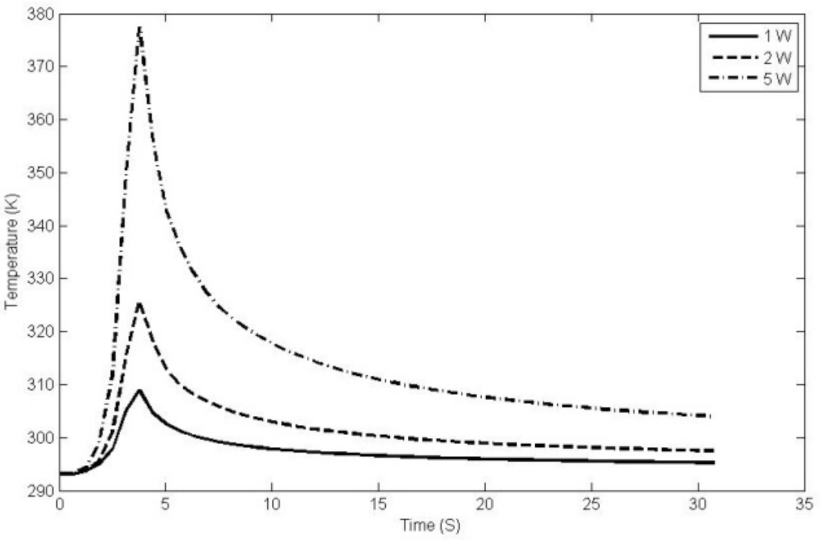
COMSOL



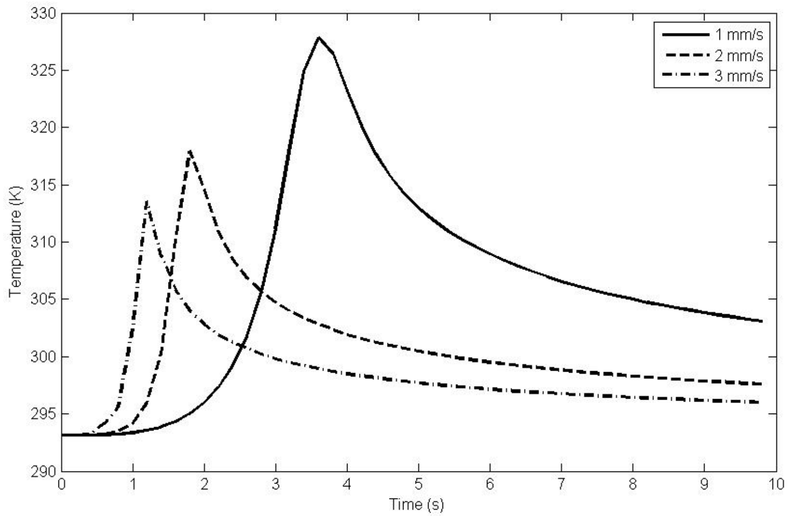
Fluid dynamics, solidification, high heat flux diffusion, microstructural evolution

Time scale ~ 10-100 µs (10-100 million time steps)
Space scale ~ 1 µm (resolution smaller than laser)

Masoomi, M., Elwany, A., Shamsaei, N., Bian, L., Thompson, S.M., 2015, “An Experimental-Numerical Investigation of Heat Transfer during Selective Laser Melting,” *2015 Annual International Solid Freeform Fabrication Symposium - An Additive Manufacturing Conference*, Austin, TX.



Effects of laser power for velocity of 1 mm/s (substrate response)



Effects of laser velocity for laser power of 2 W (substrate response)

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MSU Leads a National Consortium in Additive Manufacturing

Medium-to-Large Industry

Caterpillar, Inc. (Peoria, IL & Corinth, MS)
John Deere (Moline, IL)
Eaton Aerospace Group (Jackson, MS)

Small Industry

Rapid Prototype + Manufacturing (Avon Lake, Ohio)
HBM-nCode Federal LLC (Starkville, MS)
Hol-Mac Corporation (Bay Springs, MS)
Optomec (Albuquerque, NM)
Taylor Machine Works, Inc. (Louisville, MS)
Stratonics, Inc. (Lake Forest, CA)
Simufact-Americas (Plymouth, MI)
Mechanics & Materials Consulting, LLC (Flagstaff, AZ)
Predictive Design Technologies (Starkville, MS)

Government

NASA Marshall Space Flight Center (Huntsville, AL)
Oak Ridge National Laboratory (Oak Ridge, TN)
Air Force Research Laboratory (Dayton, OH)
Federal Aviation Administration (Washington, DC)

Academia

Mississippi State University (Starkville, MS)
Georgia Institute of Technology (Atlanta, GA)
Texas A&M University (College Station, TX)
University of Arizona (Tucson, AZ)
University of Toledo (Toledo, OH)
Carnegie Mellon University (Pittsburg, PA)

Not-For-Profit Organizations

ASTM International (West Conshohocken, PA)
SAE Fatigue Design & Evaluation Committee (Detroit, MI)

CLF²

Consortium on Laser Freeform Fabrication of Engineered Products with Enhanced Structural Integrity

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- ✓ MSU is collaborating with ASTM Committee F42 on Additive Manufacturing Technologies and ASTM Committee E08 on Fatigue and Fracture to develop standards.
- ✓ ASTM E08 workshop entitled *Mechanical Behavior of Additive Manufactured Parts* approved
  - Spring 2016 in San Antonio, TX
- ✓ CAVS is a member of ‘America Makes’

America Makes
National Additive Manufacturing Innovation Institute

CAVS offers.....

- Expertise: fatigue, heat transfer, solidification, process parameters optimization, uncertainty quantification
- Experimental capabilities: *thermally-monitored/controlled* LENS and in the process of buying SLM, uniaxial and multiaxial fatigue load frames, X-ray CT, SEM, ...
- High performance computing (HPC) for high-fidelity simulations
- Mechanical and microstructural characterizations
- “Design for AM” approaches for application-tailored parts and AM product development

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