Structure and Material Optimization with Additive Manufacturing

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HRL Laboratories, LLC

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HRL Laboratories

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Designing for Aerospace & Automotive Applications

***Topology Optimization** is performed on a component for an application*

Exemplary Component Requirements

- **Physical**: Weight, Volume, Shape
- **Primary loading**: Stiffness, Strength, Energy absorbed
- **Secondary loading**: Multi-axial, Impact, Fatigue
- **Environmental survival**: Temp., Chemical, Electrical
- **Life expectancy**
- **Environmental friendliness**: Plays well during integration, life and retirement
- **Inspectable**
- **Qualification**: Material, Process, Spot qualification
- **Manufacturable**: Rate, Cost

Advancing through Technology Readiness Levels

Increased Maturity

Increased Time and Cost: Design, Cert. and Testing

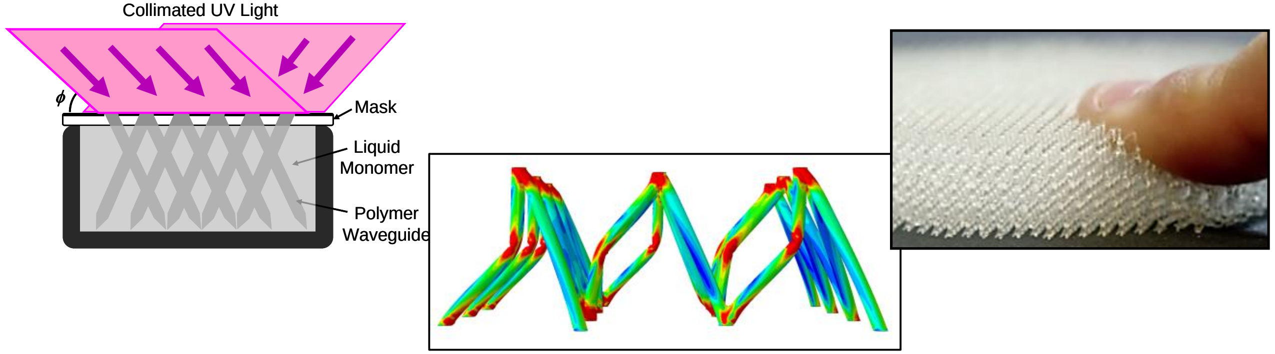
TRL: 2 3 5 6 9 → "Flight proven"

- 2 → Concept or application formulated
- 3 → Analytic or experimental proof-of concept
- 5 → Component validation in relevant environment
- 6 → Subsystem demonstration in relevant environment

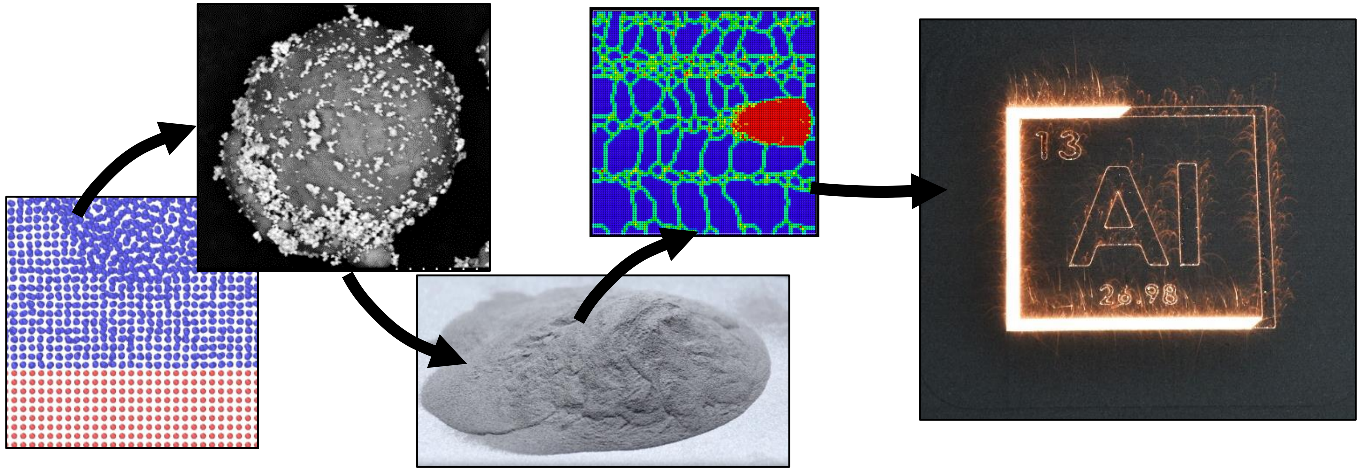
Need an approach that reduces free parameters, while considering full requirement set at initial design phase

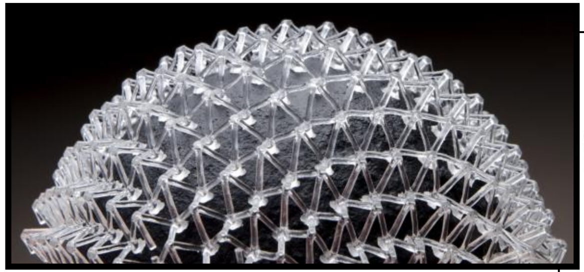
Presentation Overview

Optimization of deformable structures, using an approach of **architecture optimization of a scalable fabrication process**



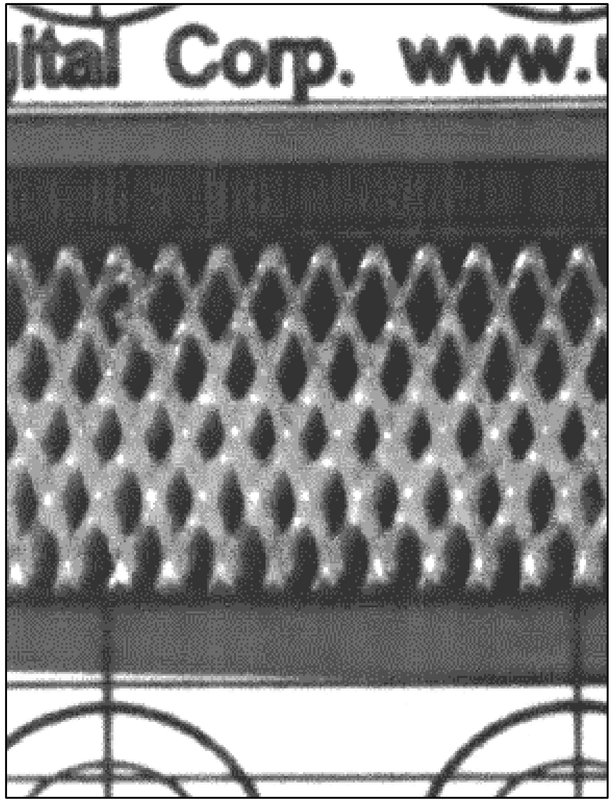
Material optimization for manufacturability and performance in freeform additive manufacturing





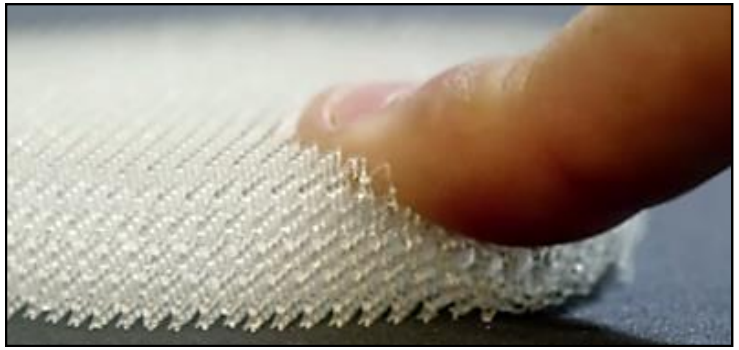
Deformable Structures for Impact Resistance

Blunt Impact

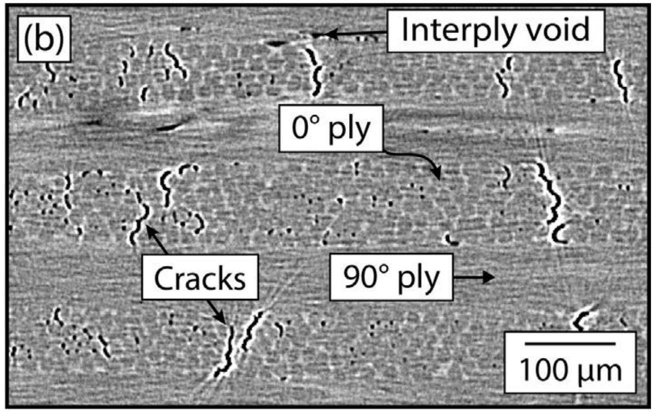


E.C. Clough, et al., Matter, (2019).

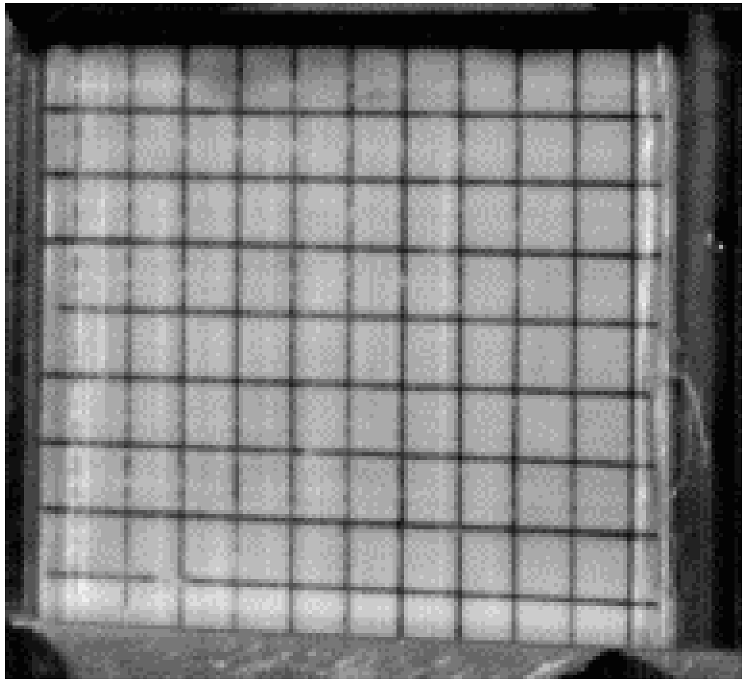
Elastomeric Lattice Structure



Fiber-reinforced composite



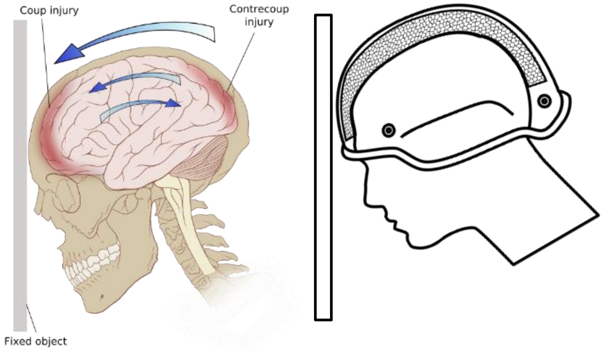
Ballistic Impact

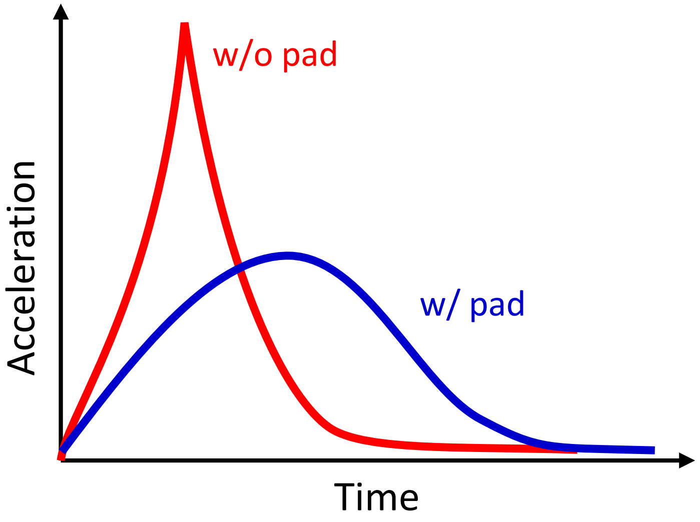


M.R. O'Masta, et al., Int. J. Impact Eng., (2014).

Problems involve damage, contact, strain rate sensitivity, non-linearity and extremely large deformation making them computationally expensive

Case Study: Designing Blunt Impact Attenuators





CDC* Stats on Annual Head Injuries:

- 52,000 Deaths (1/3rd of all injury related deaths)
- 275,000 Hospitalizations
- 1,365,000 Emergency Room Visits
- About 75% of head injuries are concussions

*www.cdc.gov/traumaticbraininjury/data/index.html

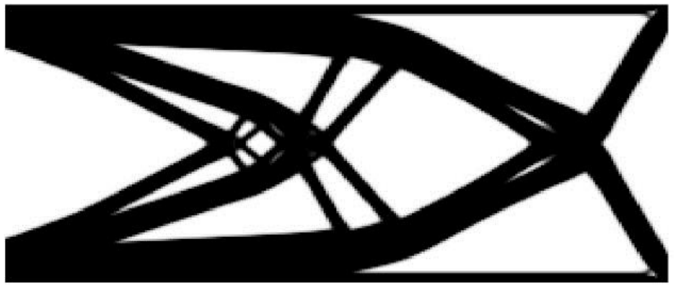
"State-of-the-Art" Impact Attenuator Materials:

- **Expanded Polystyrene** (single impact) invented in 1940's- used in most bicycle and motorcycle helmets
- **Expanded Polypropylene** (multi-impact) – used for pedestrian protection in automobile bumpers
- **Polyvinyl nitrile foam** (multi-impact) – used in football helmets

Can we architect an energy absorbing material that outperforms foam?

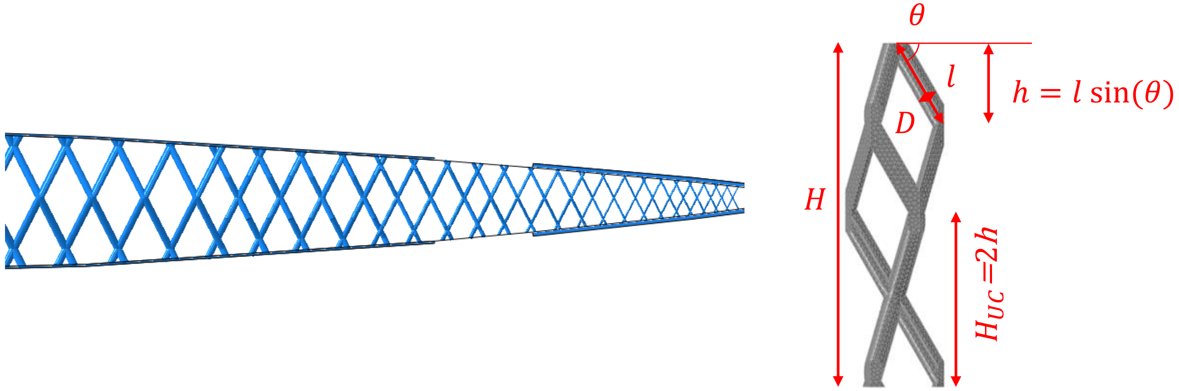
Approach: Architecture Optimization vs Topology Optimization

Topology Optimization



- Many design degrees of freedom (e.g., computationally prohibitive for present problems)
- Arbitrary design space
- However, often results in difficult-to-manufacture structures (e.g. must be 3D printed)

Architecture Optimization



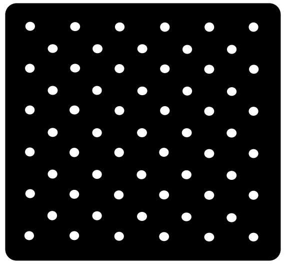
- Comparatively few design degrees of freedom
- Guaranteed to work with process
- Manufacturability is addressed from conception

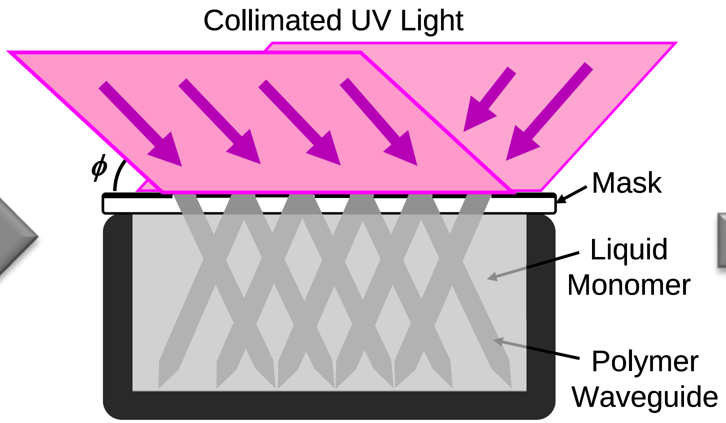
Process limited architecture optimization enables high performance structures without excessive cost or complexity

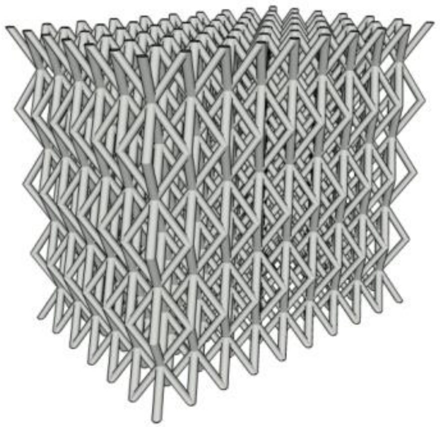
Process Driven Optimization: Microlattice Process

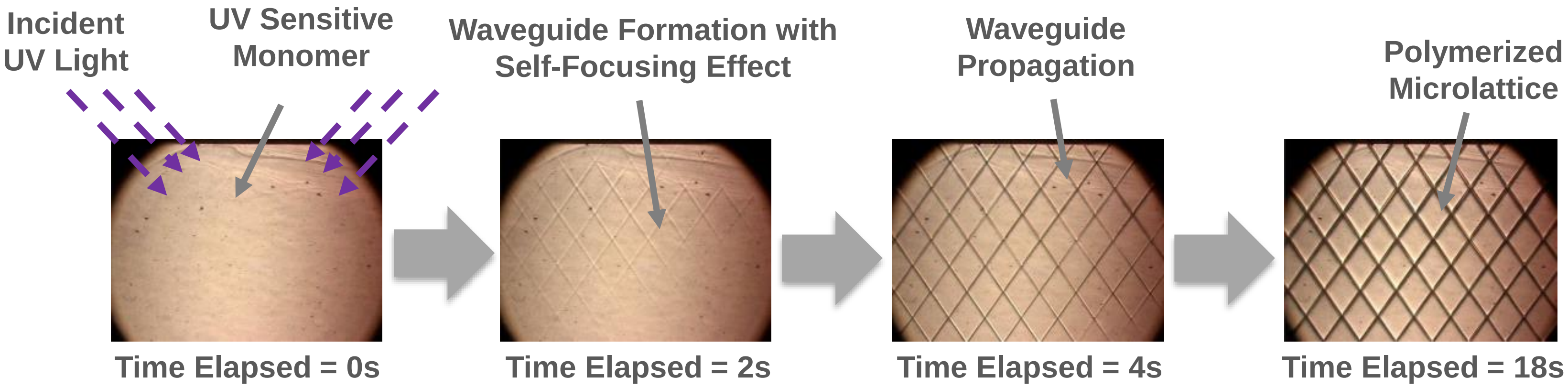
Self-Propagating Waveguides as Three-Dimensional Lattice Structures

Mask (Top View):
Defines Microlattice Architecture



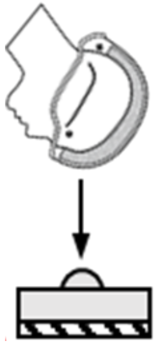


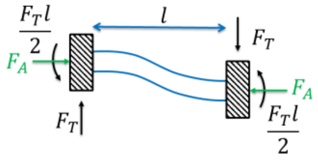




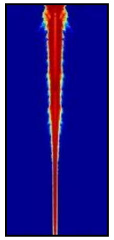
Large-area (>1000 cm^2) rapid (<1 min.) microlattice formation

Microlattice Optimization Procedure

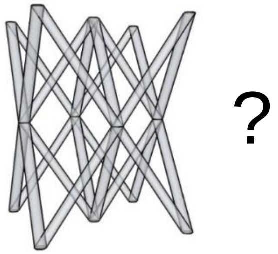




Define Problem

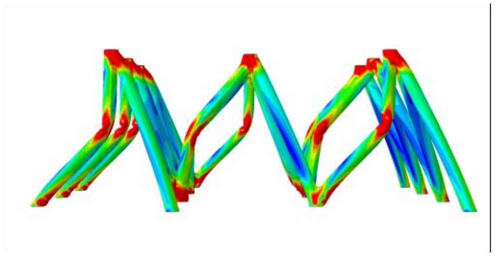


Impose Manufacturing Constraints

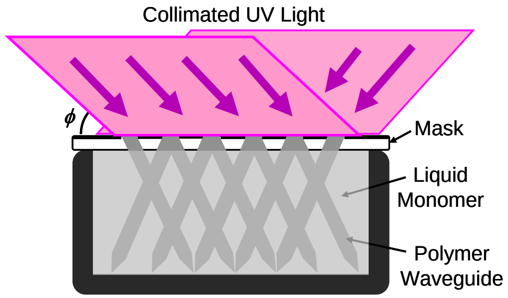


Guess a Near Optimal Structure

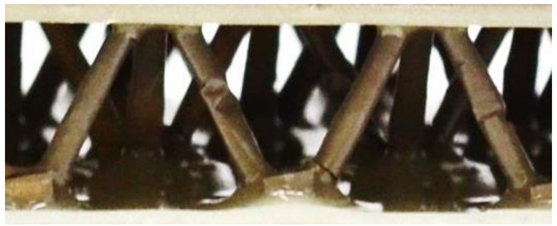
Run Architecture Optimization



Fabricate Mask and Tooling

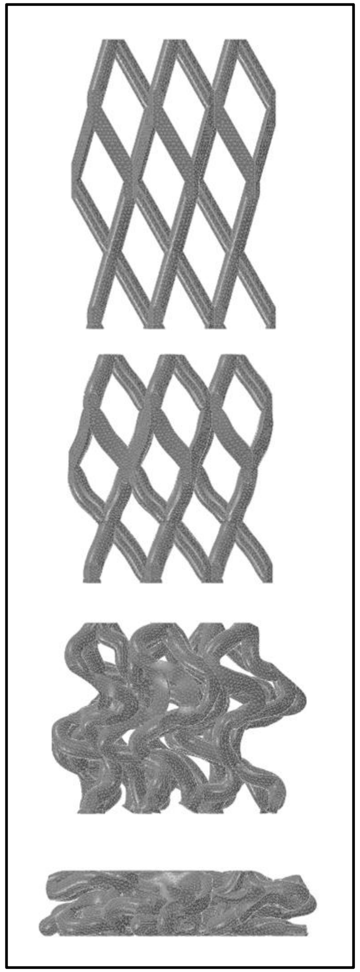


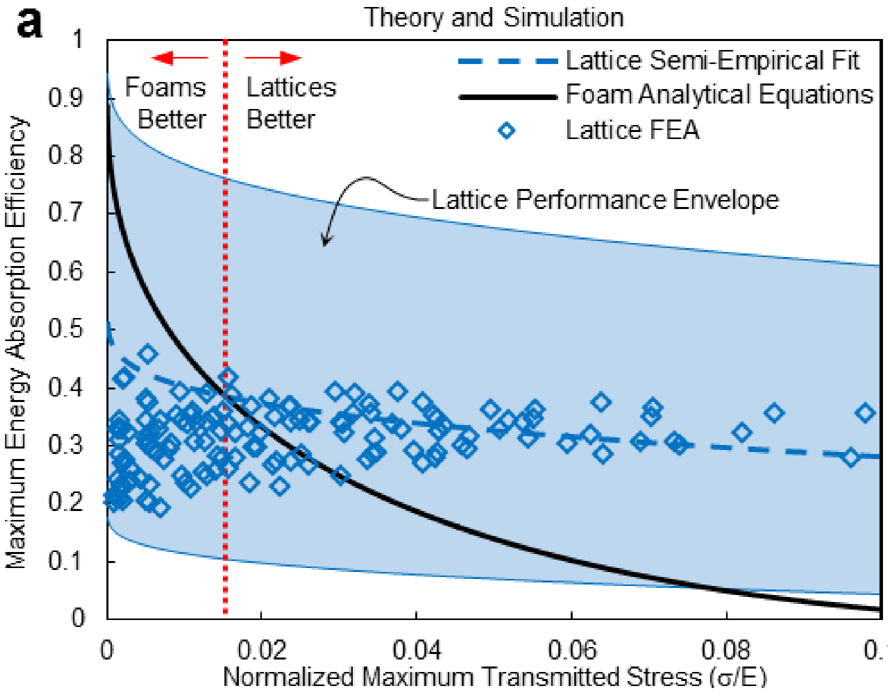
Form Structure and Test



Architecture Optimization of Microlattice

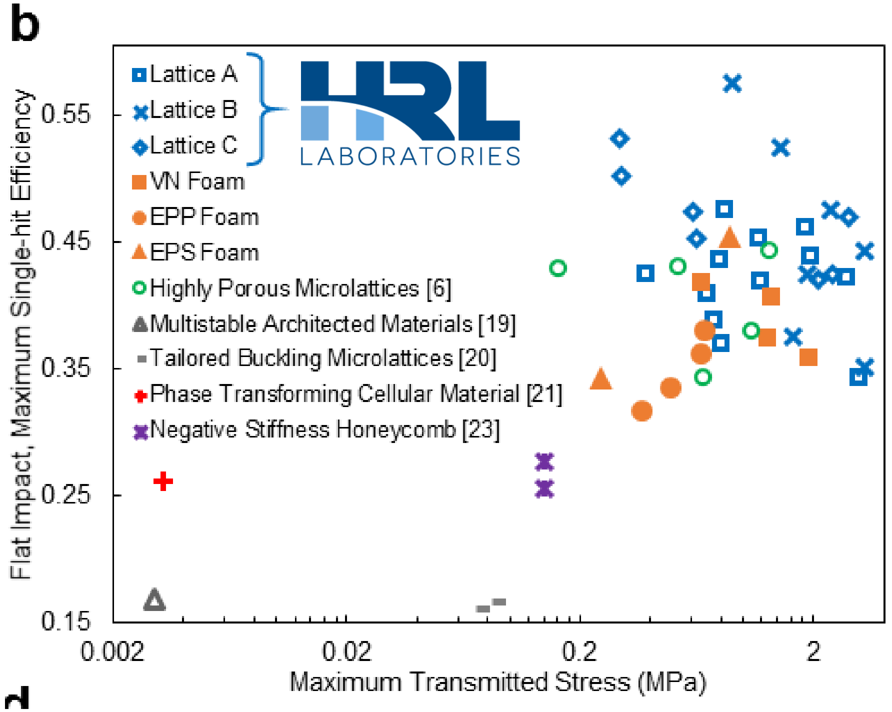
FE Simulations

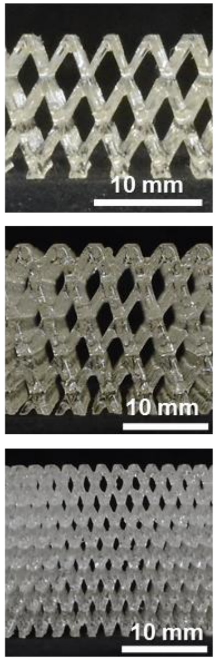




- Predicted absorption efficiency is nearly flat for lattice as compared to foams

Experimental Results





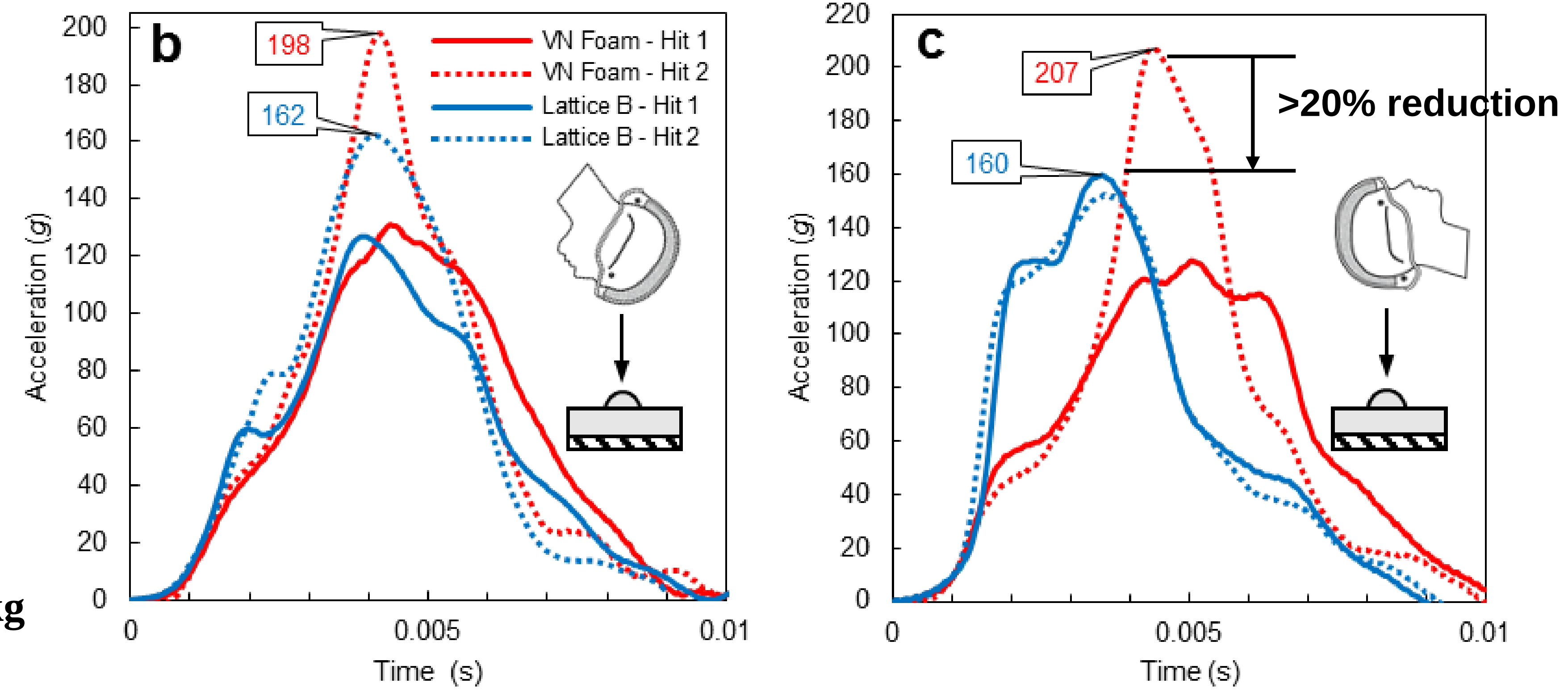
- Single hit efficiency for lattice outperforms SOA

E.C. Clough, et al., Matter, (2019).

Architecture optimization enables lattice compatible with SPPW to outperform SOA.

Helmet Pad Application: FMVSS 218 Blunt Impact Test

Forehead   Rear



DOT-C headform mass: 5 kg
Impact velocity: 4.3 m/s

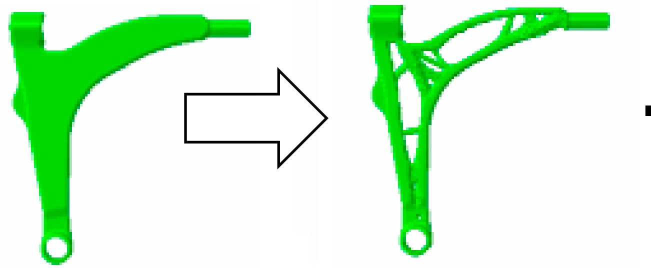
E.C. Clough, et al., Matter, (2019).

>20% reduction in multi-hit peak acceleration compared to SOA helmet pads

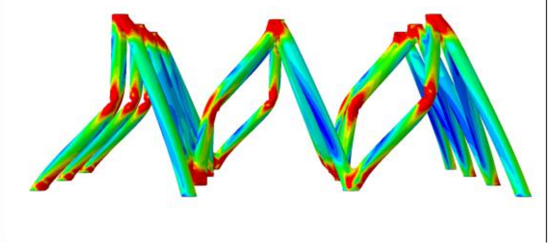
Pioneering Materials Development for Enabling Additive Manufacturing of Optimized Parts

Structural Optimization

Topology Optimization

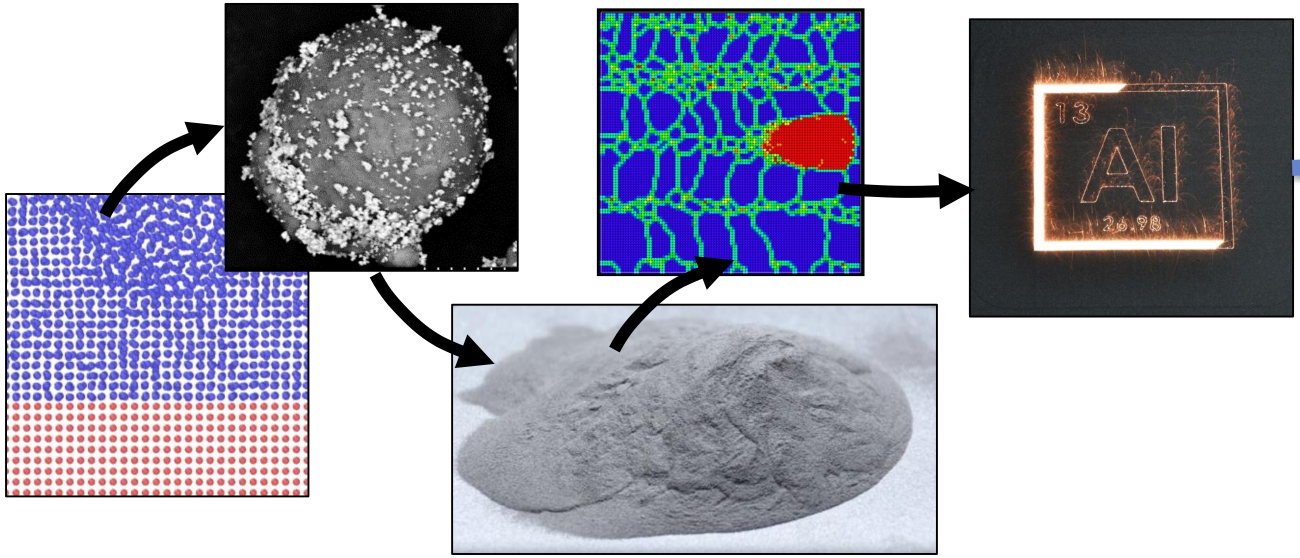


Architecture Optimization



Abaqus. Topology Optimization. (2017)

Material & Process Optimization



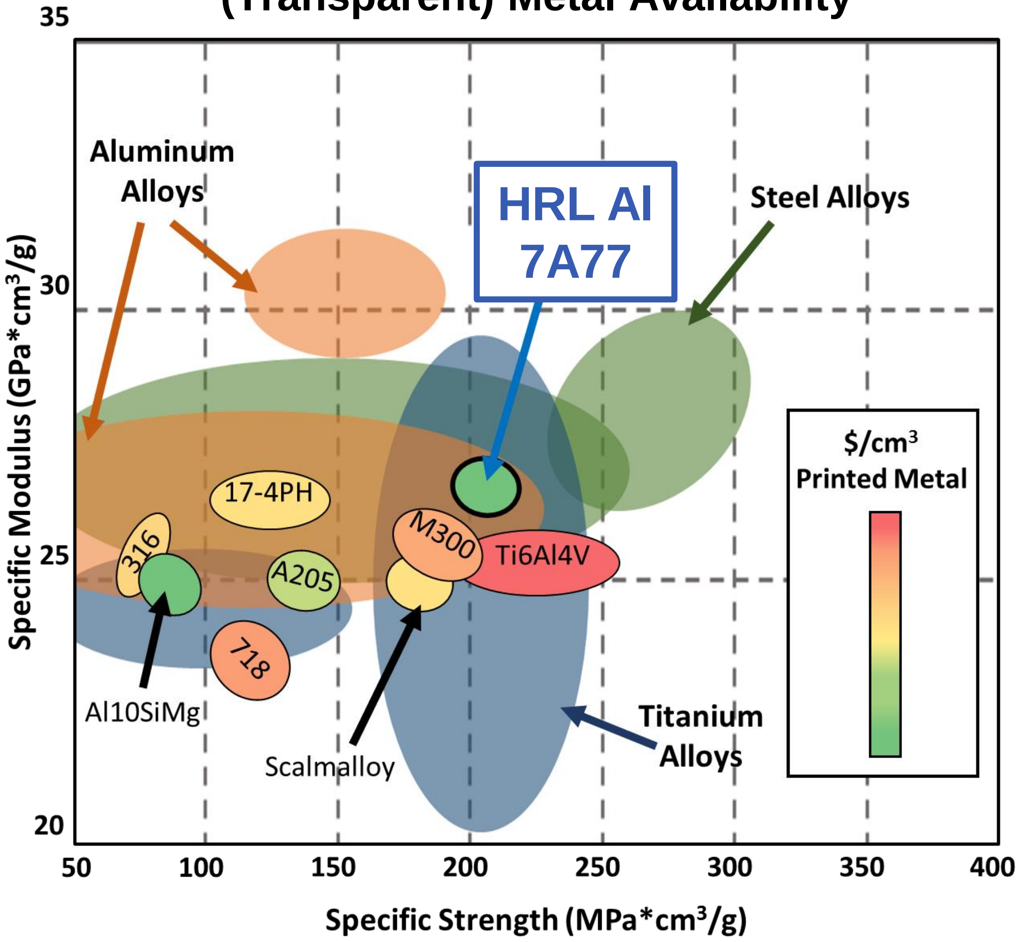
Extracting High Performance

A designed for AM, single part, counter-flow, heat exchanger.

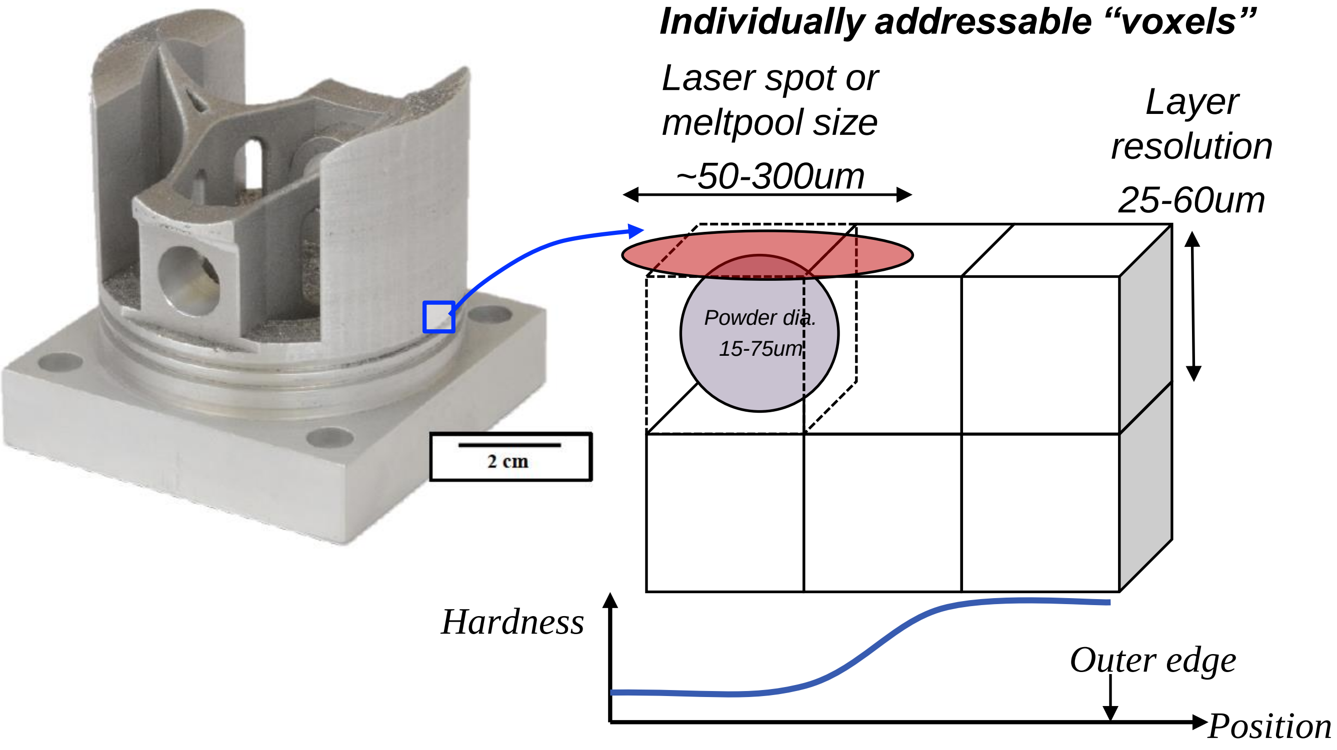
Using high strength Al vs. standard AlSi10Mg lowers mass by 40%.

The Right Materials for an Optimized Structure

Conventional (Solid) Vs. Additive (Transparent) Metal Availability



"Voxelation" in a powder-based metal additive manufacturing process

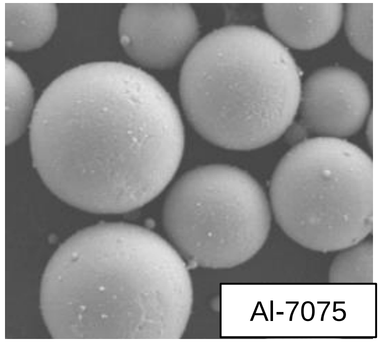


Enabling high performance materials for AM metal fabrication & tailorable properties and microstructure

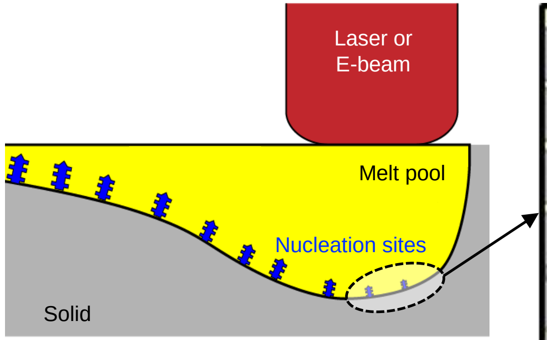
Enabling the Printing of Crack-Susceptible Wrought Aluminum Alloys

Stock 7000 Series Al Powder

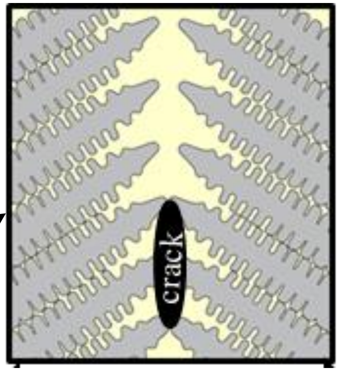
Powder feedstock



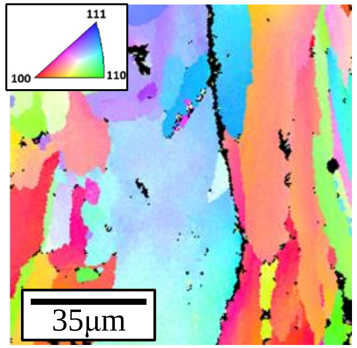
Solidification in powder bed AM



Solidifying microstructure



Grain refinement & columnar to equiaxed transition



Build direction

J.H. Martin et al., *Nature* (Sept. 2017)

Goal – Use powder surface area to deposit targeted additions that control:

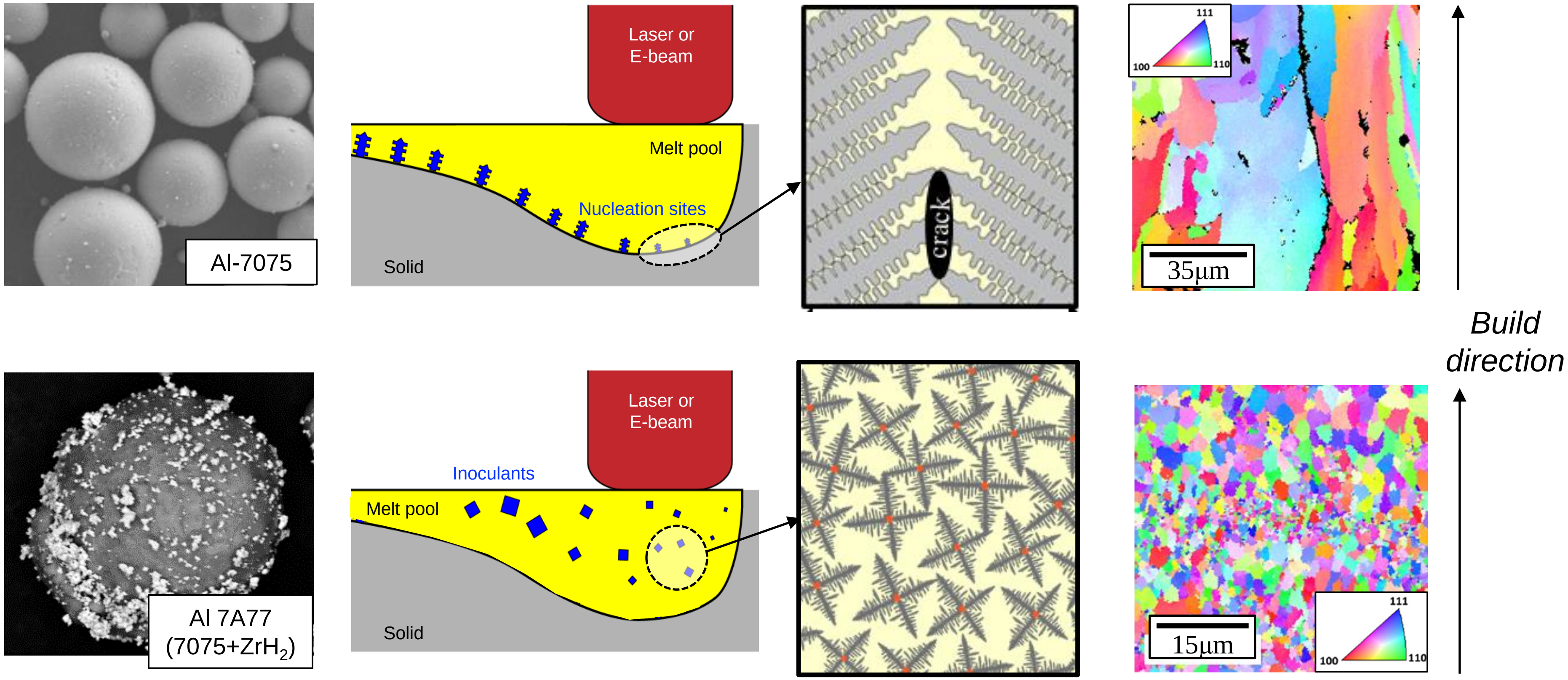
1. Solidification behavior: Make traditionally “un-weldable” alloys “weldable”
2. Material composition, grain structure and dispersions
3. Meltpool shape and stability

Enabling the Printing of Crack-Susceptible Wrought Aluminum Alloys

Powder feedstock | Solidification in powder bed AM | Solidifying microstructure | Grain refinement & columnar to equiaxed transition

Stock 7000 Series Al Powder

Functionalized 7000 Series Al Powder [4]



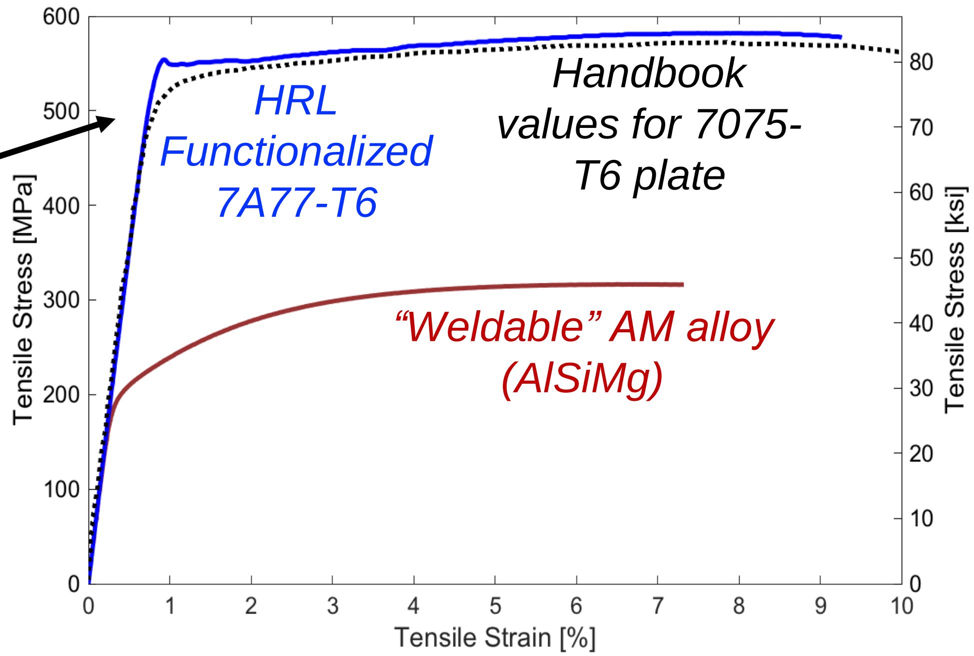
J.H. Martin et al., *Nature* (Sept. 2017)

Inoculant particles reduce grain size (>100X) to eliminate hot cracking.

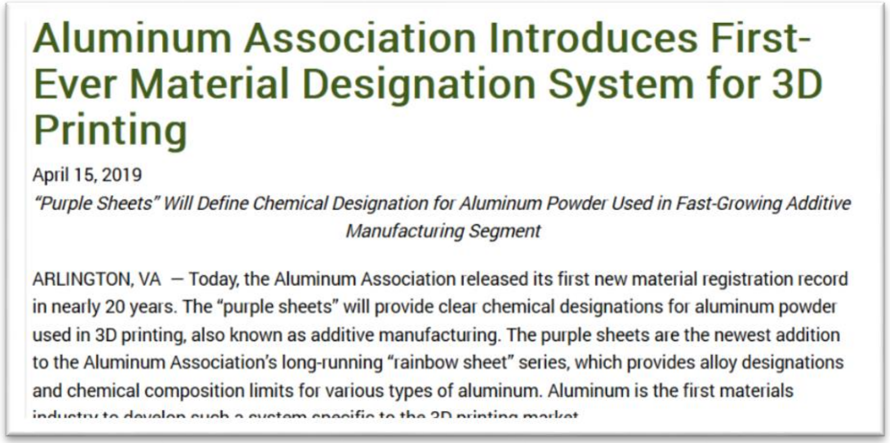
Functionalization Allows Additive Manufacturing of High Strength Aluminum

CENTER FOR ADDITIVE MATERIALS

HRL's Al 7A77 is the first alloy to receive a 3D printing material designation and is now commercially available.



HRL 7A77.50: 1st Al spec for 3D Printing

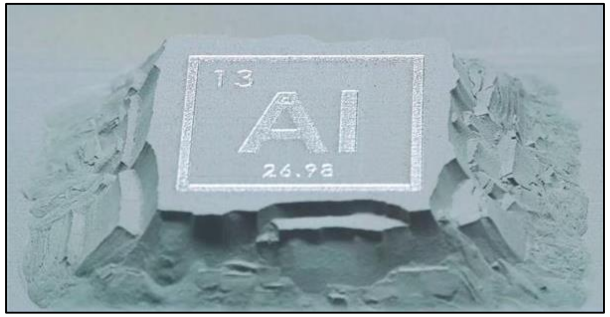


Aluminum Association Introduces First-Ever Material Designation System for 3D Printing

April 15, 2019

"Purple Sheets" Will Define Chemical Designation for Aluminum Powder Used in Fast-Growing Additive Manufacturing Segment

ARLINGTON, VA — Today, the Aluminum Association released its first new material registration record in nearly 20 years. The "purple sheets" will provide clear chemical designations for aluminum powder used in 3D printing, also known as additive manufacturing. The purple sheets are the newest addition to the Aluminum Association's long-running "rainbow sheet" series, which provides alloy designations and chemical composition limits for various types of aluminum. Aluminum is the first materials

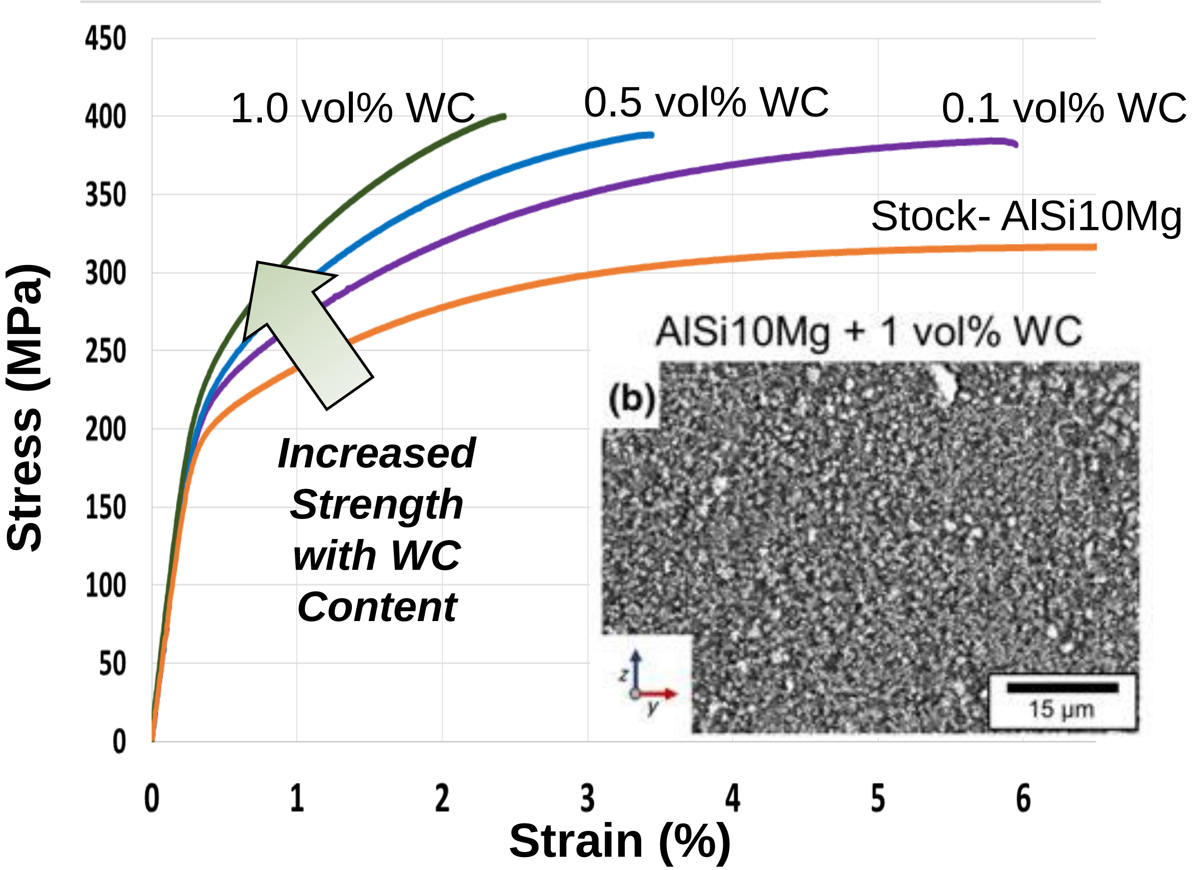


- Enables additive manufacturing of commonly used structural aluminum alloys (e.g. 2000, 7000 series)!
- Provided we computationally match the correct inoculant to a given alloy to control solidification conditions

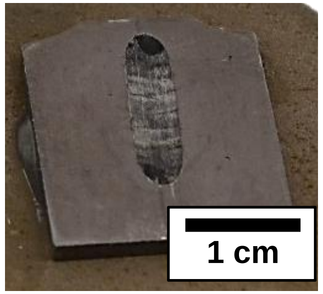
http://www.hrl.com/products-services/materials

Functionalization mechanism allows printing of desirable, yet otherwise unattainable, alloy compositions.

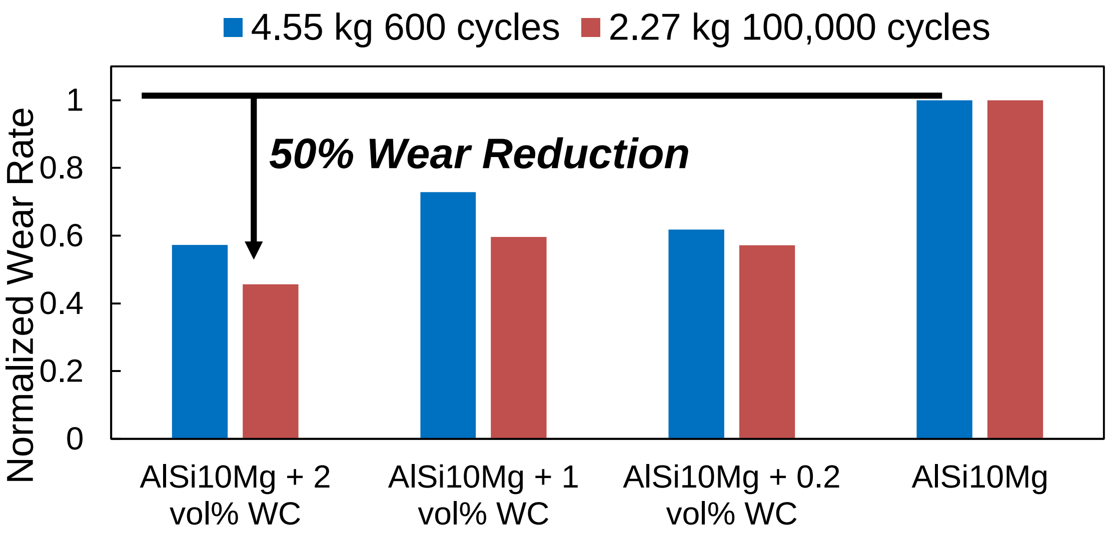
Strength and Wear Control in Additive Manufacturing via Metal Matrix Composites



AM AlSi10Mg + 2 vol% WC



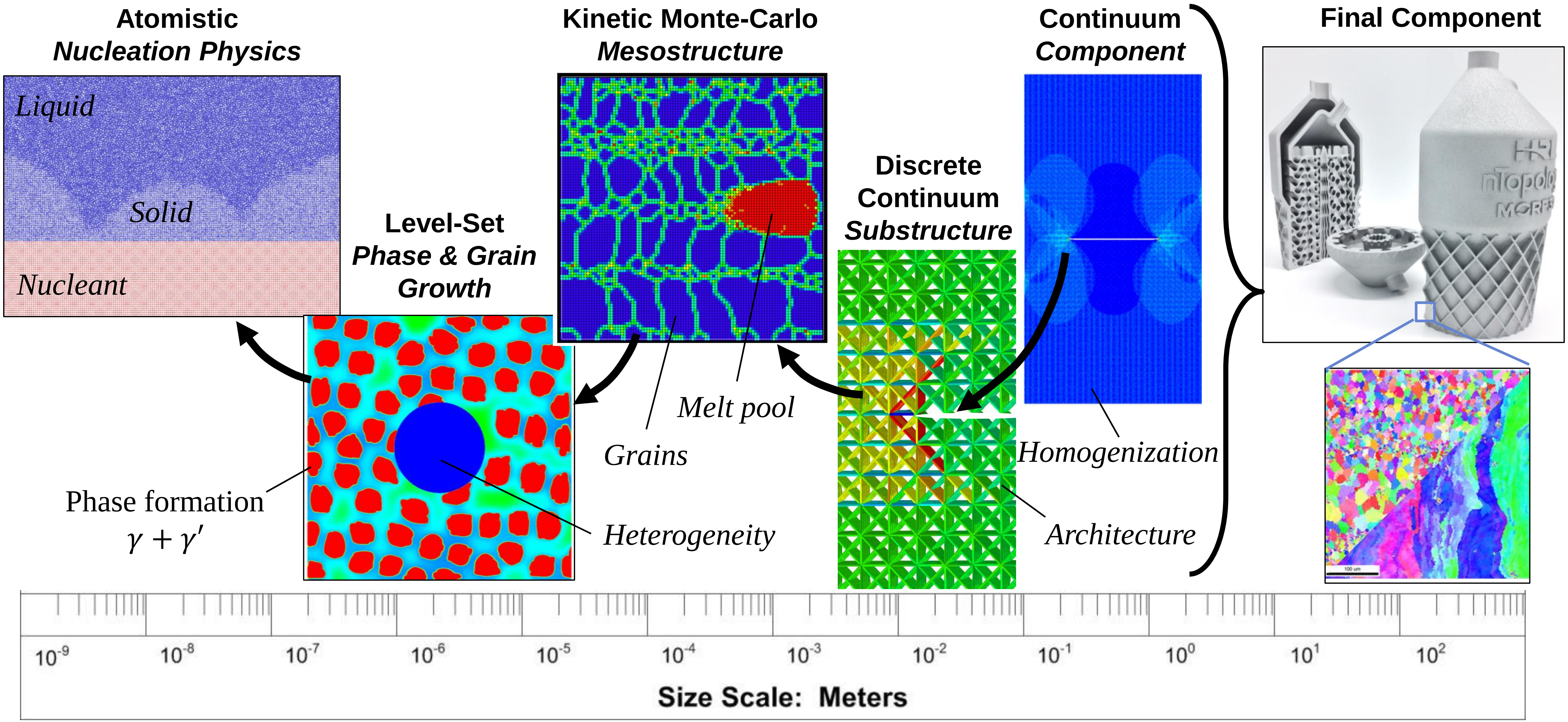
AM AlSi10Mg



J.H. Martin et al., *MRS Commun.* (June 2018)

Dispersion of uniquely small WC particles increases UTS by >20% and 2X reduction in wear over conventional stock AlSi10Mg.

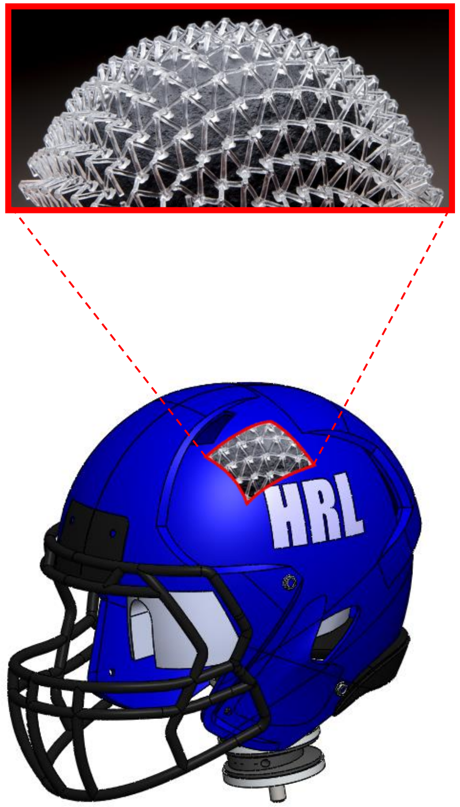
Flow Path for Optimization of Materials for Additive Manufacturing



Final Remarks

- For computationally expensive, deformable structures, we have shown >20% increase in blunt impact attenuation using architecture optimization of a scalable and cost-competitive process.
  - Technology is currently being licensed for commercial helmet applications.
- To realize the benefits of freeform additive manufacturing, materials must be optimization for both the process and performance.
- We have shown a mechanism to tailor properties and microstructure of metal alloys, with >500 MPa yield strength Al
  - Success on 7000 series Al has led to commercial sale of 7A77 Al powder

Optimized Architecture with Scalable Production



Optimized Materials for AM

http://cam.hrl.com/