Additive Manufacturing
for
DoD Applications

Ship Design & Materials Technologies Panel Meeting

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Background

• 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 to become a fully independent, nonprofit, applied R&D organization
Overview

Concurrent Technologies Corporation (CTC) is an independent, nonprofit, applied scientific research and development professional services organization. Together with our affiliates, we leverage research, development, test and evaluation work to provide transformative, full lifecycle solutions. To best serve our clients' needs, we offer the complete ability to fully design, develop, test, prototype, and build. We support our clients' core mission objectives with customized solutions and strive to exceed expectations.

Affiliates

Enterprise Ventures Corporation (EVC) is CTC’s technology commercialization arm and is organized as a wholly owned for-profit affiliate of CTC. EVC transfers advanced technologies designed and created by CTC and others to the industrial base. Together, CTC and EVC provide full lifecycle support services to clients, from innovative concepts through production and deployment.

CTC Foundation is a conduit for giving. Donations go to educational institutions, the arts, and charitable and community-service groups throughout the United States.
Our AM Areas of Expertise

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

- Reverse Engineering, Manufacturing, and 3D Data
- Education & Training
- Equipment and Post Processing Selection
- Design and Production
- Information Technology Solutions
- Cyber Security
- NDE
- Repair

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

• An ONR ManTech Center of Excellence since 1988

• Supports the Navy’s mission to reduce total ownership cost by developing and optimizing metalworking and manufacturing processes

• Primary Focus: Implementation of technology in the U.S. industrial base

• Extensively uses Integrated Project Teams, comprised of government and industry entities
Naval Problem

*PMs are facing:* **total ownership costs and** **platform availability due to a 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.

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

Morphology
size, shape, chemistry, recyclability, consistency, distribution, etc.

Parameters
power, speed, environment, consistency, calibration, setup, etc.

Secondary
surface finish, heat treat, hot isostatic pressing, machining, clean-up, etc.

Performance
strength, fatigue, wear, safety, certification, qualification, application, etc.

Part Type
optimization, part reduction, repair, novel design/features, free complexity, etc.

AM Technology
electron beam powder/wire, laser net shape, laser powder bed, ultrasonic, cold spray, binder jetting, +

Tertiary
repair, join, additional process etc.

DESIGN  MATERIAL  AM PROC.  POST PROC.  JOIN/REP.  TRANSITION
CTC’s Role in AM

• Our People ~ 25 years of designing, developing, evaluating, qualifying, and transitioning manufacturing solutions
• Testing and Analysis Infrastructure
• Equipment (SLM and FDM in house)
• Targeted and Ongoing Internal and External Efforts
  – Part Identification
  – Reverse Engineering/Solid Modeling
  – Part Manufacturing
  – Performance/Mechanical Testing and Qualification
  – Part Authentication/Cyber Security
  – Equipment Selection and Transition
  – Non Destruction Inspection Techniques for AM
  – Secondary Process of AM Components
  – IRAD’s and other activities in progress
• America Makes - National Additive Manufacturing Innovation Institute (formerly known as NAMII) Governing Board member
Additive Manufacturing Equipment

**SLM 280**
- 280 x 280 x 350 mm (11” x 11” x 14”
- 400W IR Fiber Laser
- Automated layer control system
- Real-time laser power display & monitoring
- 500 C Heated Build Plate
- Versatile, upgradable
- Materials:
  - Stainless Steel
  - Tool Steel
  - Cobalt-Chromium
  - Aluminum
  - Titanium
  - Inconel

**Stratasys Fused Deposition Modeling (FDM) Vantage SE**
- Envelope size: 16”W x 14”D x 16”H
- Materials: PC, PC/ABS, ABS, and ABSi
- Three tip sizes (.005”, .007”, and .010”) range of detail or run time
AM Solutions for the Navy
NMC
Additive Manufacturing for Shipbuilding Applications

- Team: CTC; PMS 400D; PMS 377; PMS 450; PMS 397; Ingalls; Electric Boat (EB)
- Objectives:
  - Assess and demonstrate the use of AM technology during ship construction activities and provide a recommended path toward implementation (Ingalls).
  - Develop and demonstrate a process map for the rapid production of tools and fixtures using AM technology (EB).
- NMC (CTC) Efforts:
  - Assess, identify potential applications, and fabricate demonstration articles for on-site testing to quantify cost savings at Ingalls
    - manufacturing aids
    - planning and staging aids
    - templates
    - temporary construction aids.
  - Work with EB to demonstrate new tool / fixturing opportunities using AM technology; several target applications will be selected for demonstration.

The use of additive manufacturing in ship construction will save acquisition costs on several ship classes.
Printed Sand Casting Molds and Cores for HY Steels

Team: OR and VCS Program Offices, Naval Surface Warfare Center, Carderock Division; General Dynamics Electric Boat; ExOne; Naval Undersea Warfare Center Division, Keyport; Bradken; and NMC.

- **Objectives:**
  - Investigate the use of printed sand mold technology to produce complex high yield (HY) steel castings for the Ohio Replacement (OR) and Virginia class submarine (VCS) programs.

- **NMC (CTC) Efforts:**
  - Integrated Project Team (IPT) will select a representative component to evaluate and validate the use of printed sand molds and cores for OR and VCS applications.
  - The project team will design and produce printed sand molds and conduct casting trials to demonstrate and prove out the process.
  - Bradken Inc. is expected to use the developed procedure to fabricate HY steel castings from printed sand molds and cores, with implementation planned for the first OR hull and the first Virginia Payload Module at Electric Boat in January 2019.
  - **POP:** July 2015 – Sept 2017

The use of additive manufacturing in ship construction will save acquisition costs on several ship classes.

Use of 3D printed sand molds to cast complex HY steel parts will provide producibility improvements for OR and VCS.
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
AM Solutions for the DoD and Industry

America Makes

• Electron Beam Melted (EBM) Ti-6Al-4V AM Demonstration and Allowables Development
• Northrop Grumman Prime
  – Team: CTC; CalRAM Inc.; Robert C. Byrd Institute
• Objectives:
  – Build full-scale, post-process surface finished demonstration parts
  – Develop set of B-Basis Design Allowables database at defined thicknesses and build parameters
  – Recommend and evaluate NDI methods for inspection of full-scale, post-process surface finished demonstration parts
• Material: Ti-6Al-4V
• CTC efforts:
  – Mechanical and environmental testing
  – Assess potential NDI methodologies for the inspection of EBM components (leverage NIST Program - Measurement Science Innovation Program for Additive Manufacturing)
• POP: October 2014 to March 2016
Non-Destructive Inspection (NDI) for Electron-Beam Additive Manufacturing (EBAM) of Titanium

NMC

• Team: NMC (CTC); AFRL; Lockheed Martin Aeronautics; Sciaky, Inc.
• Objectives:
  – Assess the capability of traditional and advanced NDI methods and processes to detect expected flaw types and sizes that are likely to be present in EBDM-fabricated titanium (Ti-6Al-4V) parts.
  – Quantify effects of surface finish and heat treatment on detection capability.
• Material: Ti-6Al-4V
• Inspection Methods Considered/Evaluated
  – Bulk: conventional ultrasonic inspection (UT); phased-array ultrasound (PAUT); film X-ray radiographic testing (RT); computed radiography (CR) X-ray computed tomography (CT)
  – Surface: fluorescent penetrant inspection (FPI)
• POP: September 2012 – April 2015
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

Illustration courtesy of Sciaky

Photo 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
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

Test Coupon C: contaminants

Vacuum
Oil
Aluminum
Condensate Filings
Copper
Oxidized Surface

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
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
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’d.)

### Technical Progress/Status – Build Plan Overview

<table>
<thead>
<tr>
<th>Group</th>
<th>Included Builds</th>
<th>Build Purpose</th>
<th>Inspection Focus</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>S1 through S5</td>
<td>Explore the realm of the possible wrt repeatable flaw seeding (type, location, size, orientation, etc.) in L-PBF builds</td>
<td>Preliminary assessment of NDE techniques; metallographic examination of selected areas to confirm flaw morphology</td>
<td>Builds complete*; NDE in progress</td>
</tr>
<tr>
<td>B</td>
<td>M6 through M10</td>
<td>Confirm and refine leading flaw seeding approaches from Group A; increase geometrical complexity; explore impact of heat treatment</td>
<td>Determine limits of each down-selected NDE method applied to moderately complex parts; metallographic examination of selected indications</td>
<td>Initial shapes drafted; builds &amp; NDE planned May 2015 – September 2015</td>
</tr>
<tr>
<td>C</td>
<td>C11 through C14</td>
<td>Apply best flaw seeding practices from Groups A &amp; B to more complex (“real world”) parts</td>
<td>Define limitations of leading NDE techniques applied to complex parts; metallographic examination of selected indications</td>
<td>Planned September 2015 – February 2016</td>
</tr>
</tbody>
</table>
The main objective of this work is to evaluate the effects of gas tungsten arc welding (GTAW) on the metallurgical integrity of AM Ti-6Al-4V, Inconel 625 and 17-4 PH stainless steel alloys when welded to their wrought alloys counterparts.

- **Ti-6Al-4V**
  - Powder Bed - Laser Melting
  - Powder Bed – EB Melting
  - Wire Fed – EBM Melting

- **Inconel 625**
  - Powder Bed - Laser Melting
  - Powder Bed – EB Melting

- **17-4 PH Stainless Steel**
  - Powder Bed - Laser Melting
  
* A M Only not HIP’ed
# Welding Couples and Manual GTAW Parameters

<table>
<thead>
<tr>
<th>Weld Couple</th>
<th>Alloy Couple Condition</th>
<th>Welding Wire/Process</th>
<th>Approx. Heat Input kJ/in/Pass</th>
<th>Max. Interpass Temperature °F</th>
<th>Other welding Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>PB-EBM Ti-6Al-4V to Rolled</td>
<td>AM to Wrought AM HIP’ed to Wrought</td>
<td>ERTi-5</td>
<td>72</td>
<td>258</td>
<td>• Weld Wire: 0.0625'' • No Passes: 12 • Groove: Single V 60° • Root Opening: 0.1865'' • Shielding Gas: High Purity Ar • Gas Flow: 15 ft³/h • Welding in Glove Box</td>
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<tr>
<td>Plate</td>
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<tr>
<td>WF-EBM Ti-6Al-4V to Rolled</td>
<td>AM to Wrought AM HIP’ed to Wrought</td>
<td>ERTi-5</td>
<td>72</td>
<td>248</td>
<td></td>
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<tr>
<td>Plate</td>
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<tr>
<td>PB-LM Ti-6Al-4V to Rolled</td>
<td>AM to Wrought AM HIP’ed to Wrought</td>
<td>ERTi-5</td>
<td>72</td>
<td>250</td>
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<tr>
<td>Plate</td>
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<tr>
<td>PB-EBM Inconel 625 to Rolled</td>
<td>AM to Wrought AM HIP’ed to Wrought</td>
<td>ERNiCrMo-3 Manual GTAW</td>
<td>21.0</td>
<td>350</td>
<td>• Weld Wire: 0.0625'' • No Passes: 13 • Groove: Single V 60° • Root Opening: 0.1865'' • Shielding Gas: Ultra Pure Ar • Gas Flow: 25 ft³/h</td>
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<tr>
<td>Plate</td>
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<tr>
<td>PB-LM Inconel 625 to Rolled</td>
<td>AM to Wrought AM HIP’ed to Wrought</td>
<td>ERNiCrMo-3</td>
<td>26.5</td>
<td>270</td>
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<tr>
<td>Plate</td>
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</tr>
<tr>
<td>PB-LM 17-4 PH Stainless Steel to Rolled Plate</td>
<td>AM to Wrought</td>
<td>ER630 GTAW</td>
<td>21.4</td>
<td>140</td>
<td>• Weld Wire: 0.0625'' • No Passes: 5 • Groove: Single V 60° • Root Opening: 0.1865'' • Shielding Gas: Ultra-Pure Ar • Gas Flow: 25 ft³/h</td>
</tr>
</tbody>
</table>
Ti-6Al-4V As-Additively Manufactured — Weldments Macro & Microstructure

- All three as-AM Ti-6Al-4V alloys exhibited very good weldability
- No cracks were observed at the HAZ or weld regions
- Scattered microporosity was observed in all AM alloys
- The three AM alloys have different micro and macrostructural appearance due to AM process utilized
- All AM alloys have a typical weave-like microstructure consisting of $\alpha+\beta$ lamellae
- The AM side of the weld had a thinner HAZ than that of the wrought alloy
- The WF-EBM HAZ had the coarser and more elongated grains
All three HIP’ed AM Ti-6Al-4V alloys exhibited very good weldability.

No cracks were observed at the HAZ or weld regions.

The three AM alloys have different micro and macrostructural appearance due to the AM process used to manufacture.

All AM alloys have a typical weave-like microstructure consisting of $\alpha$+$\beta$ lamellae.

The columnar grain growth of the HIP’ed WF-EBM persisted in the weld HAZ.

The HAZ of the PB-LM alloy had the finer equiaxed microstructure of all AM alloys evaluated.
Ti-6Al-4V Weldments Tensile Properties

• The three alloy weldments in both as-AM and HIP’ed had a YS within the range of the wrought alloy weldment

• HIP’ing and stress relief slightly reduced the UTS and YS of all three alloy weldments

• The relatively higher strength of the weldments made from PB-EBM and PB-LM is attributed to their finer grain size and crystallographic texture
Conclusions - Ti-6Al-4V

- All alloys in the as-AM and as HIP’ed conditions exhibited a very good weldability and had a HAZ thinner than that of the wrought alloys
- All alloys have different macrostructural appearance due to AM process but all show similar weldability
- All AM HIP’ed and un-HIP’ed alloys have the typical weave-like microstructure consisting of $\alpha+\beta$ lamellae. The WF-EBM HAZ had the coarser and more elongated grains and the AM-LM alloy had the finer and more equiaxed grain structure at the HAZ
- HIP’ing of all AM alloys slightly reduced the UTS and YS but all alloy weldments in both as-AM and HIP’ed had a YS within the range of the wrought alloy
- Crystallographic texture of the various AM alloys is responsible of their tensile ductility
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