Additive Manufacturing for DoD Applications

Additive Manufacturing for Defense and Government Symposium

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Concurrent Technologies Corporation

Background on CTC

- Established in 1987
  - Originally Metalworking Technology Inc. (MTI), a subsidiary of the University of Pittsburgh Trust
  - Adopted the name Concurrent Technologies Corporation (CTC) in 1992
  - Separated from the University of Pittsburgh Trust in 1994
- An independent, nonprofit, applied scientific research and development professional services organization
- ~ $200M in yearly revenues
- Staff of approximately 850 dedicated professionals
- Approximately 40 locations

Our Areas of Expertise

Our reach is broad; our areas of expertise, diverse.

Advanced Engineering & Manufacturing

Education & Training

Energy & Environment

Environment, Safety & Occupational Health

Information Technology Solutions

Intelligence Solutions

Logistics

Special Missions

Our strengths are derived from a broad continuum of capabilities including materials science; engineering; systems engineering; design & development; test & evaluation; and information technology & management.

DoD Problem

PMs are facing: ⇧ total ownership costs and ⇩ platform availability due to an ⇧ number of part challenges including:

1. Very long Mean Logistics Delay Time for limited production parts.
2. High cost for limited production runs to make problem parts; many of those are cast components. May include large investments to create special tooling and complex castings.
3. Lack of commercial interest in low volume complex fabrication work and significant delays in contracting and workflow.
4. Increasing pressure on organic manufacturing capability.
5. Higher failure rates; new failure modes; exigent parts demand for critical components.
6. Systems down/deadlined for part obsolescence issues; decreasing vendor supply base.
7. Ageing fleets with severe parts supply issues.
   - Examples: Amphibious Assault Vehicle will be **51 years old** at the end of service life, leading to increase in components that fail that were never expected to be repaired or replaced.

***DoD repair facilities are increasingly making parts to combat these challenges and* need new technologies for reliable & cost-effective production of low volume parts.**

Bottom Line Up Front

- Additive Manufacturing has great potential to impact the DoD across many platforms and applications
- More research, careful implementation, and qualification & certification is needed to gain confidence in additive manufacturing
- DoD is working with academia, industry, and across government organizations to mature AM
  - Material performance
    - Design and engineering of AM parts, consistency, standards, etc.
    - AM is capable of more materials, that have yet to be proven
  - Machine performance
    - Identifying, improving and documenting key process parameters to enable qualification and certification of AM. In situ monitoring, with closed loop controls
  - Digital Product Data:
    - Verification and validation of model quality and data prior to manufacturing process
      - Integrated Computational Materials Engineering
- Need to intelligently accelerate AM design loop & thoroughly understand process to build confidence in AM & increase quality. Qualification enables wider use of AM for DoD applications

AM Solutions for the DoD

America Makes Special Project (AFRL/RXMS) ~ Laser Powder Directed Energy Deposition (LPDED) for Repair

- Team:
  - Leaders: Optomec (prime); CTC; Advanced Research Laboratory at Pennsylvania State University (PSU); Connecticut Center for Advanced Technology (CCAT); Edison Welding Institute (EWI); TechSolve
  - Primary Technical Support: General Electric Aviation (GE); Lockheed Martin (LM); United Technologies Research Center (UTRC); Rolls Royce
  - Contributors: M-7 Technologies (M-7); Missouri University of Science and Technology (MS&T); Rolls Royce Corporation (RR); Stratonics; University of Connecticut (UConn); Wolf Robotics; various powder suppliers
  - Alternates: Univ of Louisville; Texas A&M; South Dakota School of Mines
- Objectives:
  - Develop guidelines on optimum powder feedstock characteristics for high part quality
  - Conduct improvements in process monitoring and control
  - Develop design allowables and guides (Lead: CTC)
  - Recommend Air Force (AF) part repair and sustainment applications (Lead: CTC)
- Materials: Ti-6Al-4V
- POP: July 2014 – September 2016

Turbine Support Bearing Housing, After LENS Repair

LPDED System Overview

Standard LENS 850R Features

- 900mm x 1500mm x 900mm process area
- Class 1 laser enclosure, hermetically sealed
- 5 axis motion control X,Y,Z with tilt & rotate table
- Gas purification system maintains O2 < 10ppm
- 2 or more powder feeders
- 380 mm diameter ante chamber
- 1kW to 10kW IPG Fiber Laser

Benefits

- Can add features or repair material to a pre-existing structure
- Microstructure and material property control (e.g., grain size)
- Multi-material gradient capabilities (layer-to-layer & in-layer)
- Builds relatively large, complex geometries
- Minimal effect on substrate microstructure (small HAZ)

In Development: Modular System for Larger Components

AM Solutions for the DoD

Navy Metalworking Center (NMC)

Non-Destructive Inspection (NDI) for Electron-Beam Additive Manufacturing (EBAM) of Titanium

- Team: NMC (CTC); AFRL; Lockheed Martin Aeronautics; Sciaky, Inc.
- Objectives:
  - Implement EBAM material in place of titanium (Ti) forgings to reduce lead time and cost wrt Ti die forgings and machined structures
  - Validate NDI methods
    - Assess capability of NDI methods (detect expected EBAM defect types)
    - Quantify effects on detection capability (surface finish and heat treatment)
- Material: Ti-6Al-4V
- Inspection Methods Considered/Evaluated
  - Bulk: conventional ultrasonic inspection (UT); phased-array ultrasound (PAUT); film X-ray radiographic testing (RT); X-ray computed tomography (CT)
  - Surface: fluorescent penetrant inspection (FPI); eddy current
- POP: October 2012 – April 2015

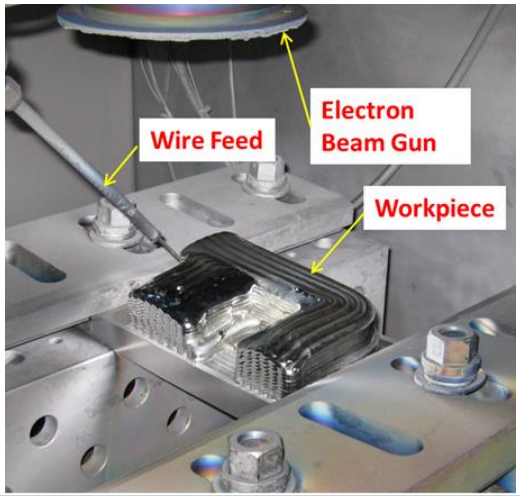


Photo Courtesy of Sciaky

The EBDM Process

- Wire-fed (1/8″ dia) feed stock
- Electron beam (EB) heat source
- Alloys processed
  - Titanium
  - Tantalum
  - Inconel®
  - Others
- Project focus
  - Ti-6Al-4V

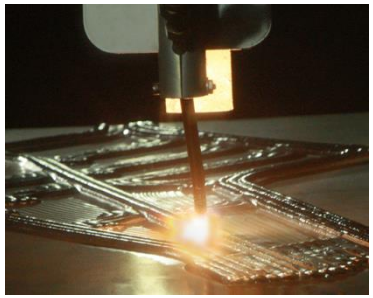


Photo courtesy of Sciaky

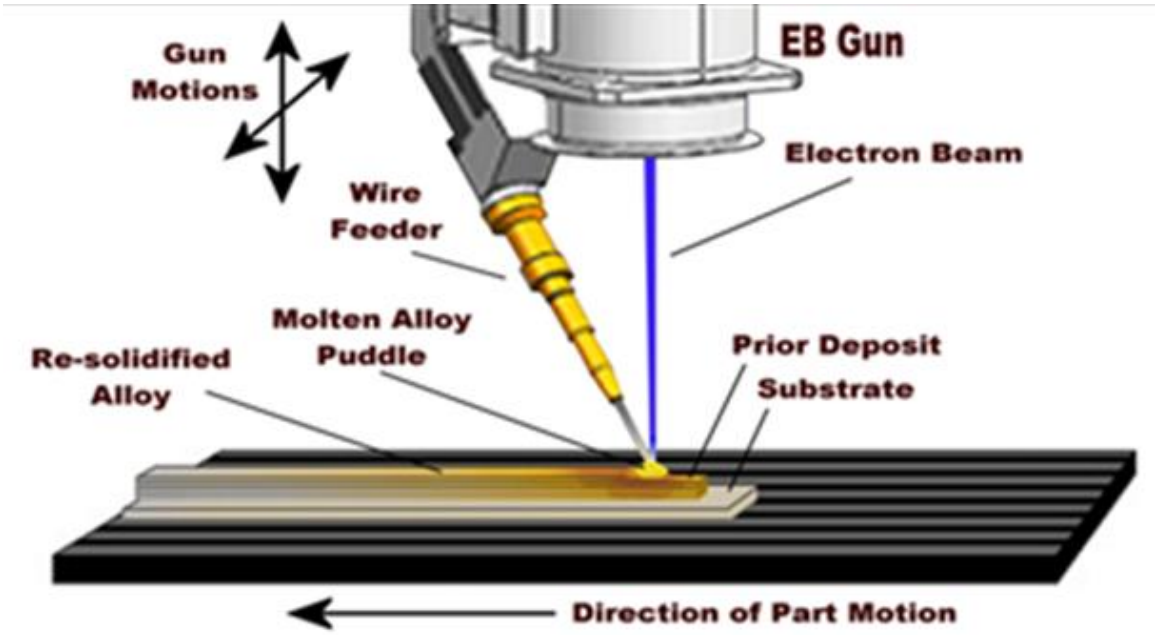


Illustration courtesy of Sciaky

Highest Payoff Applications

- High deposition rates
  - 10+ lbs/hr
- Consistent material properties have been demonstrated
- Up to 60% reduction in production cost
- Aerospace structural components
  - Bulk of details machined from substrate plate
  - Use EBDM to build up remaining details
- Thin, long and/or wide parts with protruding features
  - Lugs
  - Bosses
  - Webs

28″

118″

Photos courtesy of Sciaky

Part Inspection

- No standards currently defined for NDI of EBDM parts
- Must inspect specific areas of fracture-critical aerospace components
- Limits of inspection technologies uncertain for this product form
- Focus: understand inspection limits and begin to prepare standards for inspection of EBDM builds

Test Approach

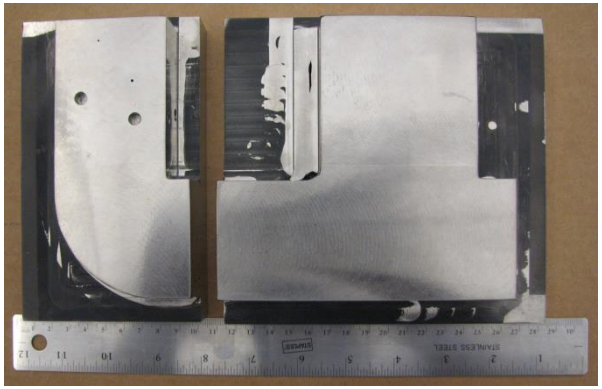
- Build geometry
  - Simple shapes (rectangular, step, F-shape)
  - Bulky “medium complex shapes”
  - Prototype flaperon spar
- Seed flaws of different type, size, location and orientation
  - Mechanically introduced
    - Flat-bottom holes (FBHs)
    - Side-drilled holes (SDHs)
    - Wire EDM slots
    - Sinker EDM notches
  - Intentional non-standard process anomalies
    - Excessive gaps between neighboring beads
    - Starts and stops
    - Contaminants (vacuum oil, copper shavings or aluminum oxide flakes)
    - Low vacuum (air or excess helium added)
- Inspect
  - NDI
  - Destructive (Metallography)

Simple-Shaped Test Coupons

Test Coupon A: as-received

Test Coupon B: defects

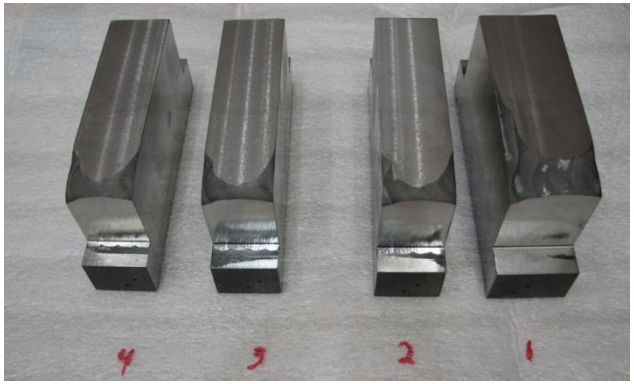
Test Coupon D: finish build



Test Coupon A: machined

Vacuum Oil | Aluminum Condensate | Copper Filings | Oxidized Surface

Test Coupon C: contaminants

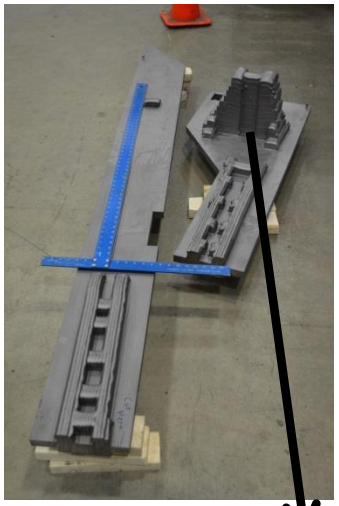


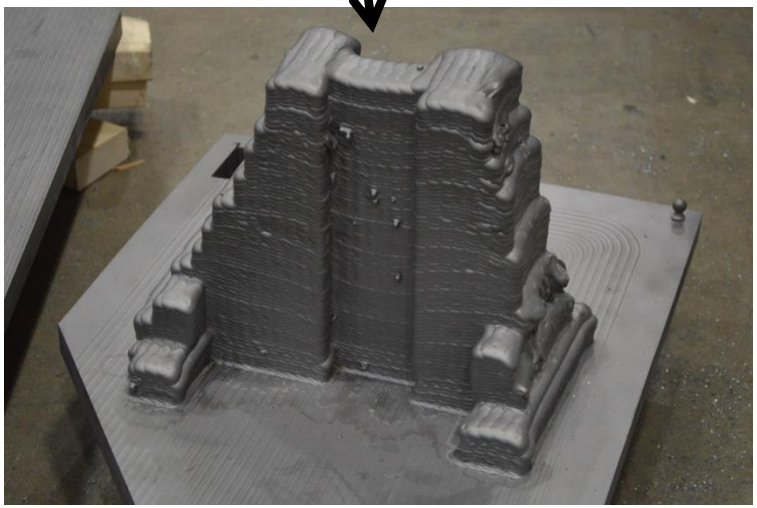
Coupons ready for NDI

CTC photos

Prototype Flaperon Spars

- Part intentionally cut into two pieces to facilitate NDI in available machine
- Rough machined and introduced FBHs and sinker EDM cuts
- CT inspections completed
  - Challenge in penetrating thick build features
- CT inspections also completed on second, near-finish machined version of part





CTC photos

Results

- Conventional Ultrasonic Testing (UT) Inspection Capability
  - 3/64″ FBH detectability limits
    - Thickness < 3″ “as deposited”
    - Thickness < 1″ Beta annealed
  - Surface roughness impact on UT signal attenuation
    - 125 μin RMS: acceptable
    - 250 μin RMS: unacceptable
- Fluorescent Penetrant Inspection FPI procedure used for wrought products acceptable
- X-Ray Radiography affected by section thickness
  - Ineffective beyond 3″ section thickness; further assessment required
  - Limits inspectability of thick sections of preforms
- CT shows promise as acceptable inspection method (more work needed)

Conclusions

- UT inspection of EBDM builds are limited by banded microstructure of deposit
  - Most pronounced after Beta heat treatment
- Viable inspection methods include -
  - Ultrasonic Testing (UT) in as-deposited condition
  - X-Ray Radiography (RT) for sections sizes under 3″
  - Fluorescent Penetrant Inspection (FPI)
  - Computed Tomography (CT) – depending on part thickness

National Institute of Standards and Technology (NIST) Project: Measurement Science Innovation Program for Additive Manufacturing

America Makes

CTC Concurrent Technologies Corporation

Develop and validate NDE techniques for post-manufacturing inspection of laser powder bed fusion (L-PBF) components.

EWI® We Manufacture Innovation

Evaluate and mature in-process sensing techniques on a L-PBF Sensor Test Bed to:

- *Enable quality monitoring*
- *Address technical gaps in post process NDI*

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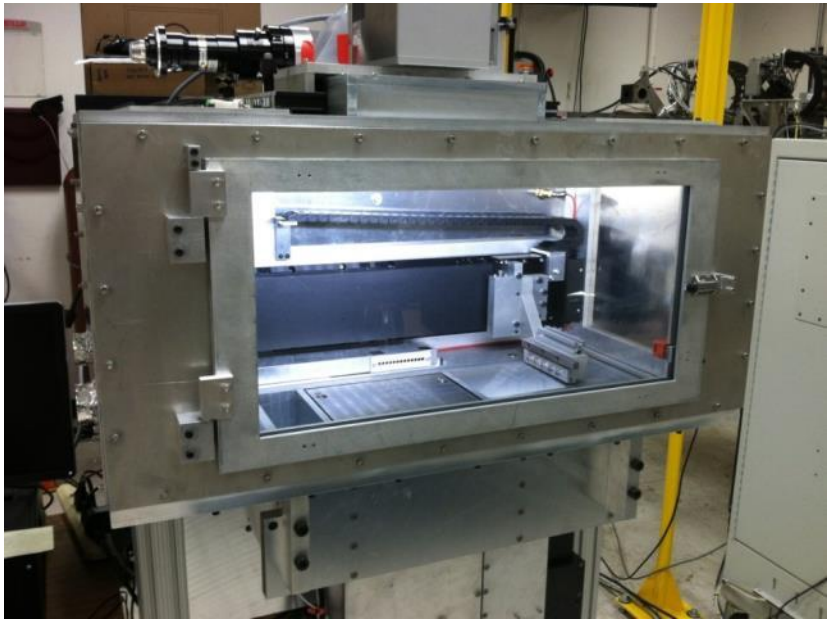
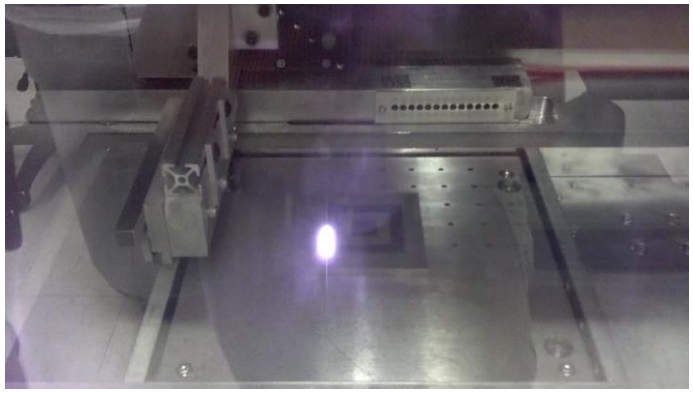
Create a 3D Quality Certificate (3DQC) for each manufactured part using run-time process monitoring data indexed to part geometry.

EWI
We Manufacture Innovation

Technical Approach



- Sensor Test Bed allows for sensor evaluation without physical or software constraints
- Local Strategies: Monitor the area near the point of material fusion
- Global Sensor Strategies: Defect occurrence over entire bed
- Passive Strategies: Continuous monitoring of environment
- Data Collection/Processing



Task Team includes:
UNC Charlotte, G.E. Aviation Stratonics, B6 Sigma, Paramount Industries, Georgia Tech, EOS

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Technical Approach

- Create template for 3DQC from part geometry file, part orientation during build, and machine layer and scan parameters
- Register layerwise monitor data to template and store continuous monitor data for each layer
- Demonstrate method using thermal imaging to monitor the polymer laser sintering process for polyamide parts
- Demonstrate method using thermal imaging to monitor the e-beam melting process for Ti64 parts
- Demonstrate method using optical imaging to monitor the metal laser melting process for IN718
- Integrate method with an “open architecture” polymer laser sintering machine

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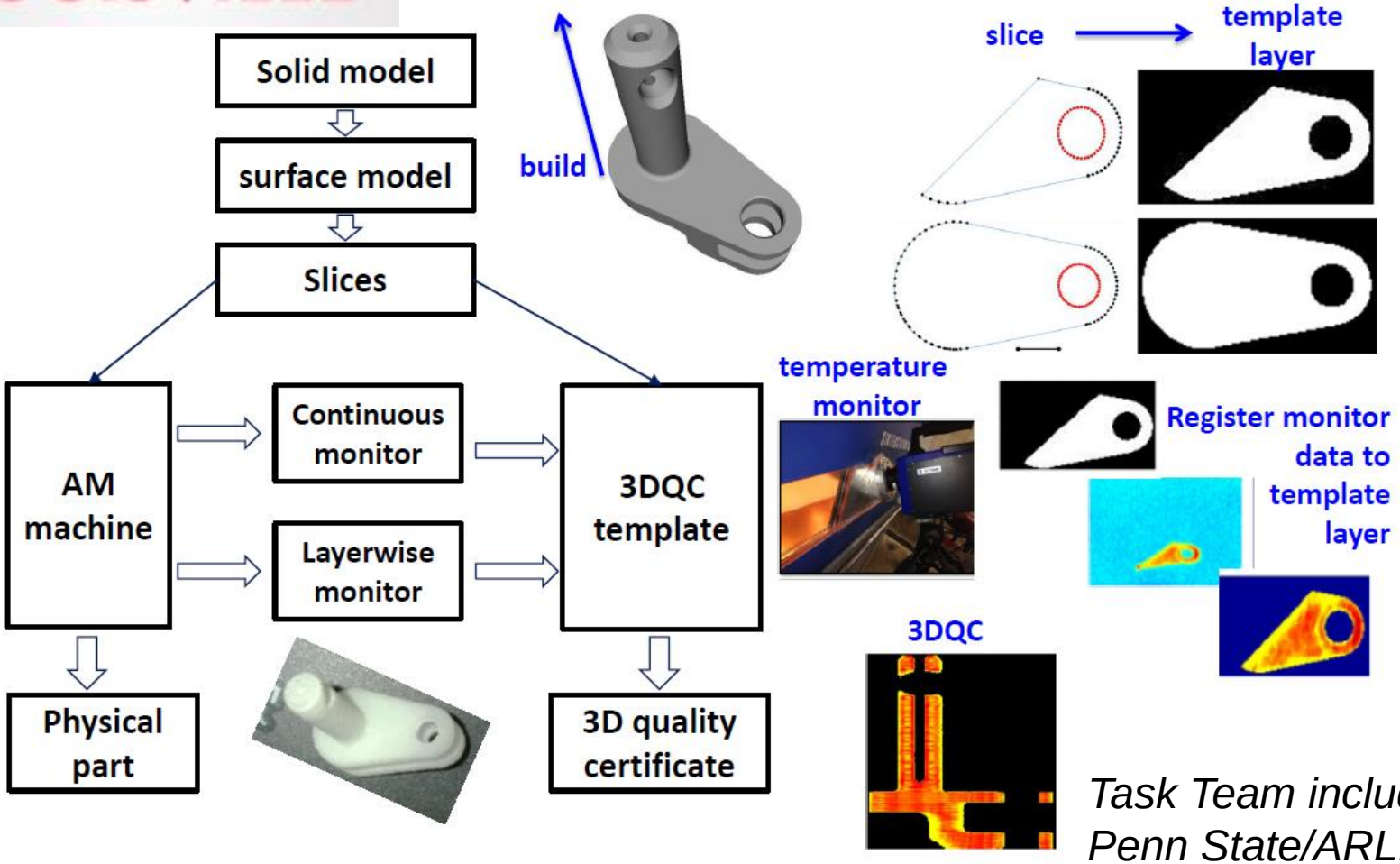
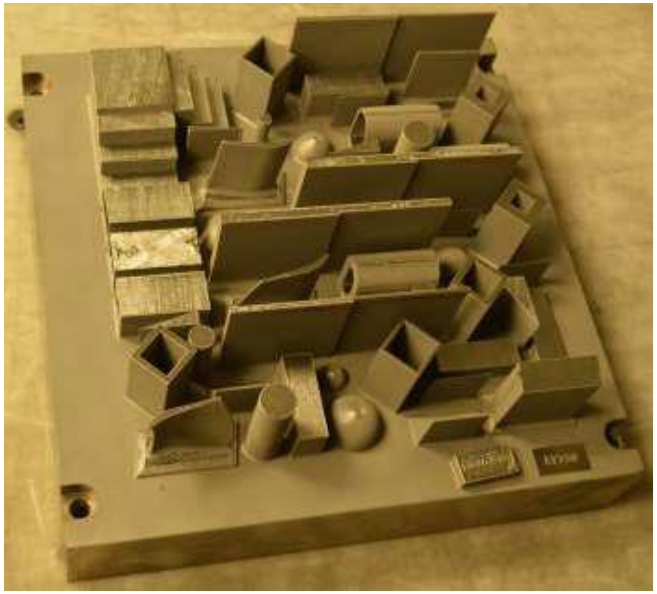


Task Team includes:
Penn State/ARL,
University of Texas El Paso,
Carnegie Mellon

AM Solutions for the DoD and Industry

NIST – Measurement Science Innovation Program for AM (cont)

- Non-Destructive Evaluation (NDE) Techniques for Post-Manufacturing Inspection of Laser Powder Bed Fusion (L-PBF) Components
  - Team: CTC; NCSU; G.E. Aviation
  - Objective: develop and validate NDE techniques for post-manufacturing inspection of L-PBF components
    - Determine reliable means to seed flaws in "simple" L-PBF parts
    - Quantify capability of NDE methods to detect seeded flaws
      - UT, RT, CT, others TBD
    - Apply knowledge to inspect complex parts with seeded flaws
  - Material: Ti-6Al-4V and CoCr
  - CTC efforts:
    - Planning of experimental validations
    - Determining types/location of seeded flaws
    - Identifying and supporting NDE testing
    - Machining
  - POP: October 2013 - September 2016



AM Solutions for the DoD and Industry

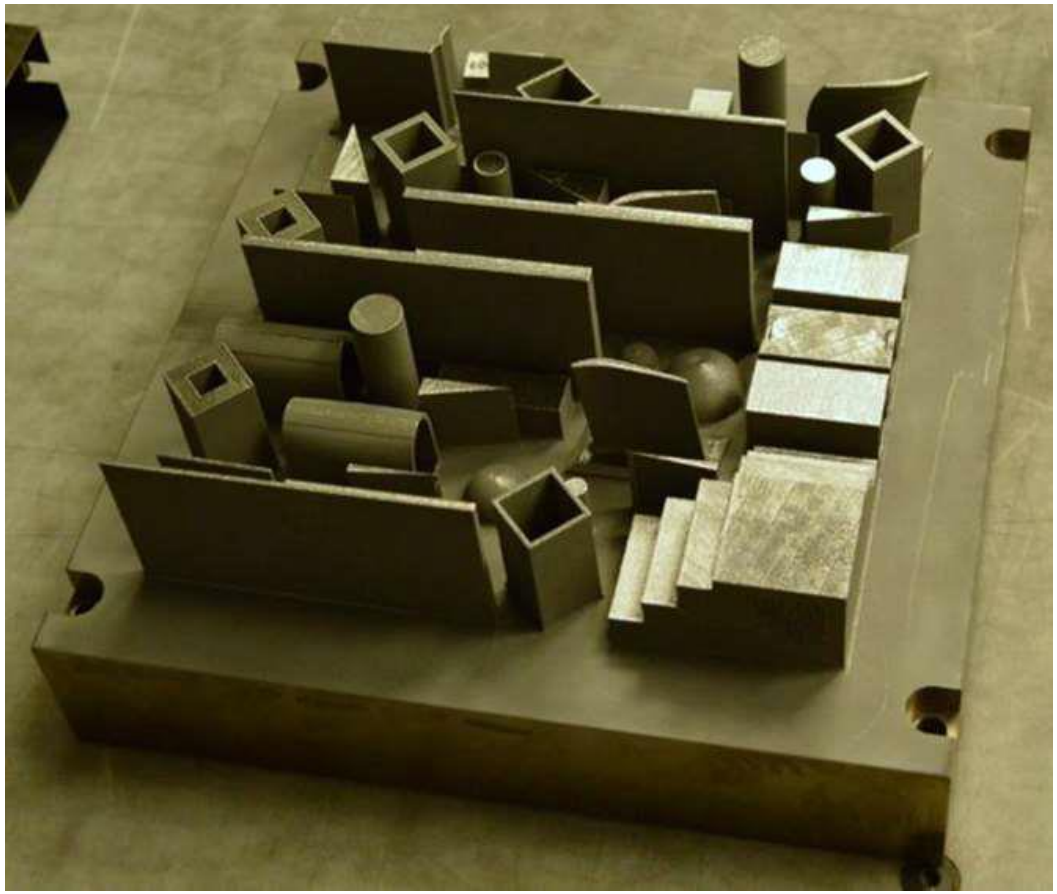
NIST – Measurement Science Innovation Program for AM (cont)

NDE Philosophy

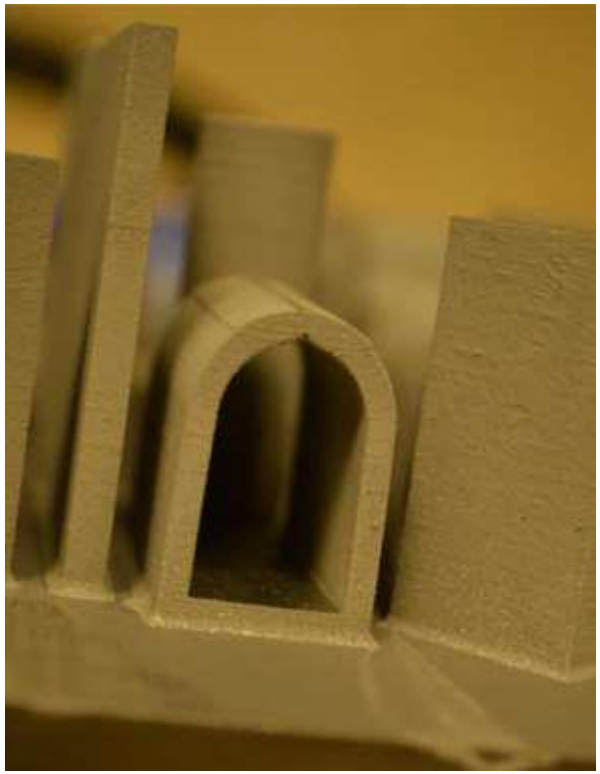
- Supposition: Computed Tomography (CT) is the gold standard of NDE for AM parts
  - Powerful combination of three-dimensional inspection and image analysis
  - GE Aviation's 100% volumetric CT inspection on every fuel nozzle
  - Effectiveness of CT for inspecting EBDM components under CTC/NMC project for AFRL
  - EWI's findings under Non-Destructive Inspection of Complex Metallic Additively Manufactured Structures
- Challenge #1: Develop reliable means to intentionally seed flaws in L-PBF parts
  - Flaws are tools for evaluating NDE limitations
  - Establish framework for similar approach beyond Ti-6Al-4V/CoCr and beyond L-PBF
- Challenge #2: Establish limits for flaw detection via CT in L-PBF parts
  - Validate CT's utility and understand inspection limitations for the specific cases of L-PBF Ti-6Al-4V and CoCr
- Challenge #3: Explore utility of alternative NDE techniques that offer advantages over CT for specific scenarios
  - Cost
  - Availability (e.g., depot vs. field inspection)
  - Schedule
  - Etc.

AM Solutions for the DoD and Industry

Build #1



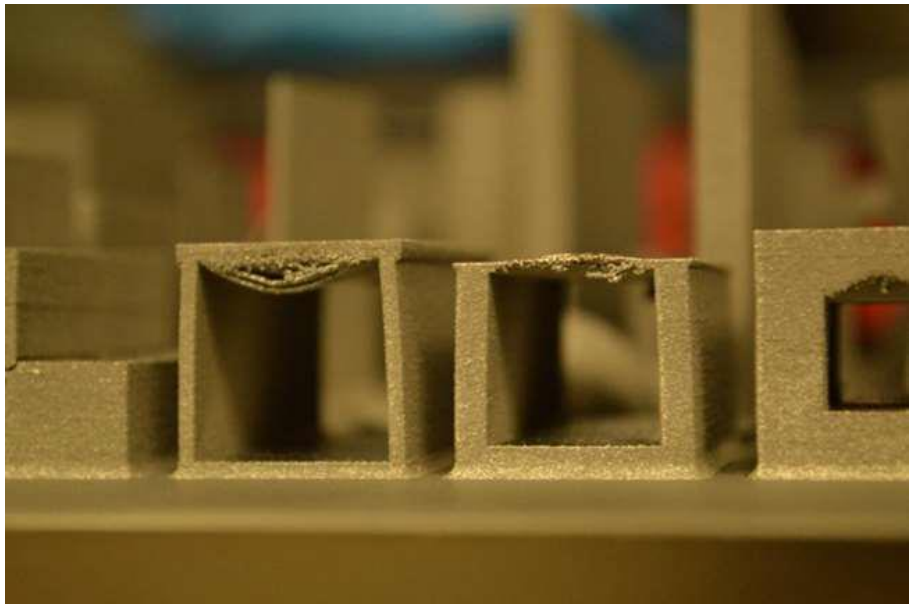
Build #1 (alt. view)



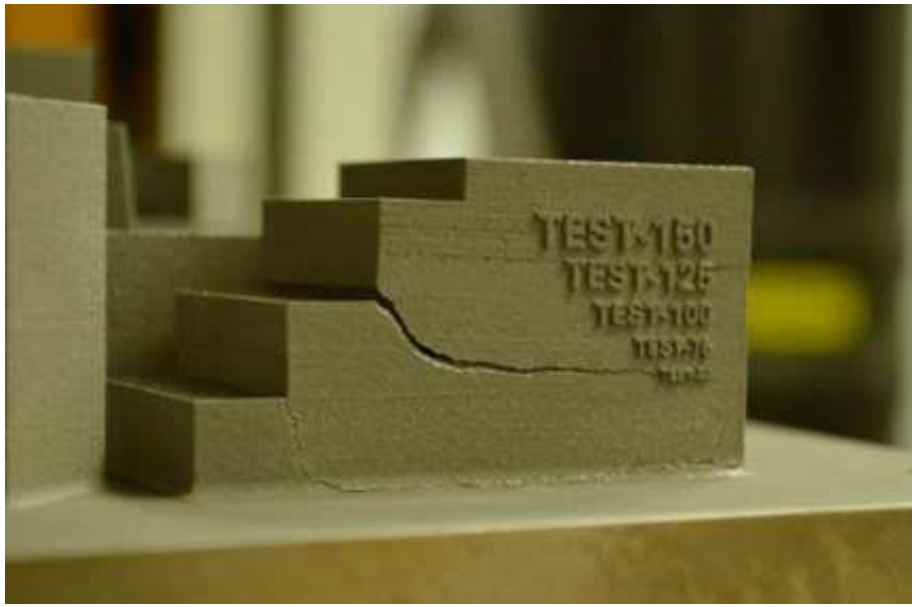
Build #1 horizontally oriented arch with witness lines

AM Solutions for the DoD and Industry

Build #1



Build #1 horizontally oriented tubes with flaws



Build #1 stair-step feature with cracks
at stress concentrations

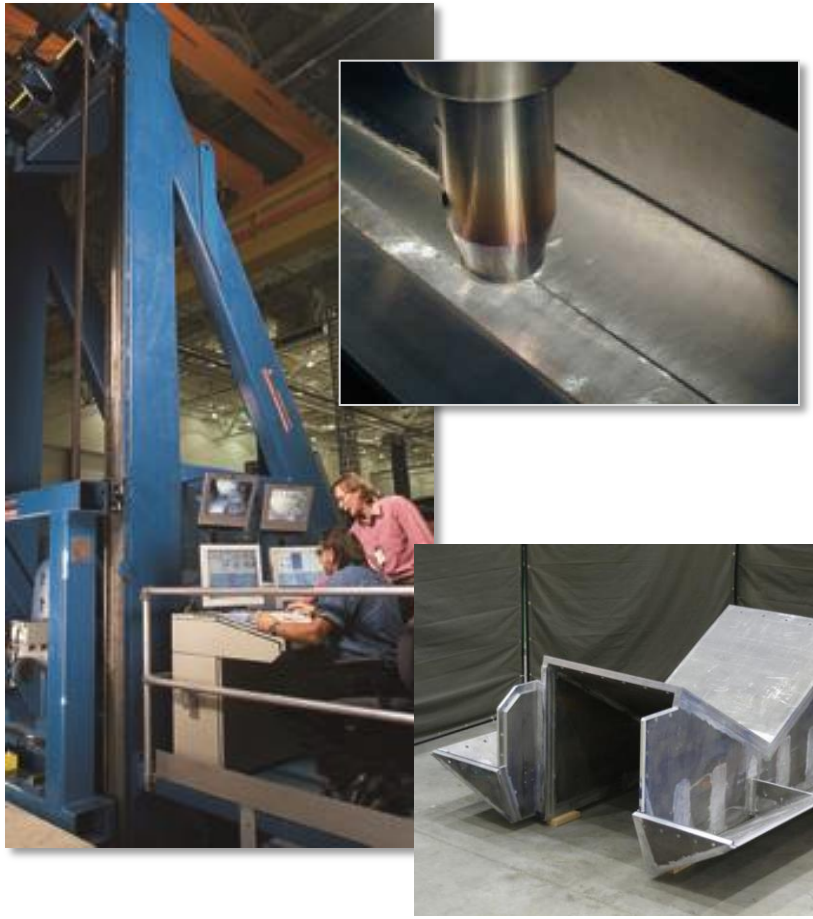
AM Solutions for the DoD and Industry

NIST – Measurement Science Innovation Program for AM (cont)

Technical Progress/Status – Build Plan Overview

Group	Included Builds	Build Purpose	Inspection Focus	Status
A	S1 through S5	Explore the realm of the possible wrt repeatable flaw seeding (type, location, size, orientation, etc.) in L-PBF builds	Preliminary assessment of NDE techniques; metallographic examination of selected areas to confirm flaw morphology	Builds complete*; NDE in progress
B	M6 through M10	Confirm and refine leading flaw seeding approaches from Group A; increase geometrical complexity; explore impact of heat treatment	Determine limits of each down-selected NDE method applied to moderately complex parts; metallographic examination of selected indications	Initiate shapes drafted; builds & NDE planned May 2015 – September 2015
C	C11 through C14	Apply best flaw seeding practices from Groups A & B to more complex ("real world") parts	Define limitations of leading NDE techniques applied to complex parts; metallographic examination of selected indications	Planned September 2015 – February 2016

Friction Stir Welding at CTC……



CTC's Friction Stir Welding system is designed to fabricate a full-size combat vehicles, and supports a full-scale systems approach compared with many R&D FSW machines.

Introduction: Consider Two Aluminum Alloys…

- Aluminum 6061-T6 alloy is:
  - Well-known for its good weldability characteristics,
  - Relatively high strength, and
  - High resistance to corrosion along with good machinability.
- Aluminum 7075-T7351 alloy is:
  - Well-known for its high stress structural strength,
  - Relatively good corrosion resistance
  - Good machinability in the annealed condition, yet
  - Poor fusion weldability and
  - Weld and HAZ regions prone to Stress Corrosion Cracking (SCC) during service.
- Assess potential for FSW processing of a combination of two alloys offers possibility to alleviate Al 7075 SCC problem.

HAZ – Heat Affected Zone

Objective:

- Evaluate metallurgical properties of Friction Stir Welded (FSW) component consisting of two different grades of wrought Aluminum 6061-T6 and 7075-T7351 Alloys,

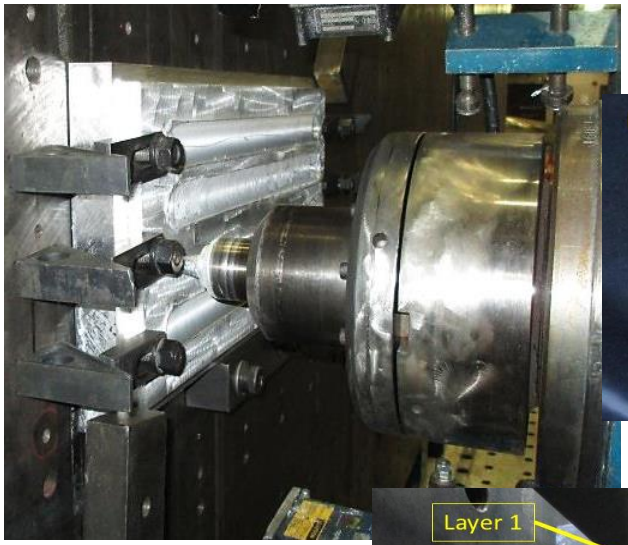
and,

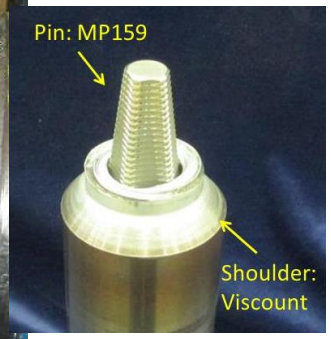
- Demonstrate potential to utilize individual favorable material property characteristics of Al 6061-T6 and Al 7075-T7351 alloys to deliver blended materials that can be used to build ***additive manufactured layered structures*** for a diverse array of applications (armor, structural components, etc.).

Technical Approach: FSW Process

Strip Geometry*:*

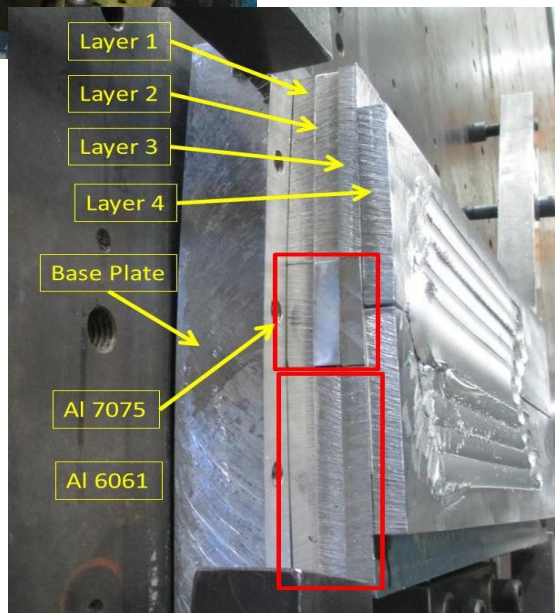
- 6061 strip dimensions: 4” wide x ½” thick x 20” long
- 7075 strip dimensions: 2”wide x ½” thick x 20” long
- Started with a base plate of 6061, 11” wide x 1-½” thick x 24” long





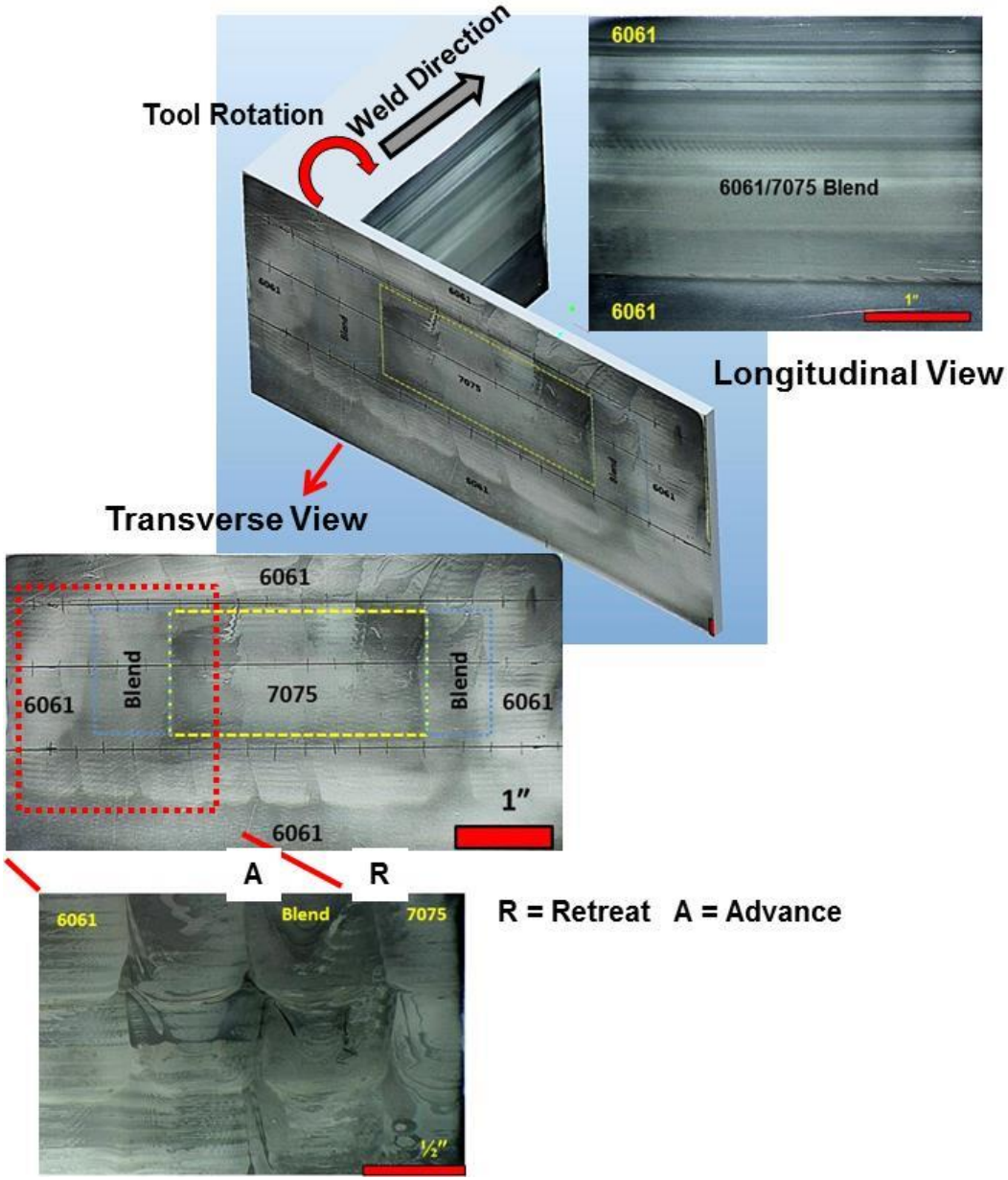
Weld Set-up and Technique:

- Standard toe clamps were used to secure base plate to anvil
- Toe clamp 6061 and 7075 strips to base plate
- Pin Length was set at 1.25” for the lap welds
- Perform FSW lap welds on 6061 strips
- Perform FSW seam and lap weld on either side of 7075 strip
- Perform FSW lap welds to overlap each other from the center out
- Machine surface for the addition of the next layer



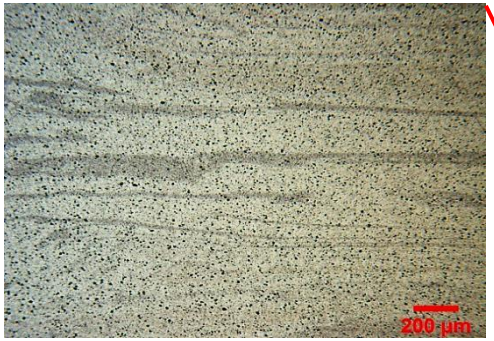
Macrostructure

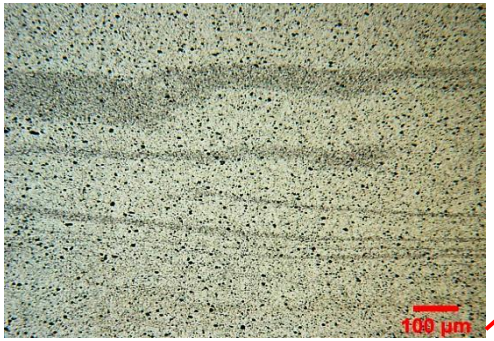
- Macrostructure of 6061/7075 FSW consisted of a well-defined array of weld nuggets. Good mixing by FSW of two alloys was observed
- FSW array was free of macro-porosity, cracks and other discontinuities (un-welded/un-mixed regions)

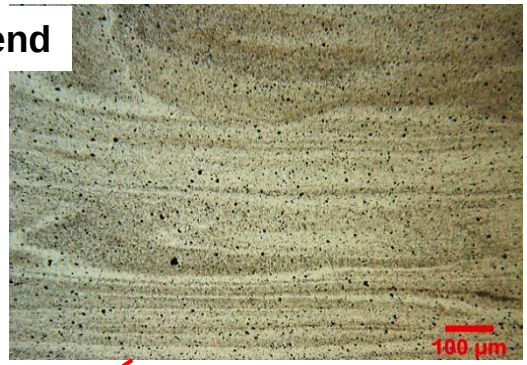


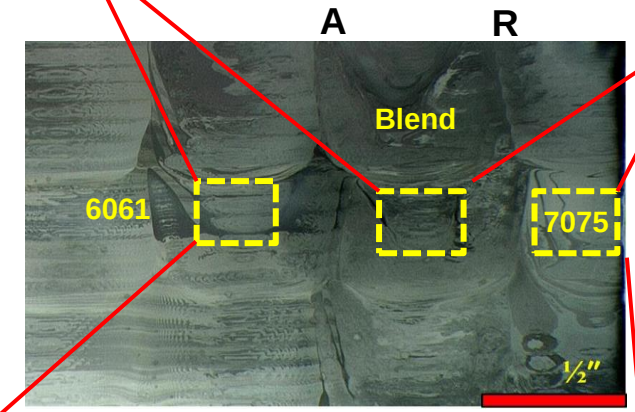
Microstructure: Transverse Direction

6061



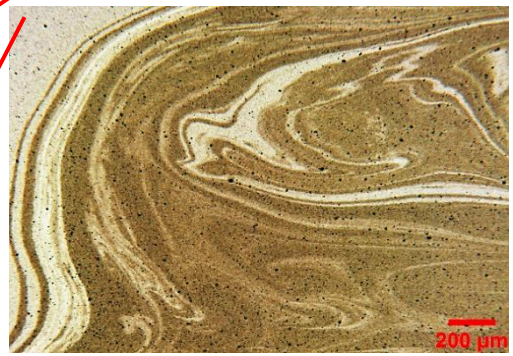


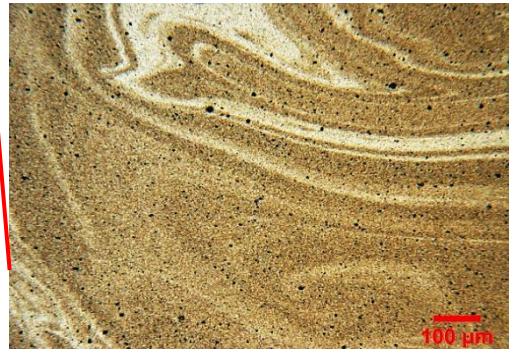




R = Retreat A = Advance

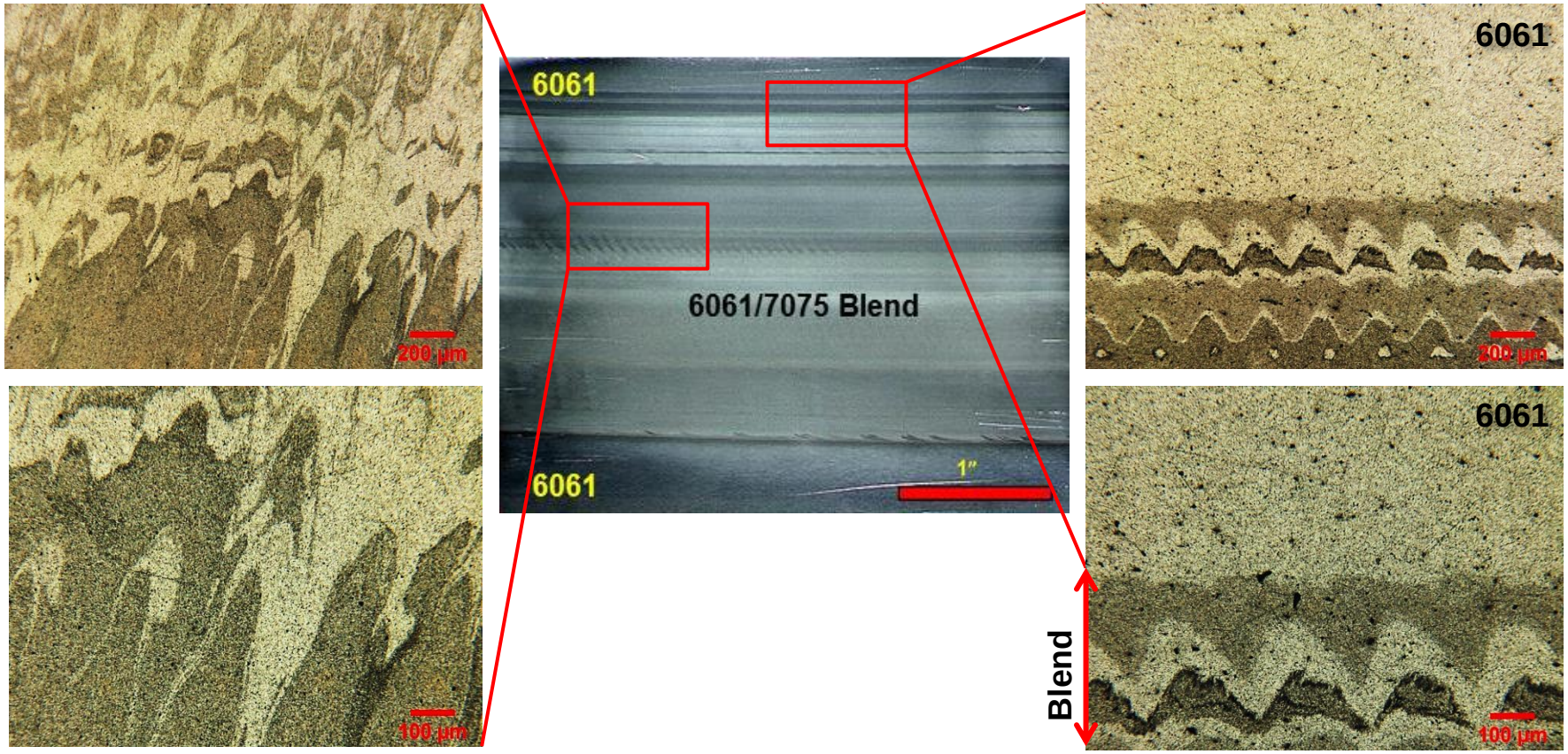
7075





- FSW 7075 shows pronounced flow lines produced by mechanical work of FSW
- Flow lines are not as pronounced in 6061 alloy as those in blend and 7075 materials
- Blend region shows well defined flow lines due to mechanical work

Microstructure: Longitudinal 6061/7075 Blend

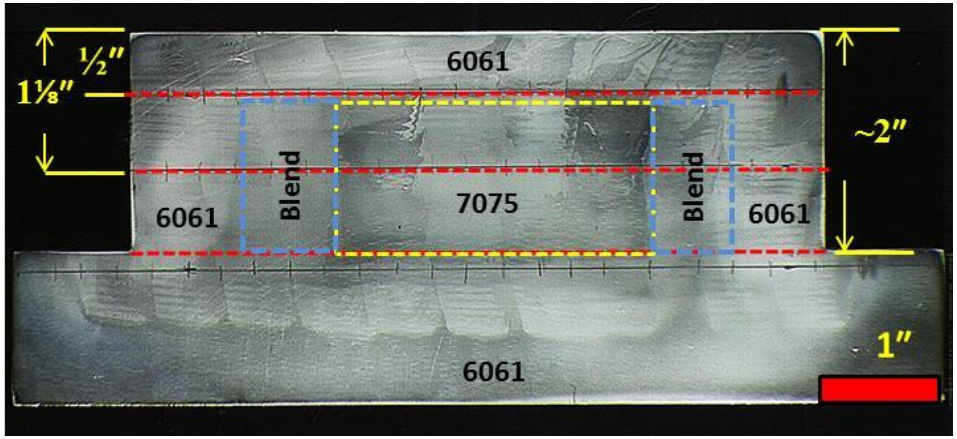


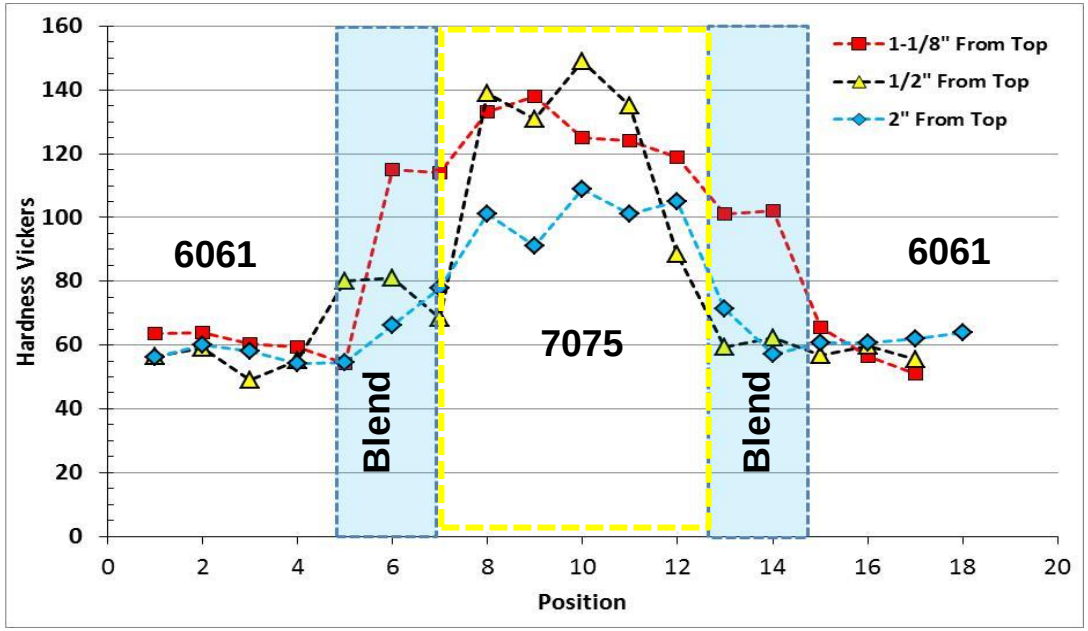
- 6061/7075 blend material shows ragged-like pronounced flow lines produced by mechanical work of FSW and tool geometry
- Darker and lighter phases are presumably heavily deformed Al 7075 and 6061 alloys; **mixed and bonded but not fully alloyed**
- Wave-like periodic pattern of two alloy phases that mimic travel of FSW tool is observed at blend-6061 interface

Microhardness Profile

- Hardness of FSW 7075 alloy varies from ~114 HV at blend interface to ~140 HV at middle of the (1⅛ ″ from top)
- Hardness of FSW 6061/7075 blended alloy varies from ~55 HV at blend interface to ~115 HV at middle of blend (1⅛ ″ from top)
- Hardness of FSW 6061 alloy varies from ~50 HV at blend interface to ~64 HV at middle of 6061 weld

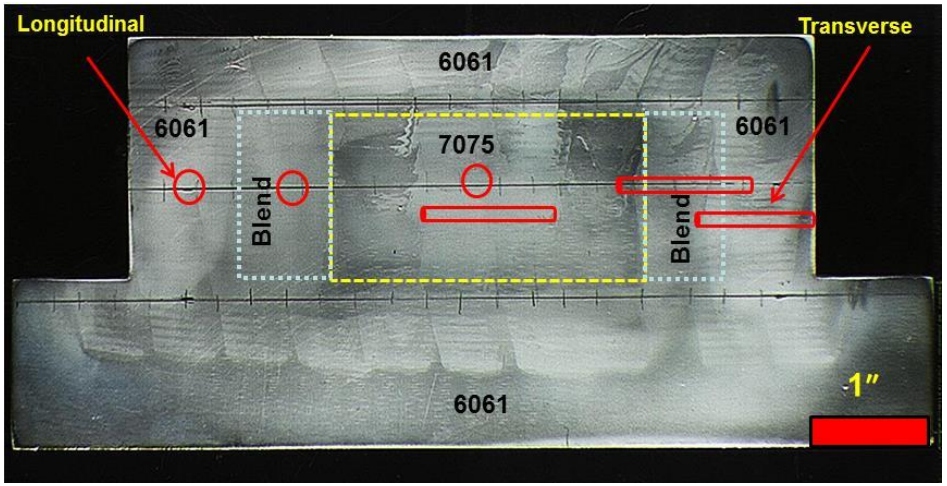
Variation in hardness for all regions of the welds is attributed to variation in <u>strain hardening in materials' flow lines</u> induced by mechanical work during FSW.





Tensile: Average Properties

- Variation in strength (UTS* and YS*) between longitudinal and transverse directions of monolithic FSW 6061 and 7075 is relatively small
- Strength in longitudinal direction of 6061/7075 blend FSW is larger than in transverse direction (likely caused by flow lines)
- Ductility in transverse direction of 6061/7075 blend FSW is larger than that in longitudinal direction



	UTS	YS	El%	RA%
Longitudinal to the FSW Direction				
Al 6061	25.5	15.9	31.5	71.6
Blend 6061/7075	51.1	32.7	15	19.5
Al 7075	53.9	34.8	19	29.1
Transverse to the FSW Direction				
Al 6061	24.3	17.4	27.3	64.1
Blend 6061/7075	25.5	17.4	24	57.4
Al 7075	49.8	35.4	13.3	14.5
Typical Wrought Products				
6061-T6	45.0	40	17	-
7075-T7351	69.0	57.0	6 - 7	-

**UTS: Ultimate Tensile Stress*
**YS: Yield Strength*
El%: Elongation Percent
RA%: Reduction in Area Percent

Strength of FSW material is lower than that of wrought material because FSW is no longer a tempered alloy

FSW AM Summary:

- FSW processing of two dissimilar alloy grades, Al 6061 and Al 7075, has been successfully conducted
- Macrostructure of 6061/7075 blended join was free of porosity, cracks and regions of un-bonded material
- Microstructure of 6061/7075 blended join shows mixed flow patterns of both 6061 and 7075 alloys. Flow patterns were well-defined in longitudinal direction of FSW
- Vickers hardness of 6061/7075 blended alloy vary from ~105 HV at blend interface to ~115 HV at middle of the blend, which is higher than the FSW 6061 hardness yet lower than the FSW 7075
- Strength in longitudinal direction of FSW 6061/7075 was ~2X that in transverse direction
- Loss of strength (UTS and YS) of FSW compared with wrought material is attributed to FSW process and that material is no longer in tempered condition

Summary

- Additive Manufacturing has great potential to impact the DoD across many platforms and applications
- DoD is working with academia, industry, and across government organizations to mature AM
  - Material performance
  - Machine performance
  - Digital Product Data
- AM has applications for DoD to:
  - Reduce lead time and increase availability for small production runs
  - Mass customization and enabling geometric complexity
  - Weight reduction via part consolidation/material substitution
- Need to intelligently accelerate AM design loop & thoroughly understand process to build confidence in AM & increase quality. This enables wider use of AM for DoD applications