Recycling and Reuse of Metal Alloys by a Single Solid-State Additive Manufacturing and Repair Process

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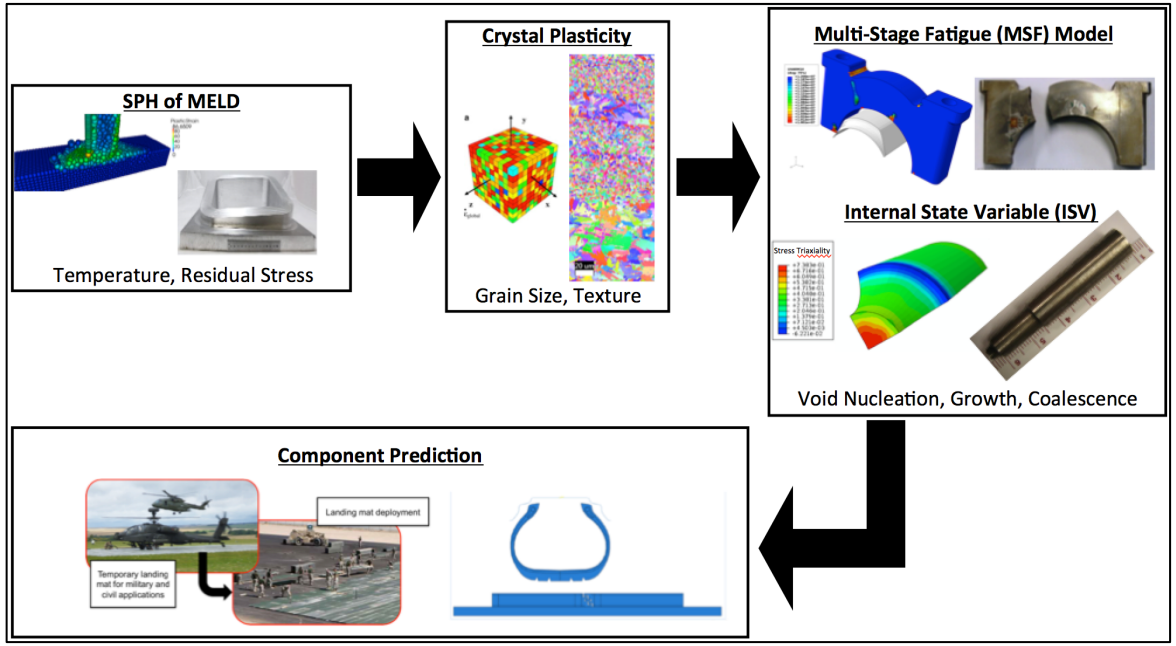
Solid-State Additive Manufacturing and Repair Motivation Paradigm: Economical and Expedient

- **Goals:** Engineer a solution for manufacturing new and repair of damaged mission critical components.
- **Deliverables:** Provide a novel paradigm shifting approach to repair components with a minimal logistical footprint for aerospace applications.
- **Technical Approach:** Process-structure-property characterization to develop, calibrate and validate physics-based multiscale modeling of Additive Friction Stir – Deposition (AFS-D) components.
  - Smooth particle hydrodynamics (SPH) of AFS-D (MELD) process model
  - Crystal plasticity modeling
  - Physics-based internal state variable (ISV) plasticity-damage models
  - Multistage fatigue model (MSF)
  - Provide end-user a component design and performance prediction tool for solid-state additive manufactured and repaired components.

UA Computational and Experimental Paradigm



Background of the Problem: How to Fabricate Parts With Limited Resources – *Direct Recycling for the Warfighter*

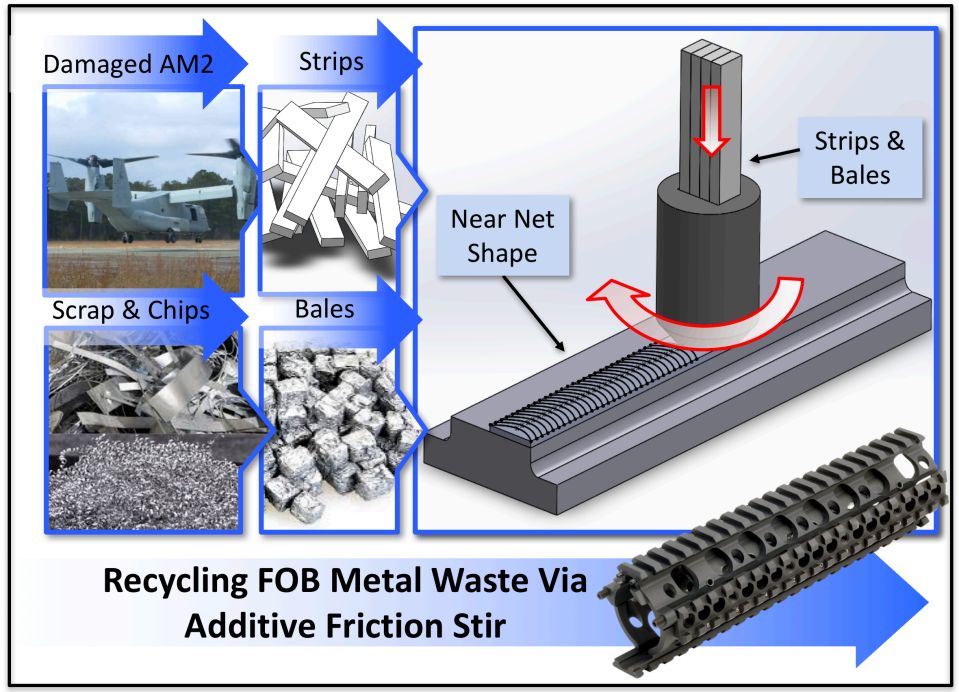
Forward Operating Base (FOB) Manufacturing Barriers:

- Need to reduce logistical tail by fabricating/repairing mission critical components in combat zones.
  - Risks with resupply convoys (i.e., enemy activity, time-sensitive missions, large energy consumption)
  - Challenges associated with manufacturing parts at a FOB (i.e., energy, powders, respiratory problems)
- Military Occupational Specialty (MOS) units at FOB generate waste as buildup of scrap metal, unserviceable equipment, and battle-damaged equipment[1-4].

The eliminated metal additive manufacturing powder production cycle by direct recycling scrap with the AFS-D Process.
(http://www.praxairsurfacetechnologies.com/-/media/us/images/components-materials-and-equipment/additivemfgprocess

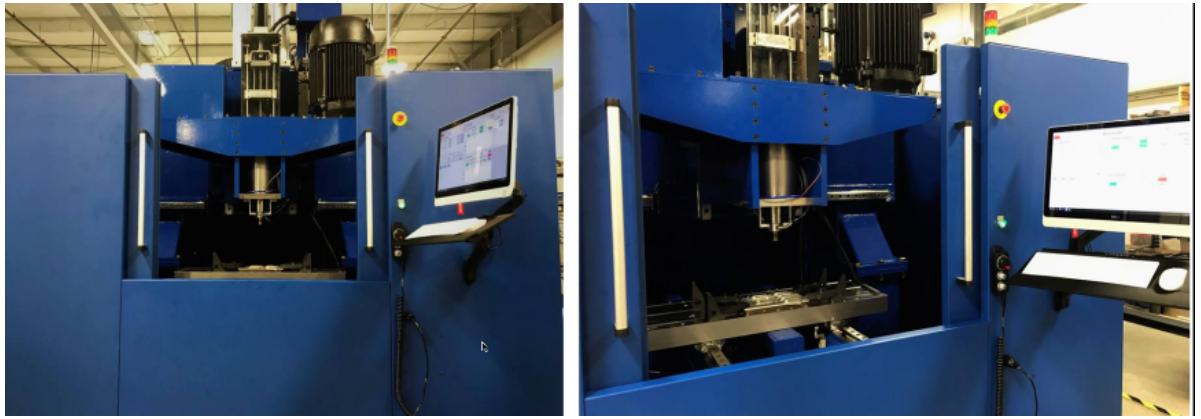
Direct Additive Recycling at FOBs: Recycle Metal Waste into New Components

- ***Understand the influence of recycled feedstock (scrap FOB metal waste) on the microstructural evolution of solid-state additive manufactured components.***
- ***Recycle two FOB waste streams.***
  - Stream 1: Scrap metal machine chip waste from maintenance-MOS activities
  - Stream 2: Unserviceable and battle-damaged equipment from damaged operational activities
- ***Produce fully dense AM components with isotropic wrought mechanical properties.***

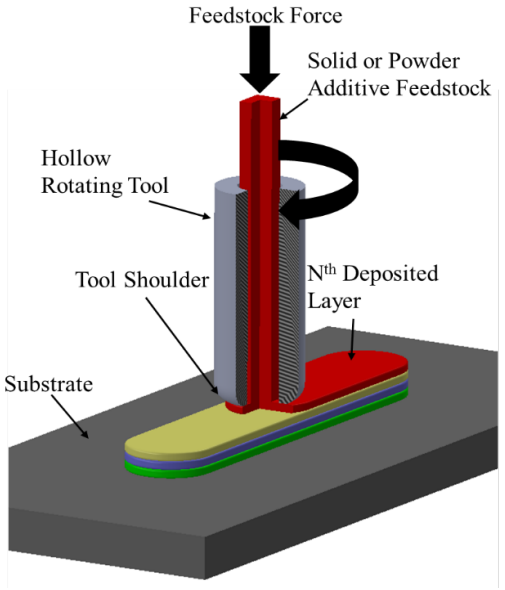


Schematic of proposed Additive Friction Stir - Deposition (AFS-D) manufacturing process for recycling of FOB metal waste. (http://www.navair.navy.mil/nawcad/lakehurst/about.cfmContentID=EAFPhoto&NavIID= About&NavgID= Standard&NavgID2=About)

Introduction of Additive Friction Stir - Deposition (AFS-D) Technology for Direct Additive Recycling and Repair



B8 Model AFSD machine at The University of Alabama.



Schematic of the AFS-D process.

AFS-D is a solid-state thermo-mechanical process:

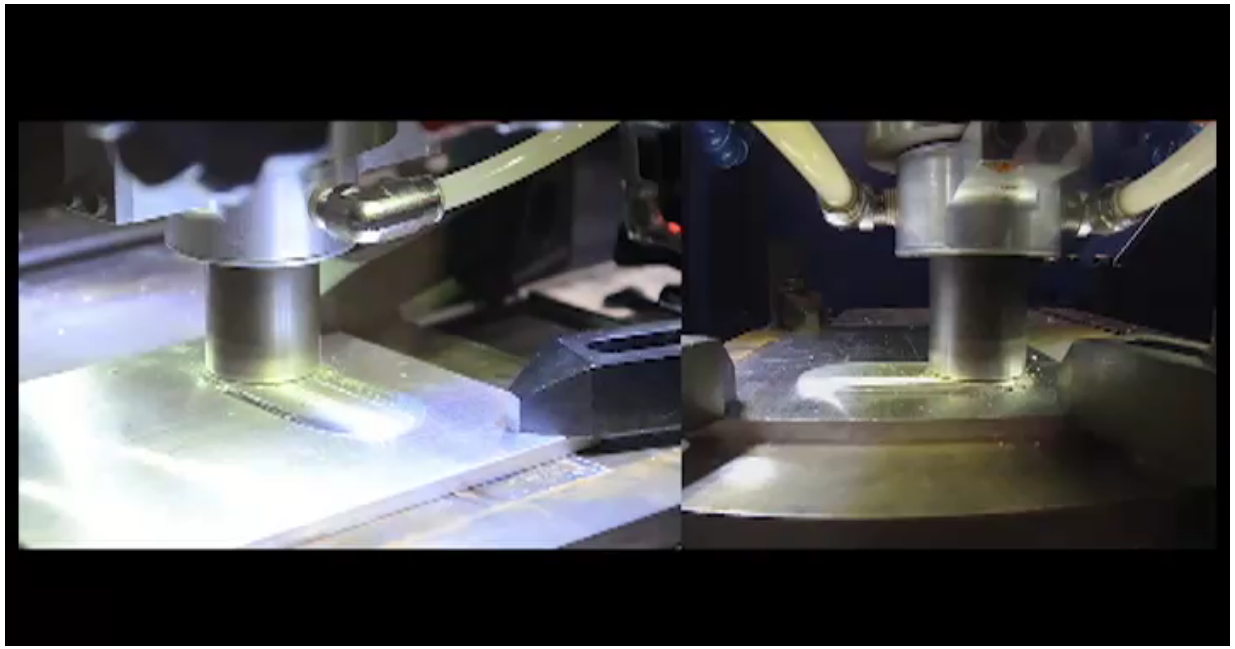
- Similar temperatures as FSW
- Fully dense material deposition
- Refined and equiaxed grains
- Minimal distortion of substrate

Benefits of AFS-D for AM and Repair:

- Use common alloys (AA6061, AA5083, AA7075, IN625, HY80, Ti64, WE43, AZ31)
- Complex geometry
- Near net shape
- Fast – high deposition rates
- Quality Parts (wrought microstructure)
- Functionally graded parts
- Powder or solid raw material
- Open atmosphere process

Introduction of Additive Friction Stir - Deposition (AFS-D) Technology for Direct Additive Manufacturing and Repair

AFS-D of AA6061 at The University of Alabama

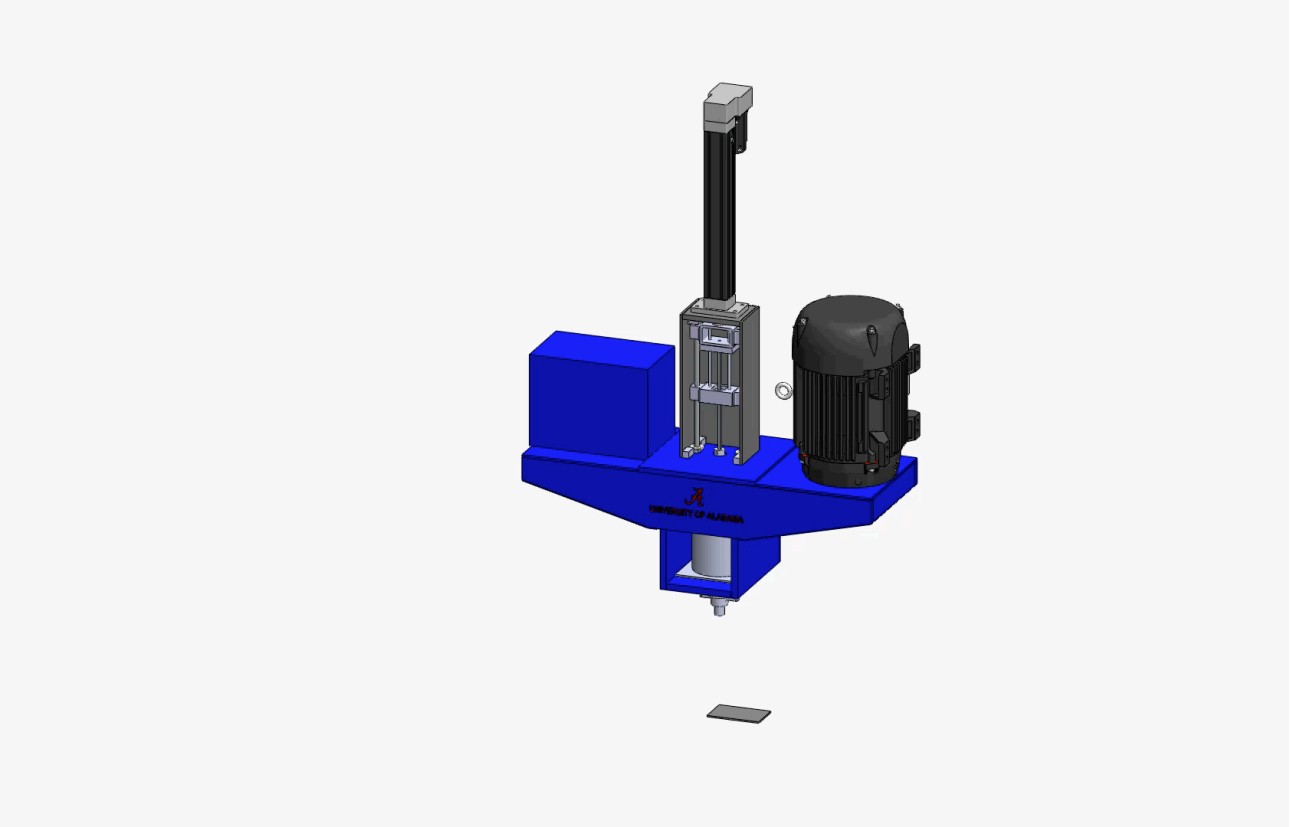


AFS-D rapidly deposits material:

- Al and Mg alloys at ~9 kg/hr (20 lbm/hr)
- Steel alloys at ~4.8 kg/hr (10.7 lbm/hr)
- Ti alloys at ~2.5 kg/hr (5.5 lbm/hr)
- Ni base superalloys at ~0.7 kg/hr (1.5 lbm/hr)

AFS-D machine has lower energy than FOB Mazak machining centers:

Energy usage	*Power requirements*
• 47 J/mm^3	• ~5 kW



Direct Additive Recycling at FOBs: AFS-D Offers Significant Process Controls

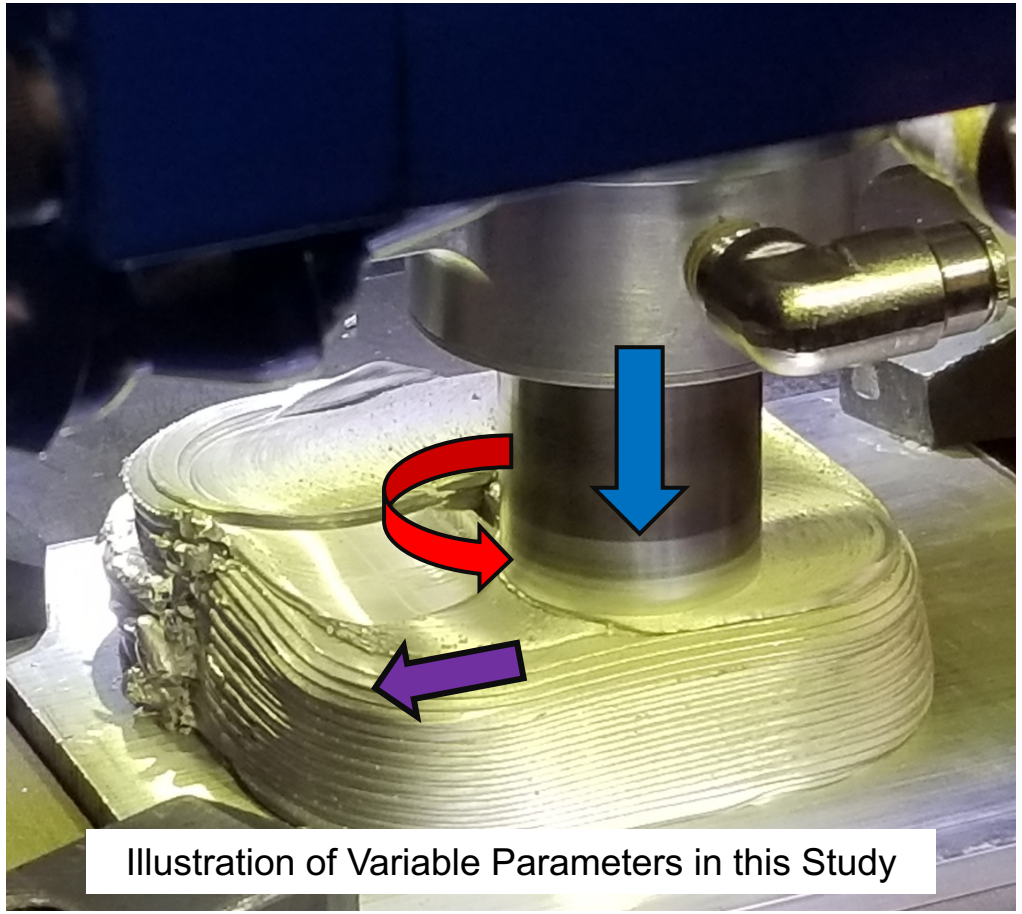


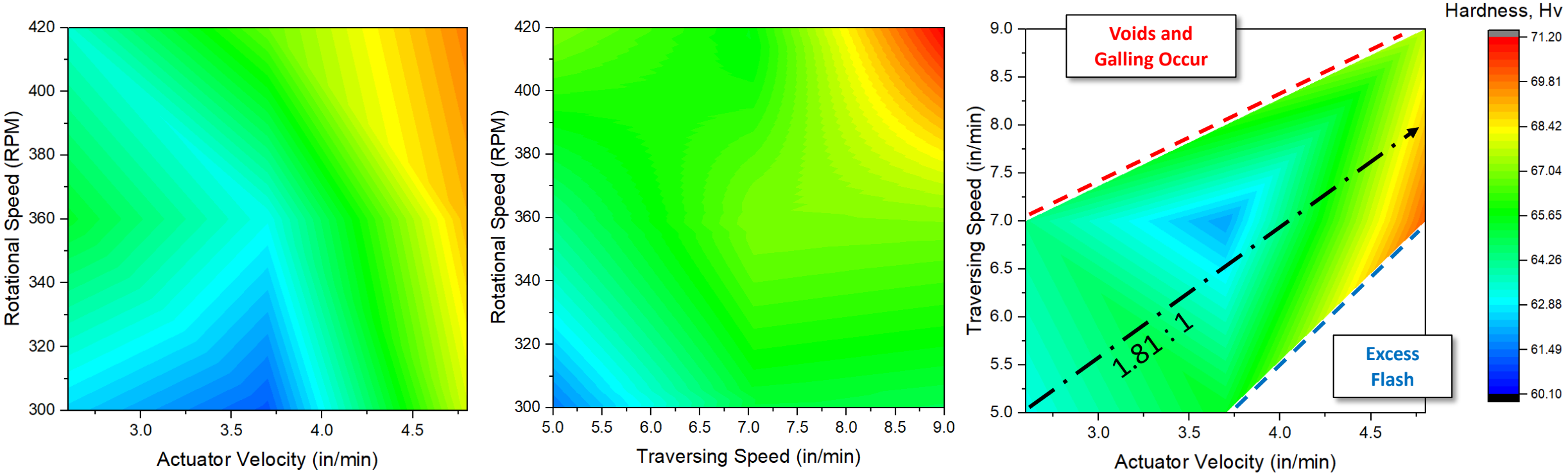
Illustration of Variable Parameters in this Study

- 5 user-defined parameters available
  - **Spindle Speed [RPM]**
  - **Actuator Feed Rate [in/min]**
  - **Traversing Velocity [in/min]**
  - Layer Height [in]
  - Vertical (Z-axis) Build Rate [in/min]

- This work will maintain constant layer height (1 mm) and vertical axis build rates as to minimize study size
  - Prior work has determined highlighted parameters are most critical to quality deposits

Direct Additive Recycling at FOBs: Higher RPM and Traverse Correspond to Higher Hardness Values

- Contour maps created from hardness profile maps from defect-free deposits
- General trends show that higher deposition rates produce harder builds
  - However, an appropriate balance is necessary to prevent excess flash or high amounts of galling in the deposits



Contour maps relating rotational, actuator, and traversing parameters to average hardness

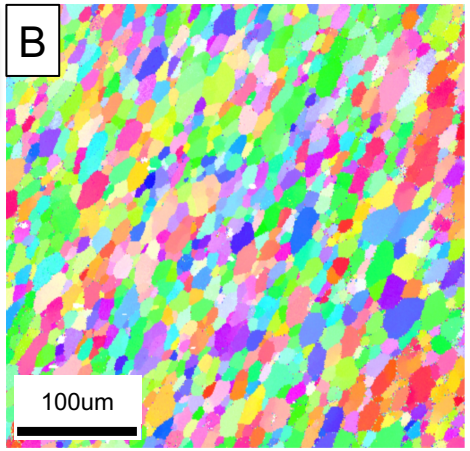
Direct Additive Recycling at FOBs: AFS-D Provides Hall-Petch Strengthening of Materials AA6061 has 93% Average Grain Size Reduction

AA6061-T651 Extruded Feedstock
(100µm Scale Bars)
200 µm average grain size

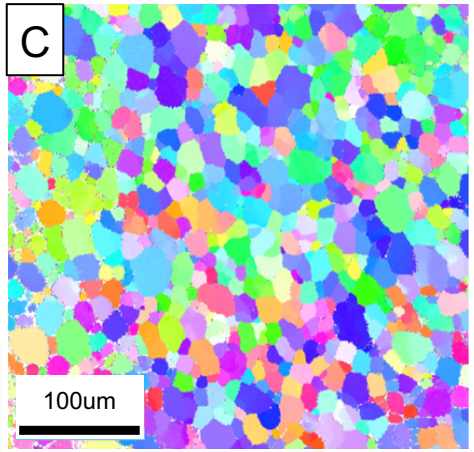
"Slow" Deposit"
15±4 µm average grain size

A

B

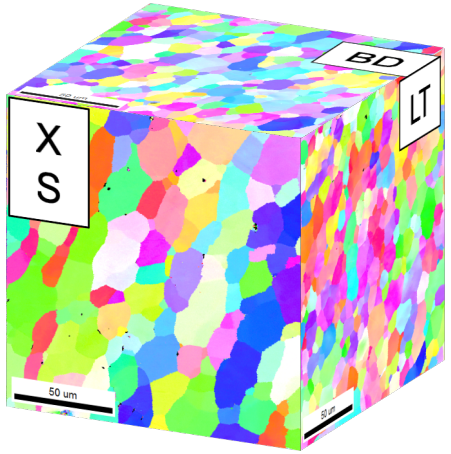


C



"Rapid" Deposit
15±4 µm average grain size

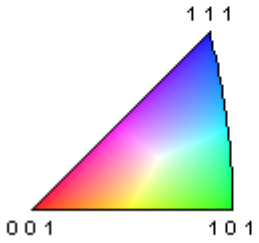
D



(50µm Scale Bars)

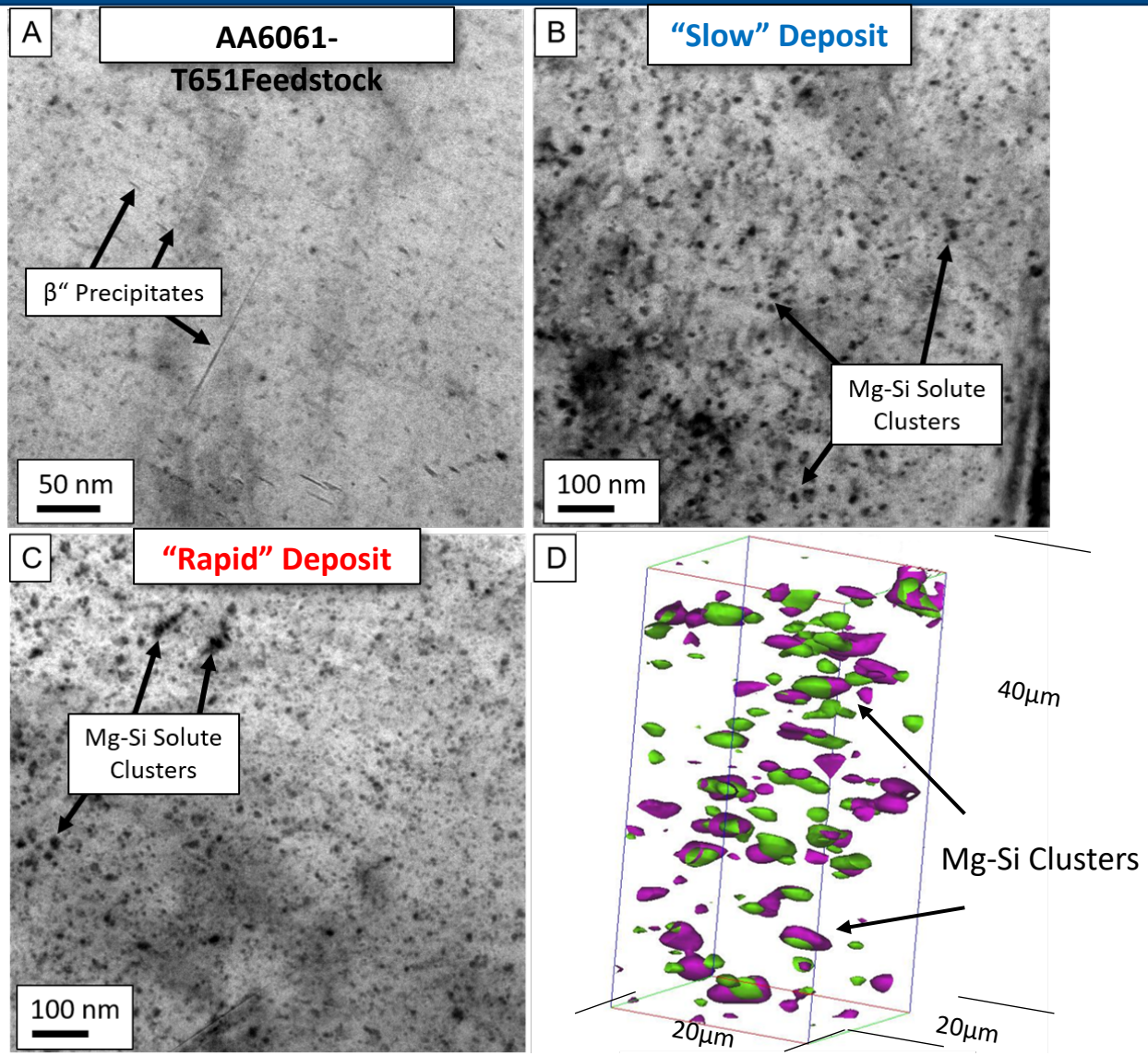
E

Aluminum

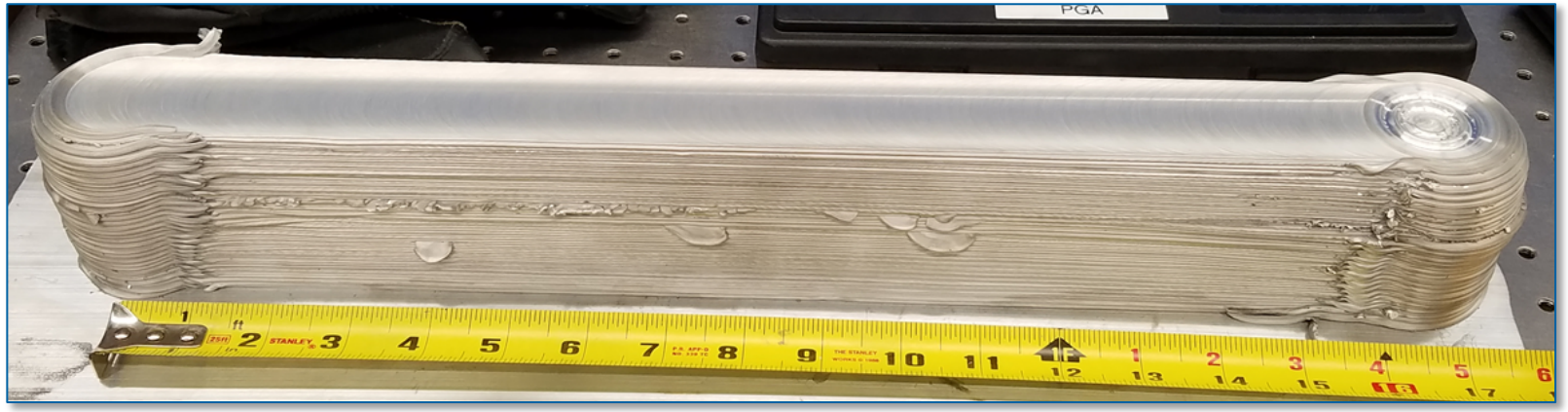


Direct Additive Recycling at FOBs: Traditional β" Dissolved and Re-Precipitated as Circular Mg-Si Clusters

- High shear deformation and temperature dissolved conventional β" strengthening precipitates
- Atom probe tomography (Fig. D) revealed Mg-Si circular clusters
  - Temperature retention following a deposit is enough to re-precipitate into clusters
- Despite parameter variance, microstructure in both samples remain similar

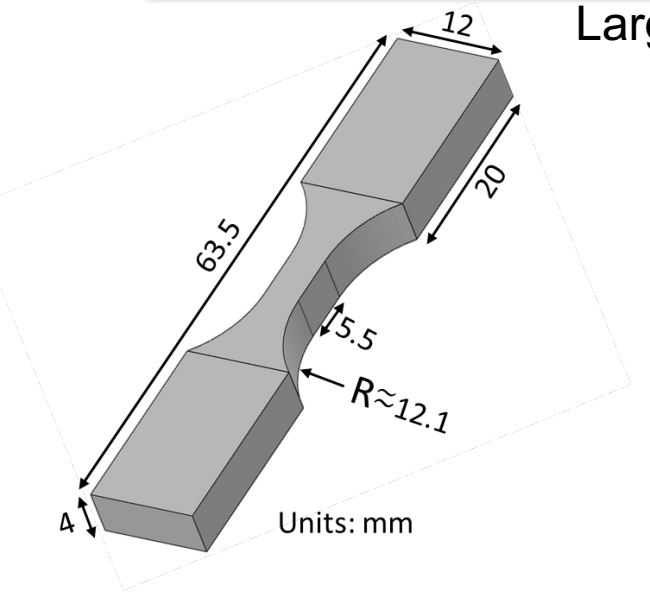


Direct Recycling at FOBs: Large AA6061 AFS-D Build Deposited For Mechanical Characterization

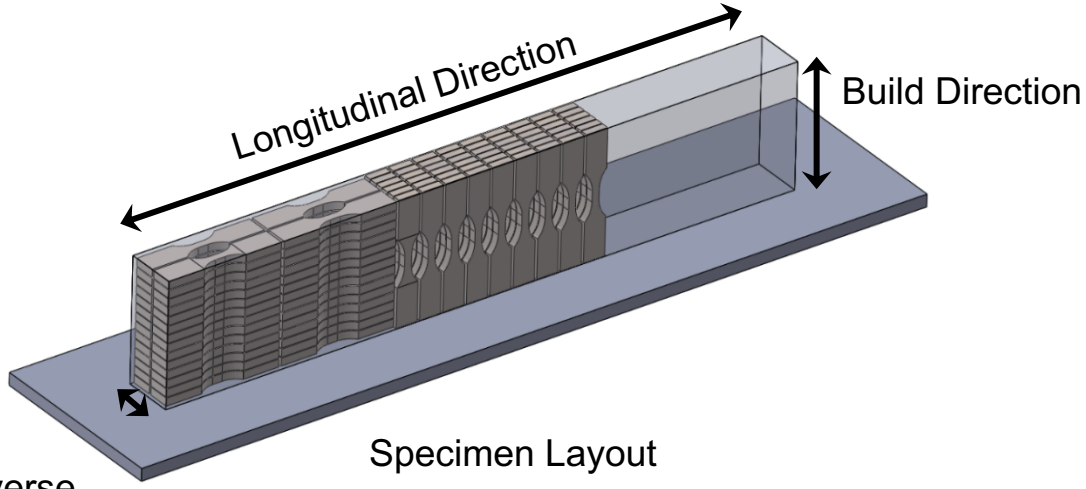


Large AFS-D AA6061 Deposition

- Deposited 16.5” length AA6061 to get build direction samples



Specimen Design

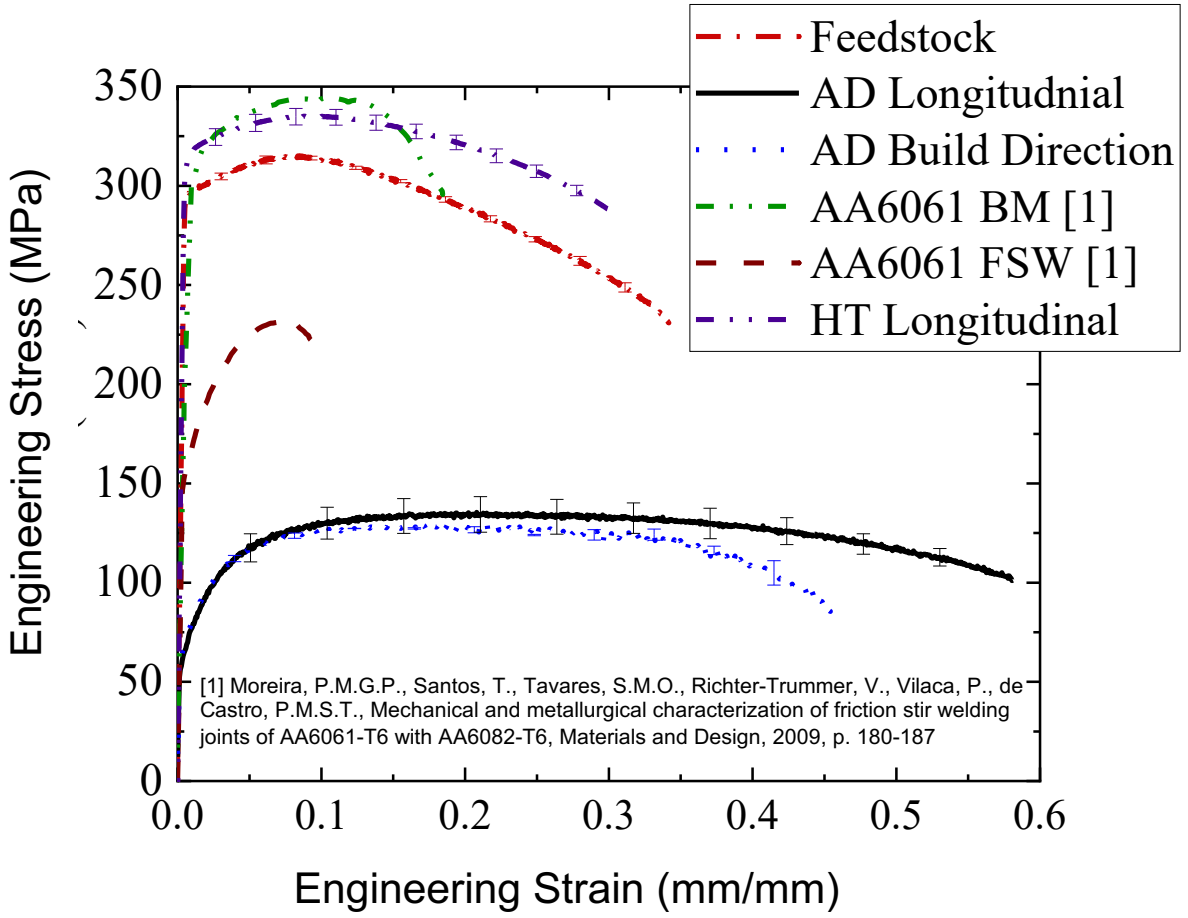


Specimen Layout

- Monotonic and fatigue specimens were machined out using wire-EDM

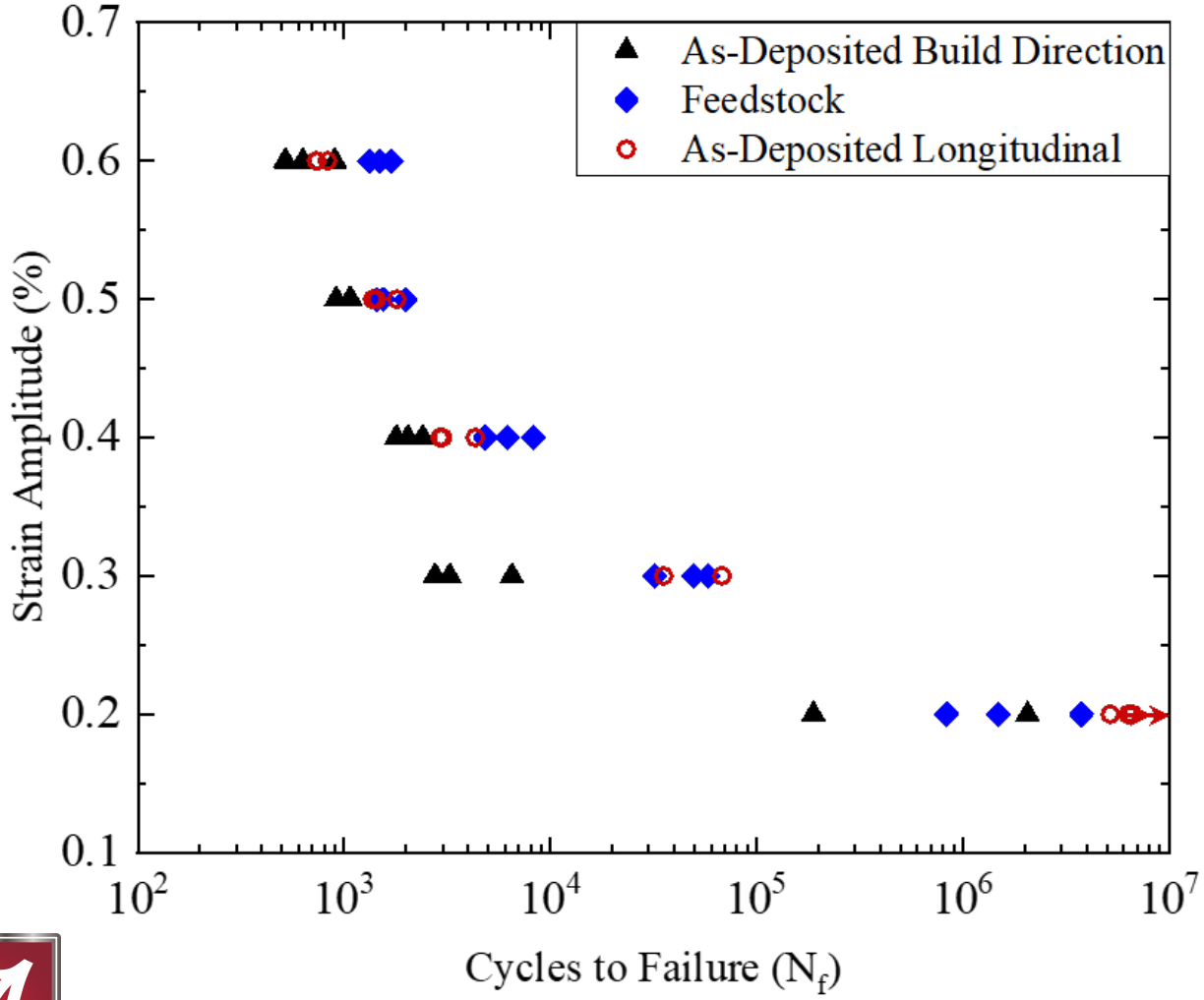
Direct Additive Recycling at FOBs: Heat Treated AFS-D Provides Increased Tensile Strength Compared to Heat Treated Feedstock

- AFS-D Heat Treatment:
  - Solutionized at 565°C
  - Quenched, then aged at 177°C
- Heat treated samples demonstrate greater strength to the feedstock at the cost of ductility
- Ongoing work to characterize additional orientations and microstructure



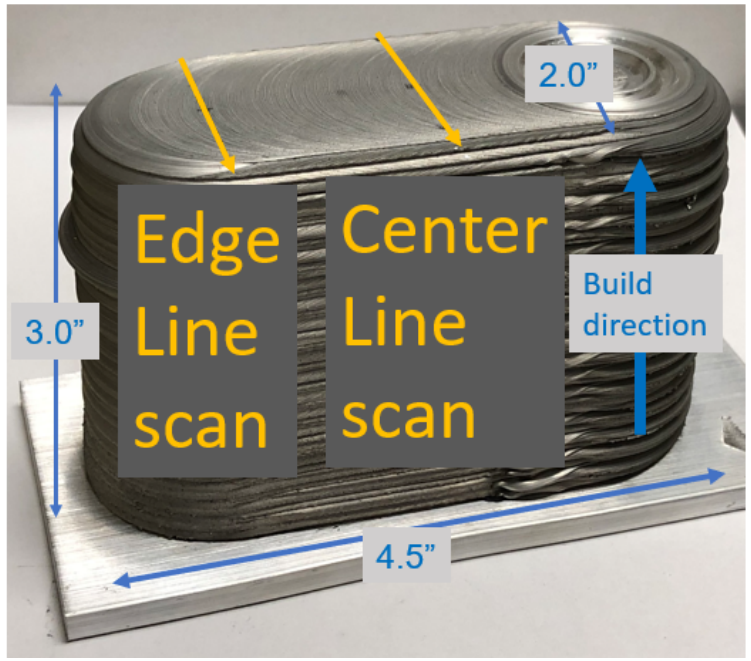
Comparative Tensile Stress-Strain Data of AFS-D AA6061

Direct Additive Recycling at FOBs: Fatigue Behavior of As-Deposited AA6061 Similar to Feedstock AA6061-T6



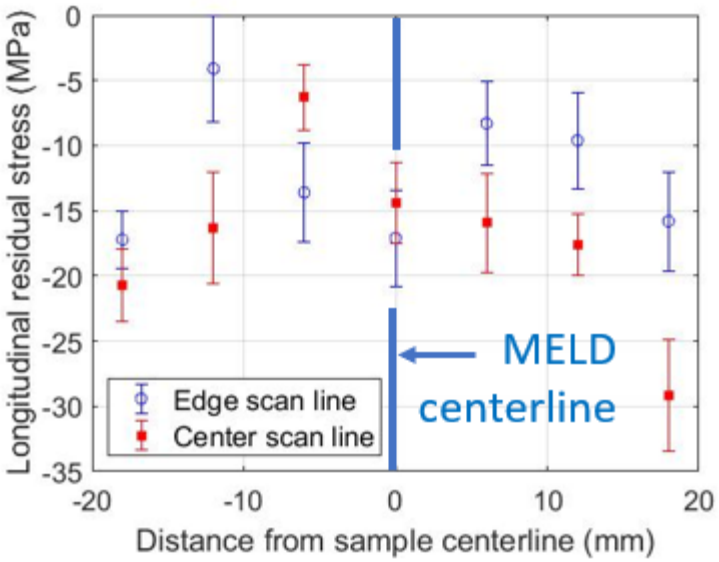
- As-deposited material experiences similar fatigue performance to feedstock material under strain-control (R=-1)
- Cycles to failure for build direction as-deposited material performs lower when compared to longitudinal as-deposited, possibly due to interlayer crack initiation
- Although feedstock possesses higher strength, the refined, equiaxed microstructure of the longitudinal as-deposited samples possibly delays crack nucleation, leading to increased fatigue life

Direct Additive Recycling at FOBs: Compressive Surface Residual Stress on AFS-D AA6061 Helps improve Fatigue Performance.



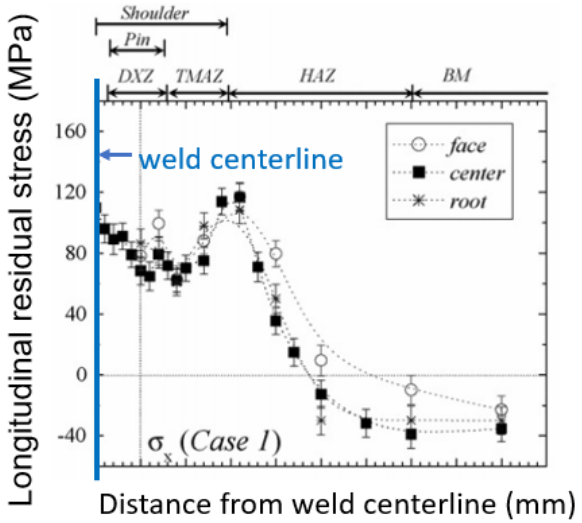
XRD residual stress large anodized feedstock build of AA6061 for process model calibration

AFS-D (MELD) AA6061



- Small constant compressive residual stress around -20 MPa.
- Potential increase of fatigue life due to surface compressive residual stress.

Friction stir welded AA6061



Residual stress distribution of friction stir welded AA6061-T6 (Woo et al., 2006).

- Large inconsistent tensile residual stress with peak at +120 MPa.
- Induction of fatigue cracking, stress corrosion cracking.

Necessary analysis of through thickness residual stress distribution from Neutron Diffraction. Beam time has been awarded from Oak Ridge National Laboratory.

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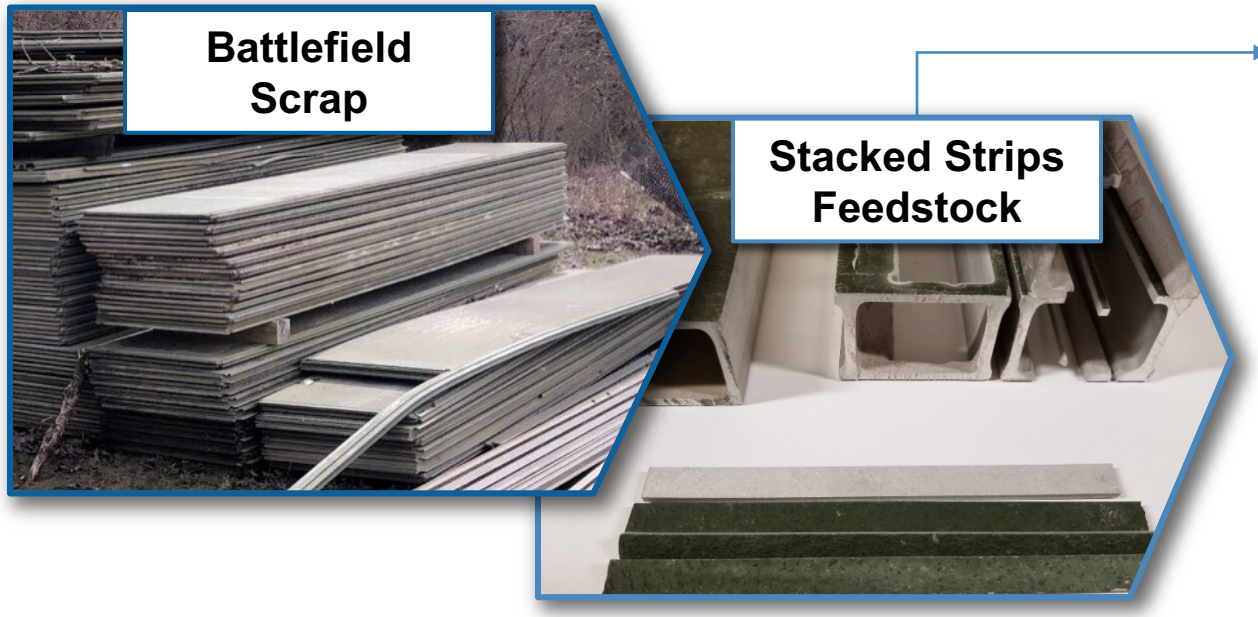
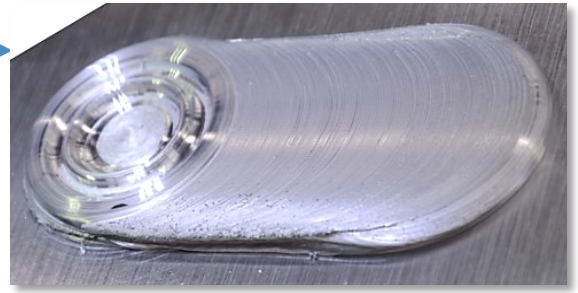
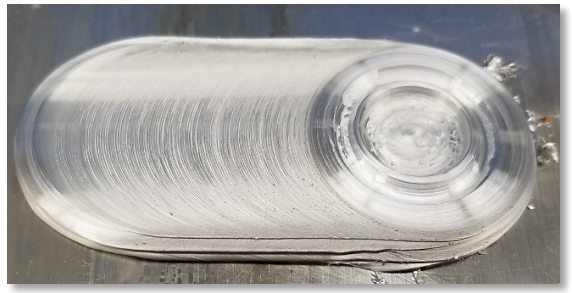
Direct Additive Recycling at FOBs: Stacked Strip Waste Stream Repurposed Stacked Aluminum Strips Exhibit Similar Deposition Qualities to Solid Rod





Recycled Battle Damaged Airfield Mat Deposition



Deposition from Solid Feedstock is Similar to Recycled Material

- 3 strips of damaged airfield landing mat aluminum were stacked and inserted as feedstock
- Processing parameters developed for 3 aluminum alloy 6061 feedstock materials:
  - (1) New wrought solid rods
  - (2) Stacked strips of recycled waste
  - (3) Anodized rod with controlled surface oxides

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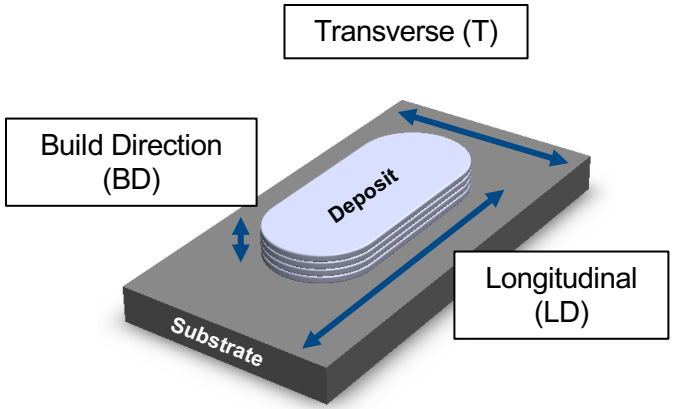
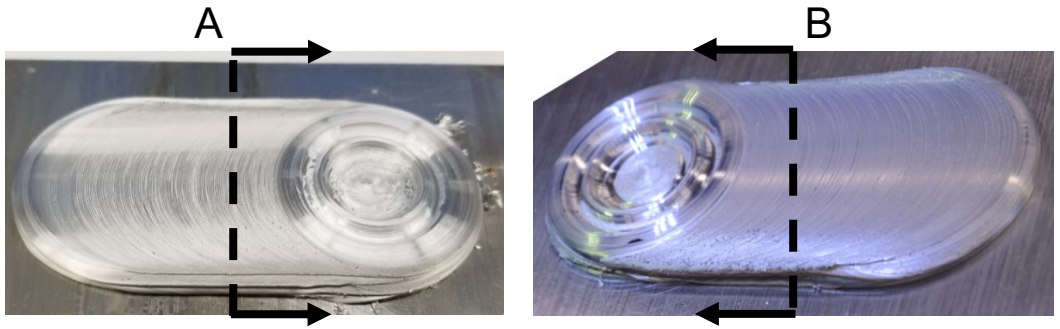
Direct Additive Recycling at FOBs: Stacked Strip Waste Stream Depositing Recycled Strips Revealed Similar Microstructures as New Wrought Feedstock



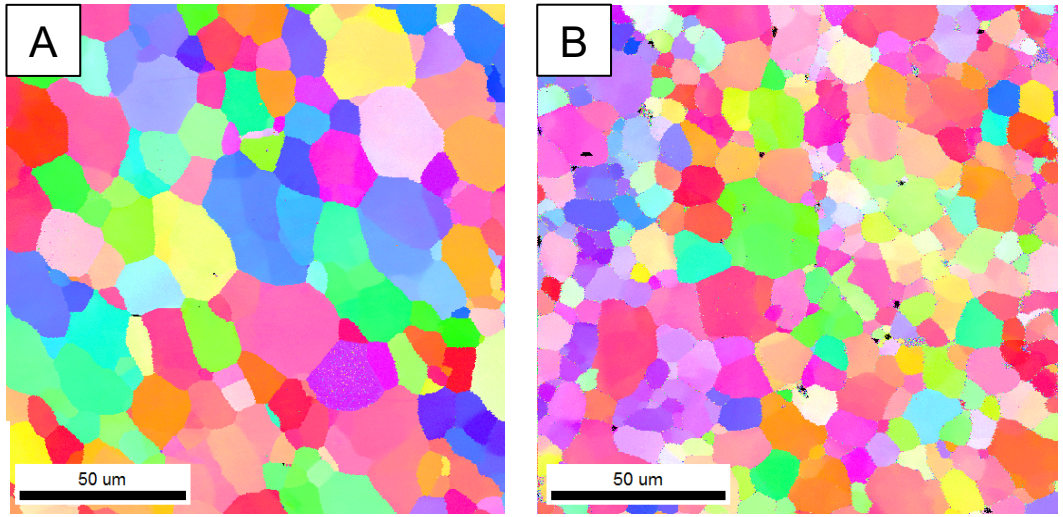
Schematic of Deposited Material Identifying Directions

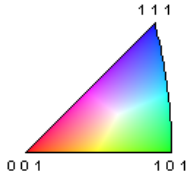


Solid Rod Deposit

Recycled Strips Deposit

- 15μm equiaxed grain structures evident in both deposits
- Average hardness as-deposited:
  - Solid Rod = 60.8 ± 3.2 HV
  - Recycled Strips = 55.6 ± 4.0 HV





EBSD Cross-Section of As-Deposited Solid Rod of AA6061

EBSD Cross-Section of As-Deposited Strips of AA6061

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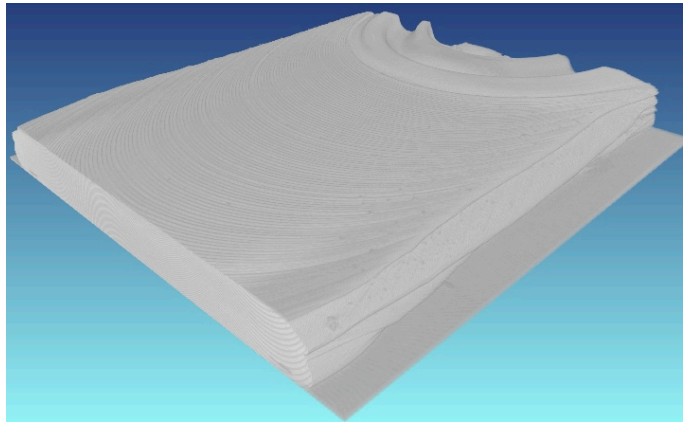
Direct Additive Recycling at FOBs: Stacked Strip Waste Stream X-Ray CT Scans Show Fully Dense Builds For AA6061 Strips and Solid Rod Feedstock Deposition

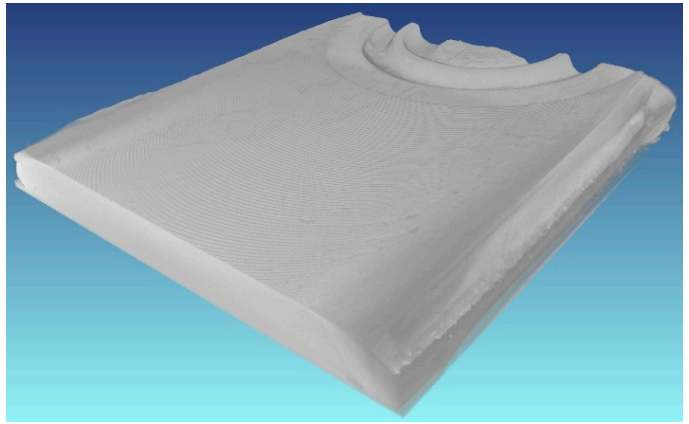
- Representative cross-sections from the middle of the respective CT scans show no porosity.
- The red dotted lines mark where the flash and deposition meet.

Cross section from the middle of X-Ray CT scan of AA6061 strip deposition



X-Ray CT scan showing 3D view of fully-dense AA6061 strip deposition

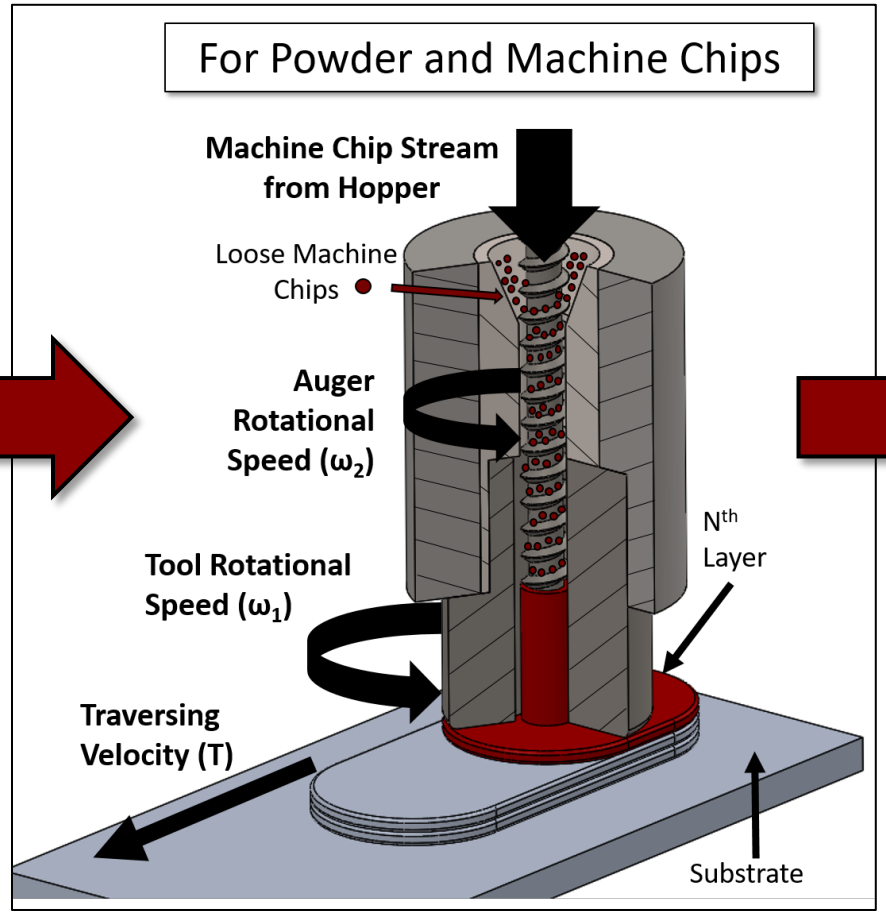
Cross section from the middle of X-Ray CT scan of AA6061 solid deposition



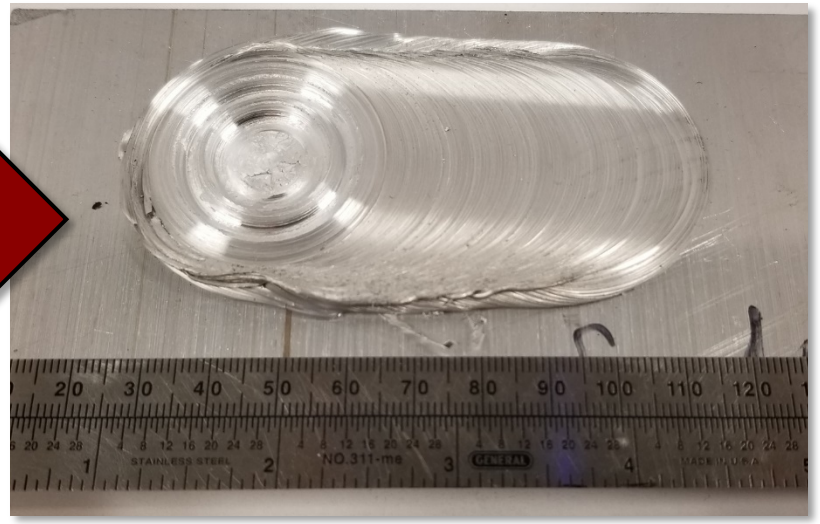
X-Ray CT scan showing 3D view of fully-dense AA6061 solid rod deposition

Direct Additive Recycling at FOBs: A Method for Direct Recycling Machine Chips at FOBs and Depots

Aluminum Alloy 5083 Machine Chips from CNC Mill



Schematic of the AFS-D Process for Machine Chips



AFS-Deposited AA5083

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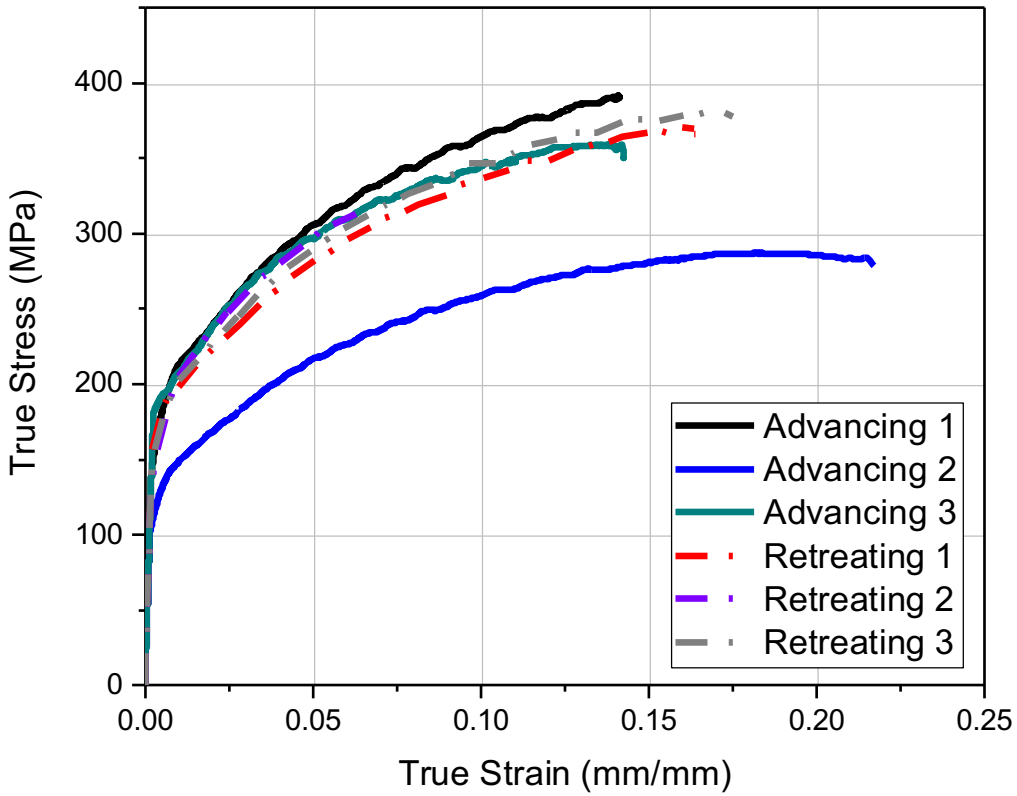
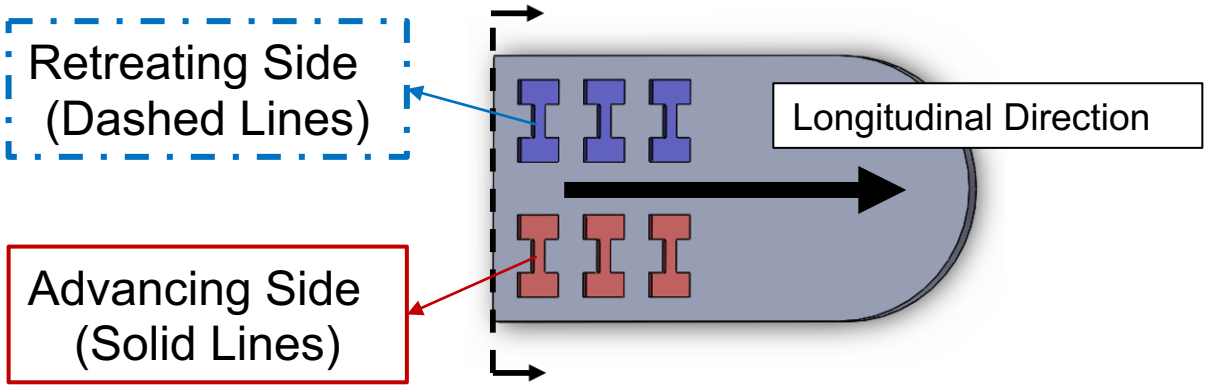
Direct Additive Recycling at FOBs: Machine Chips Provides Higher Tensile Strength and Ductility Than Feedstock



Comparative tensile stress-strain data of AFS-D AA5083 machine chip depositions



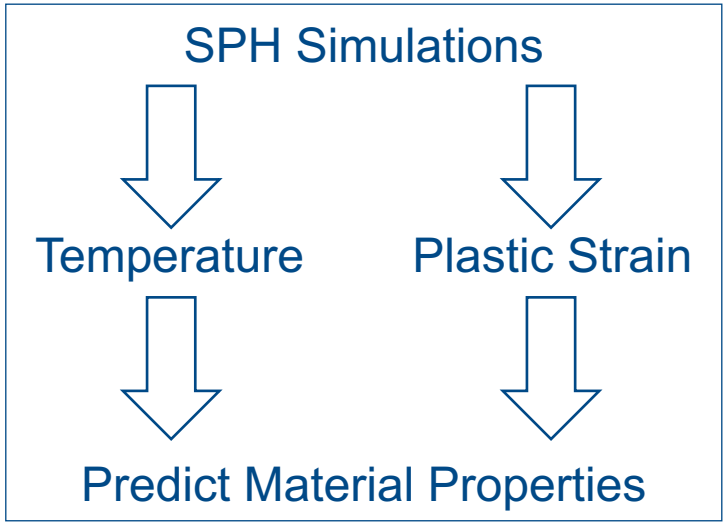
	Yield Strength (0.2%) [MPa]	Ultimate Tensile Strength [MPa]	Elongation at Break [%]
AA5083-H131 Plate (Nominal)	190	323	13
AA5083 Advancing	167.6 ± 32.6	342.5 ± 30.3	17.0 ± 3.9
AA5083 Retreating	170.4 ± 7.5	368 ± 13.7	14.9 ± 3.0

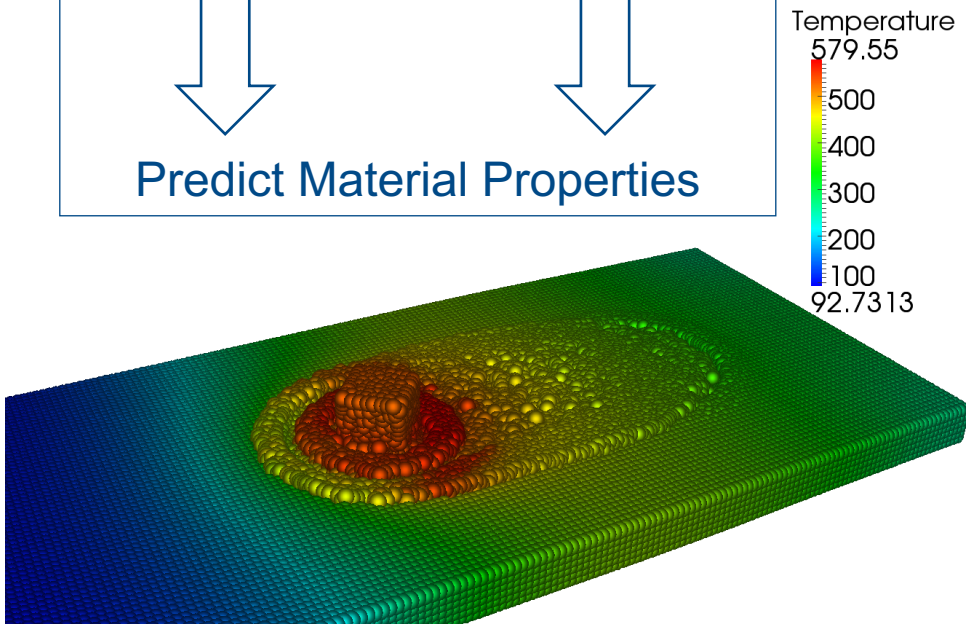
Tucker, M. T., et al. "The effect of varying strain rates and stress states on the plasticity, damage, and fracture of aluminum alloys." *Mechanics of materials* 42.10 (2010): 895-907.

Direct Additive Recycling at FOBs from Multiple MOS Waste Streams: Conclusions and Future Work

- Continue calibration and validation of history dependent material modeling:
  - Smooth Particle Hydrodynamics (SPH) process model
  - Internal State Variable (ISV) plasticity-damage model
  - Multistage fatigue model
- Quantifying Processing-Structure-Property-Performance relations of Direct Additive Recycled:
  - New wrought material
  - Continuous and discontinuous machine chips (Maintenance-MOS)
  - Multiple strips of damaged airfield matting (EAF-MOS)

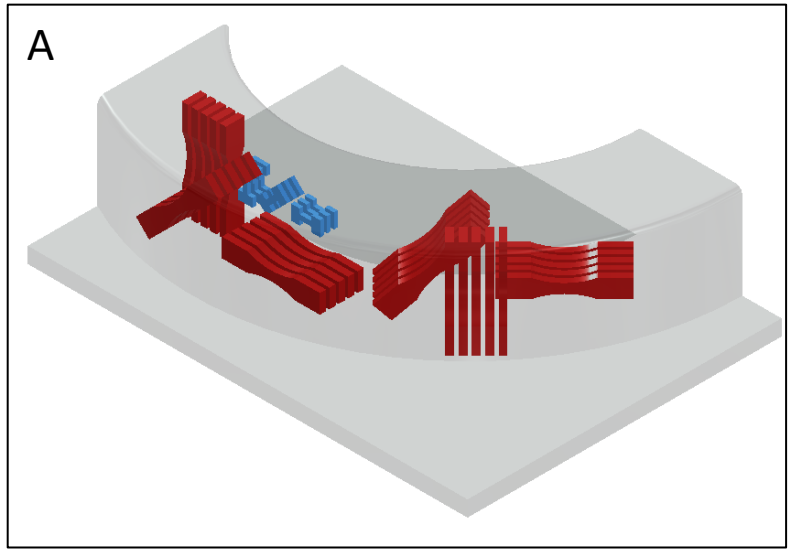
Digitally-Driven Manufacturing





Direct Additive Recycling at FOBs from Multiple MOS Waste Streams: Conclusions and Future Work

- Quantify influence of maintenance-MOS mix aluminum alloy machine chip waste stream builds
  - What happens if different machine chips get mixed and used to repair a component?
- Deposition path and specimen orientation influence
  - Curved build properties
  - Crater repair with overlapping passes
  - Monotonic and cyclic behavior of specimens with varying orientations in helical deposition path
- Further examine the microstructure and properties of the heat-treated AFS-D deposits
- Repair of mission critical EAF-MOS components
  - Successfully repaired EAF edge clamp for component testing in collaboration with US Army ERDC



A. Tensile (blue) and fatigue (red) specimens taken in the 0˚, 45˚ and 90˚ direction with respect to build direction. Fig. B. AFS-D AA6061 8-inch diamter circular build.

Published Journal Article:

"Microstructure-Deformation Relationship of Solid-State AM AFS-Deposition Aluminum Alloy 6061"

BJ Phillips, DZ Avery, T Liu, OL Rodriguez, CJT Mason, JB Jordon, LN Brewer, PG Allison. Materialia (2019).

Thank You

Questions?

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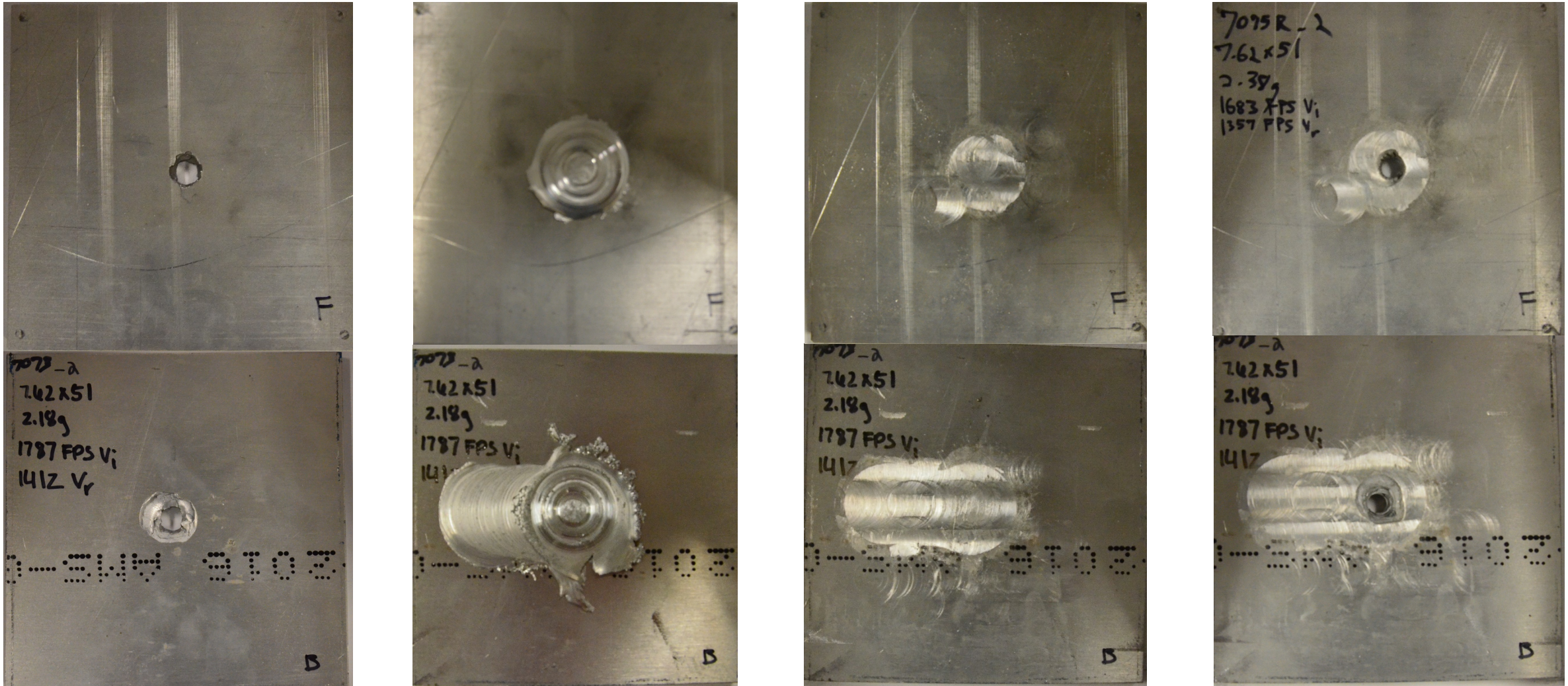
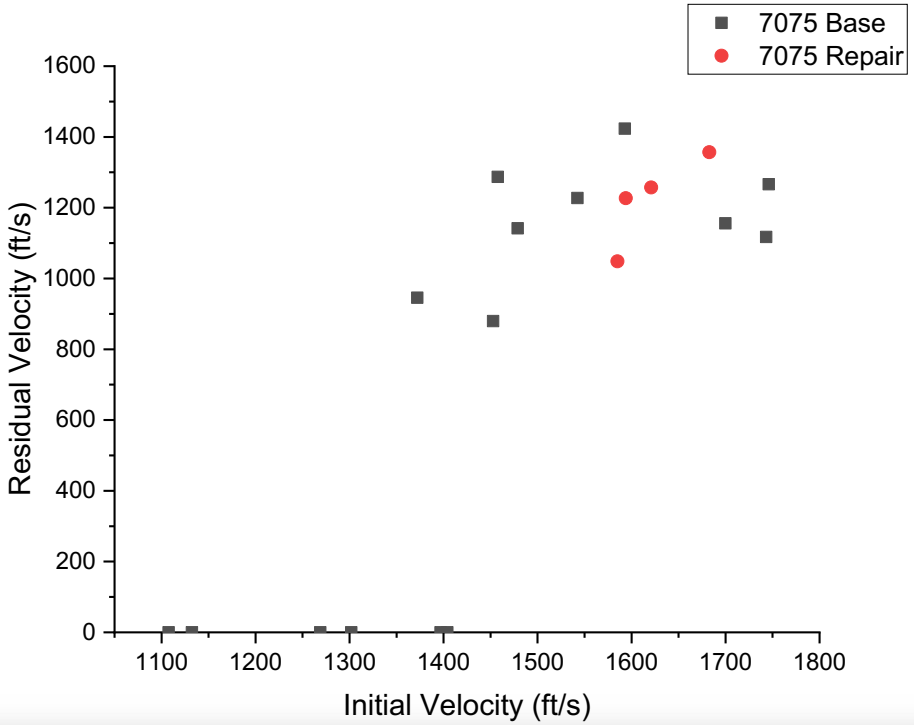
Solid-State Simulations, Processing, & Deposition

AFS-D Successfully Repaired Ballistic-Damaged Material

First Shot → AFS-D Repair → Excess Material Machined → Second Shot



Repaired Material Shows Comparable Ballistic Resistance To Base Material

- Ballistic performance of repaired material fits within scatter of base material
- Future testing will determine ballistic limits of both Base and Repaired material