# Robotic Arc Directed Energy Deposition of Additive Manufacturing

NSRP Project Manager: Nick Laney (ATI)
NSRP Program Technical Representative: Mark Poitras (Bath)
Principal Investigator: Dennis Harwig (EWI)


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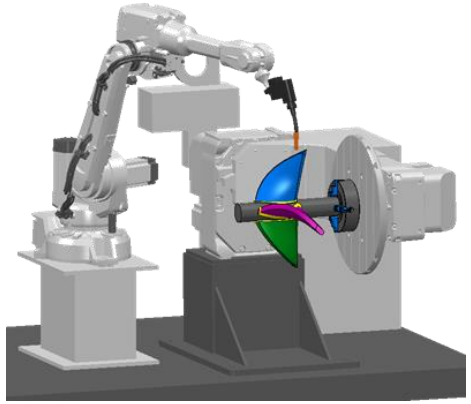
Ship Design & Materials Panel

# NSRP Robotic Arc Directed Energy Deposition Additive Manufacturing for Shipbuilding



**Project Budget: $2.84M**
**NSWCCD: $49K**

**Cost Reduction: $5.44M**

**Period: 2 years**

## Project Team

**EWI – Project PI**
**Navus Automation**
**Newport News Shipbuilding**
**Austal USA**
**NSWCCD**
**ABS**


**Arc DED AM Propeller built with Powermill at RAMLAB**

# NSRP Project Overview

## Purpose

- Develop agile automation and robotic arc DED Additive Mfg. technology for shipbuilding
- Create capability to build AM large structures and/or add features to structures fabricated from plate, pipe, castings and/or forgings.

## Goals

- Reduce barriers to implement AM
- Develop the digital data workflow processes
- Develop advanced training materials - workforce competencies
- Demonstrate representative qualifications
- Provide standardized equipment & services for arc DED AM implementation
- Build prototypes of increasing complexity
- Identify shipyard implementation opportunities

## Benefits

- Additive manufacturing provides:
  - Design topology optimization,
  - shorter schedules/lead times,
  - small batch manufacturing,
  - less material usage,
  - less total energy,
  - smaller factory footprints,
  - Potential for better properties than castings, and
  - Unique supply chain opportunities for sustainment.

## Business Case Impact

- Provide essential capabilities to shipyards,
- Minimize redundant development and learning curve costs, and
- Reduce risks and uncertainty to implement a new technology.

# NSRP Project Benefits

- Standardized ‘big-area’ gantry
  - Maximize flexibility / lower system costs
  - Access to test-bed control platform
- Accelerate Transition
  - Powermill digital data workflow competencies & training
  - DED AM process qualification scheme
  - Additive Mfg. Procedures Specs (AMPS)
  - Develop technology for:
    - High quality DED AM builds & properties
    - Alternate DED processes
    - Prototypes, benchmarking & design data
- Accelerate innovation
  - Advanced process development
  - Multi-process
    - Cleaning, Grinding, NDE
  - Thermal control schemes
  - Dimensional control schemes
  - Property control & optimization
  - Quality monitoring & control
- Workforce & Training
  - Beta test site for Basic and Advanced Powermill DED AM

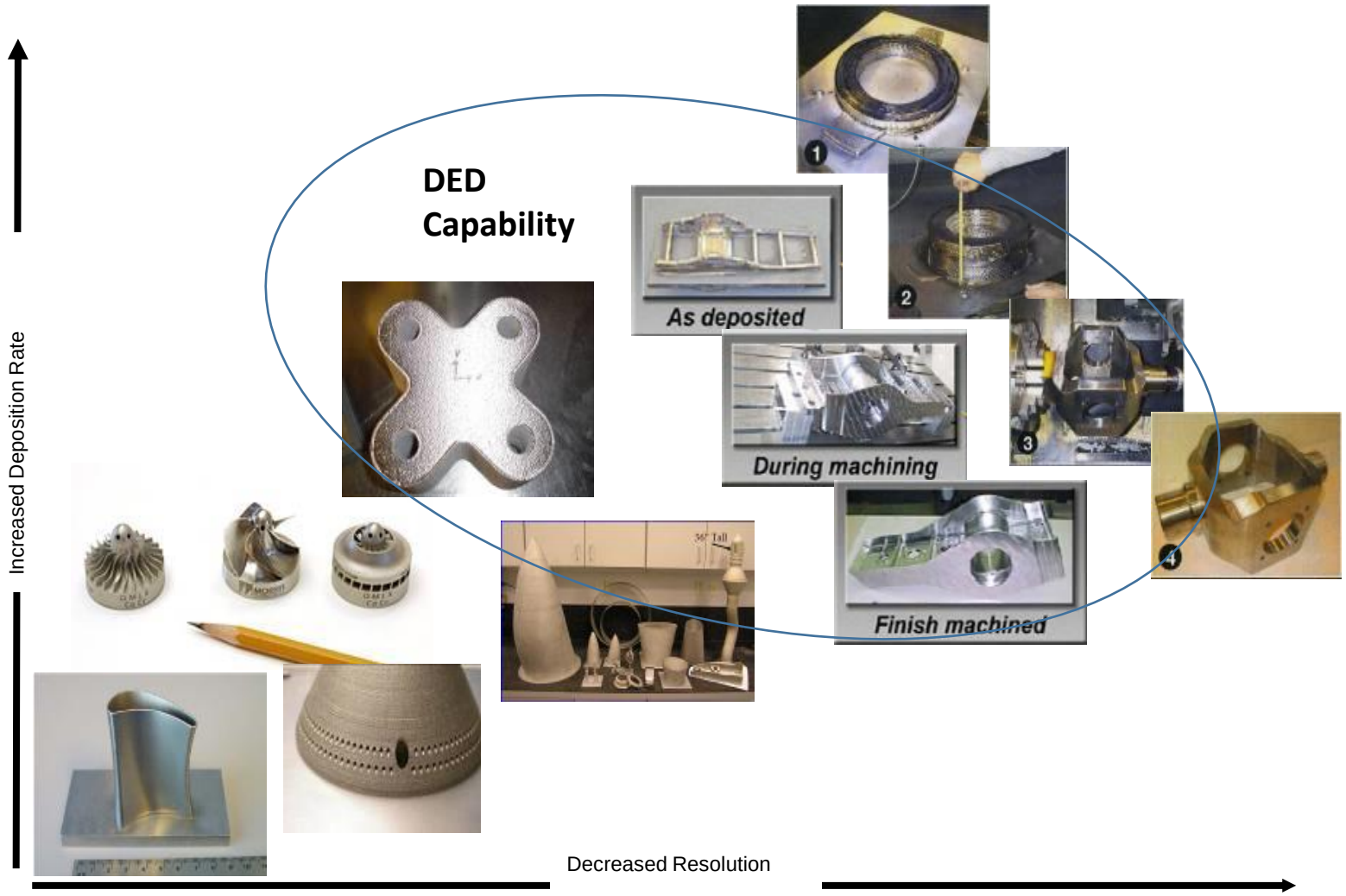
# DED Metal AM Characteristics

- Two main types of metal AM:
  - Powder-bed
    - melting, sintering, binder-jet variants
  - Directed Energy Deposition (DED)
    - arc, laser, or electron beam with wire or blown powder feedstock

- DED Characteristics
  - CAD to Path Digital Manufacturing
    - Main difference versus shape welding and structural buttering
  - Leverage welding process equipment
  - Leverage welding engineering technology
  - Leverage welding standards

# DED Deposition Rate vs Resolution

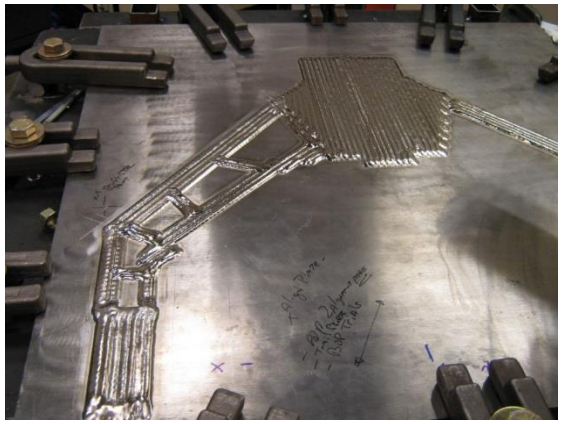
Courtesy Boeing
for EWI Use

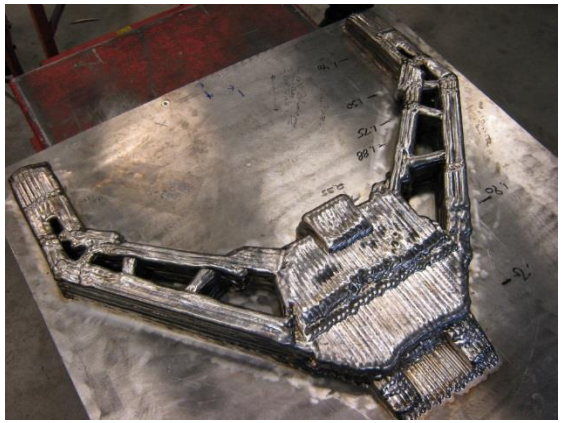


# Arc DED - Numerous combinations of processes & consumables

- GMA - Gas Metal Arc
- GMA - Pulse (GMA-P)
- GMA - Pulse Short Circuit (GMA-PSC)
- GMA - Reciprocating Wire Feed (GMA-RWF)
- GMA - Multi-mode (GMA-P / GMA-RWF)
- Tandem GMA (multiple mode & waveforms)
- GTA - Gas Tungsten Arc
- GTA - GTA-RWF
- PA - Plasma Arc
- Hot / cold wire feed additions to any process
- Etc…….

**+ Numerous Laser & EB DED process combinations (powder, cold / hot wire)**





**Double-sided DED of structures – control distortion with integrated build plate (Courtesy EWI)**

# Robotic DED AM Systems

**New Navus DED Gantry / 2020**

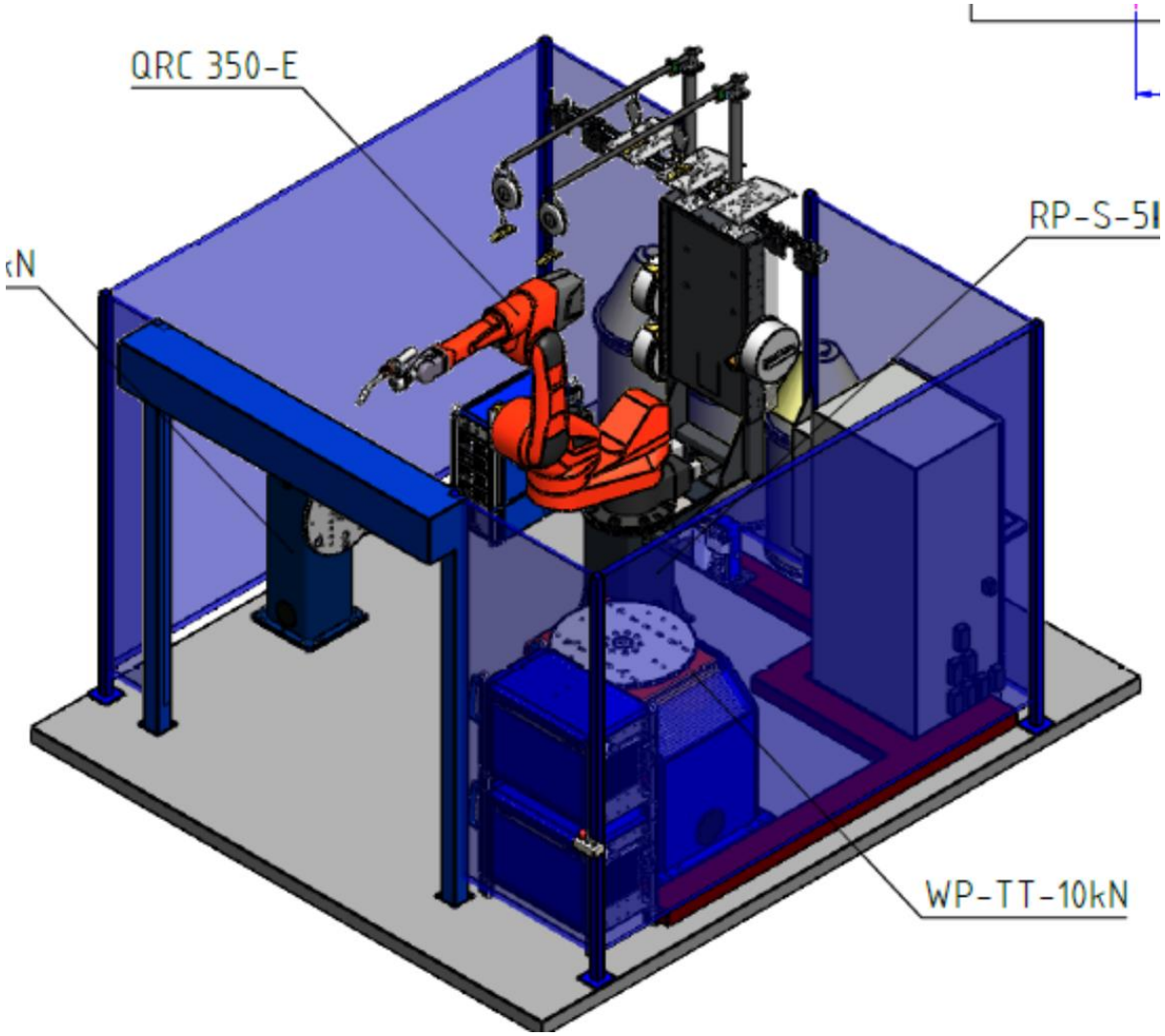
**Motoman 7-axis DED System**

- ABB*
- Cloos*
- FANUC
- Kuka
- Motoman*
- OTC*
- Panasonic
- Sciaky

*** Powermill DED AM**

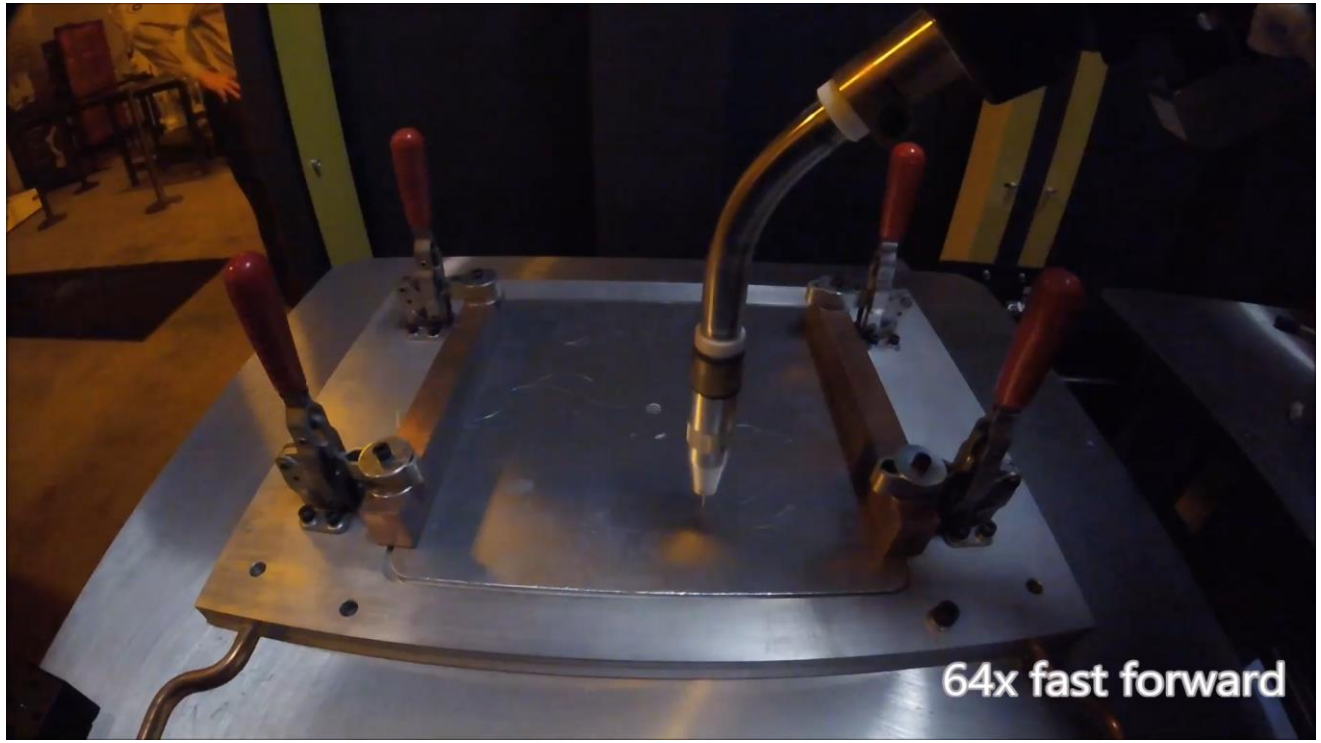
# Cloos Robotic Arc DED System

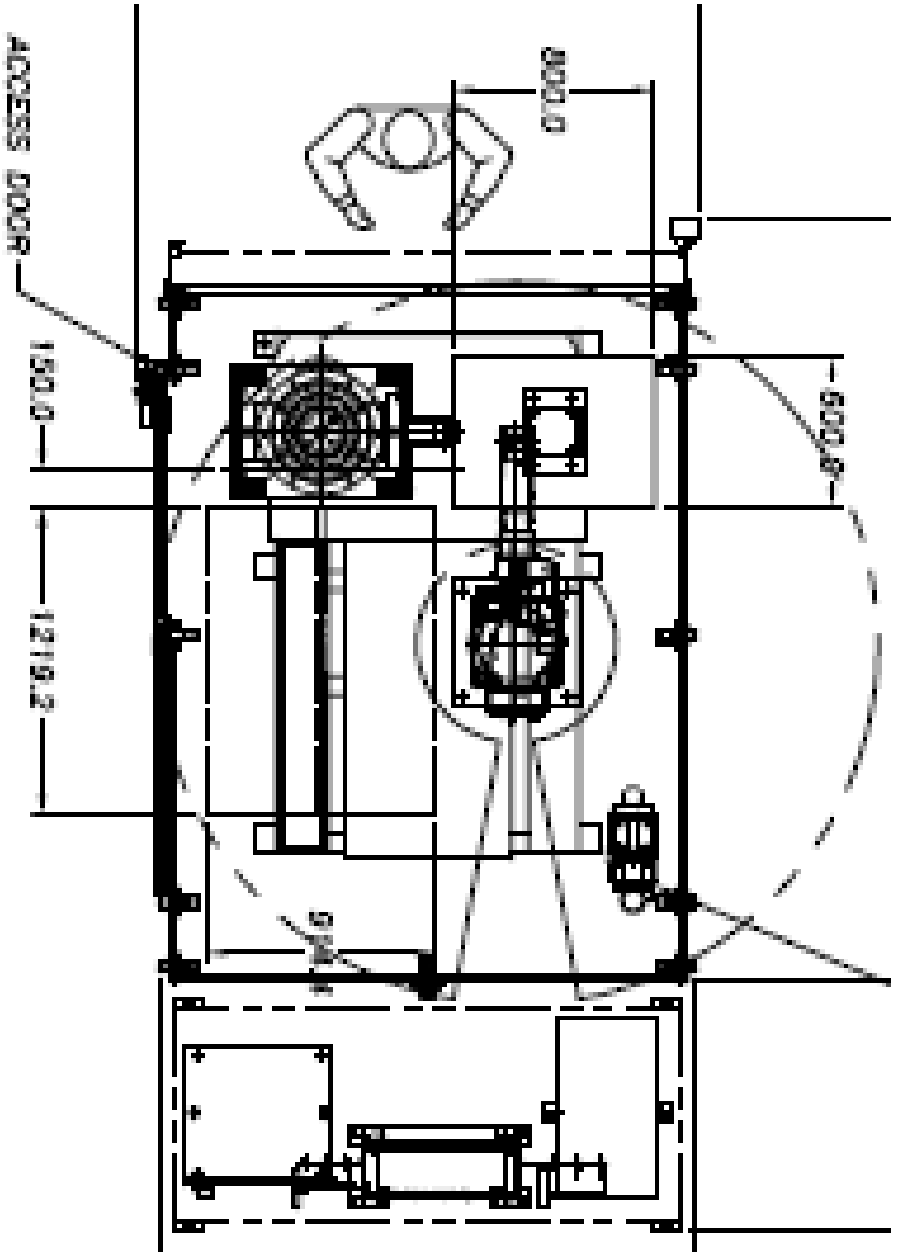
- Dual Process
  - Motion and Tandem GMAW
- High melting rate waveform TGMAW control technology / test bed
- Interpass temperature (cooling rate) control – feature - property relationships
- Change waveform conditions based on build feature to max productivity and control properties.
- 1-ton positioner capacity - large single- or double-sided integrated build platform structure(s)



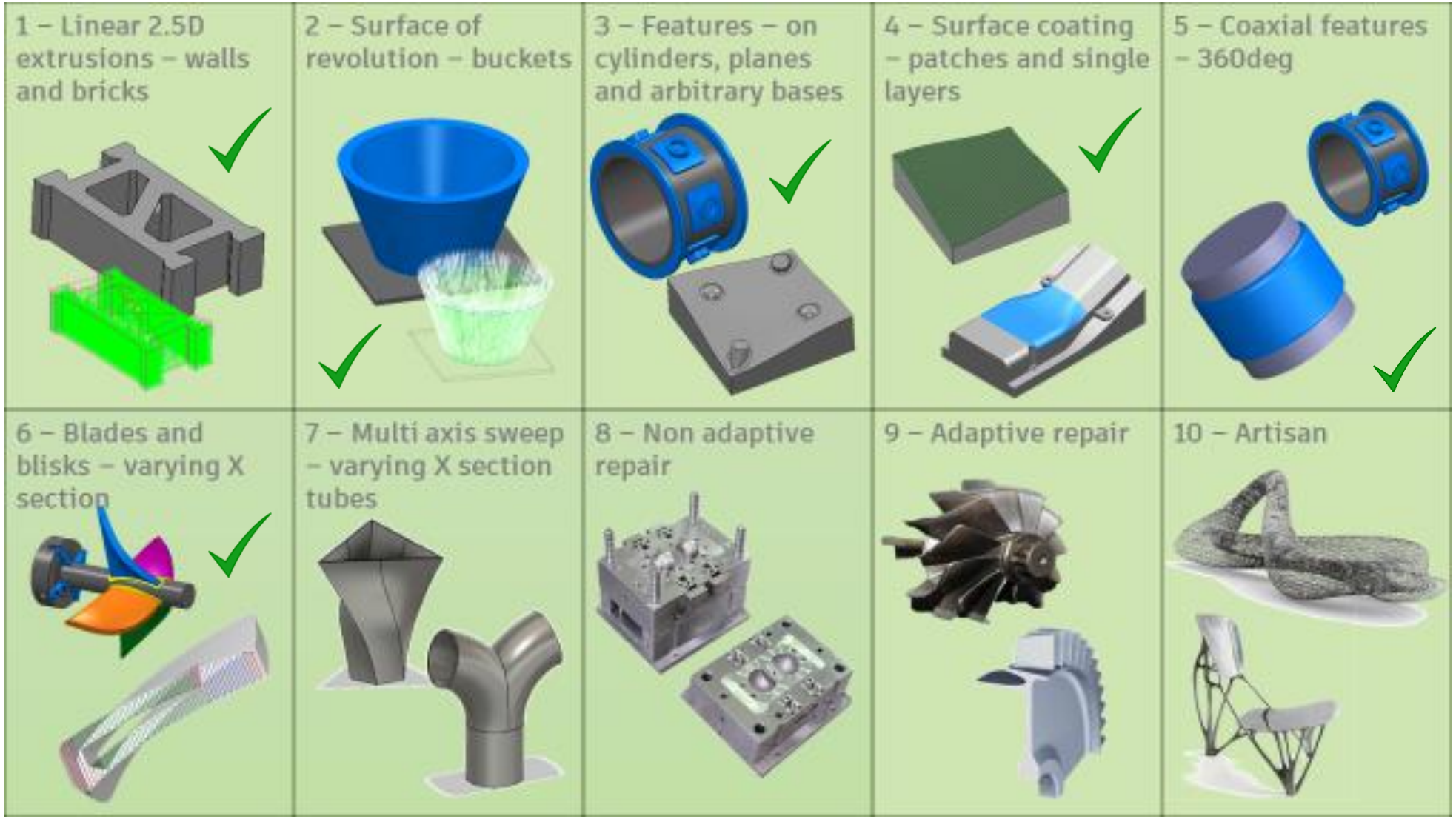
# OTC Robotic Arc DED AM System

- Multi-process power supply (GMAW-P, -Syncro-feed, etc)
- GMAW Synchro-Feed
  - Spatter-free low heat input



# Powermill™ Robotic AM –DED Build Categories



# Task 1: Project Kickoff Meeting and Programmatic Setup (all members)

- Project Kickoff Meeting, Program Management, and Reporting (all members)
  - Project Management Plan
  - Project kickoff meeting – complete 9/26/19.
  - Quarterly Reports
  - Status/Deliverable/Milestone Report
  - Final Technical

# Task 2 - Design Multi-process Gantry for Arc DED AM (Navus, EWI, HII-NNS)

- Navus - design robotic DED AM gantry/test bed for shipbuilding
  - Develop a detailed functional specification for team review and approval.
- The spec will describe system integration within EWI's flexible manufacturing cell and establish "test bed" for this project and ongoing services. The spec will provide details such as:
  - 3-axis gantry and 6-axis inverted robot integrated for 9-axes of coordinated motion.
  - Large build area, approximately 10-ft high × 15-ft wide × 20-ft long
  - 2-axis tilt/turn positioner that can be located at various locations within the cell.
    - 11 axes of coordinated motion to build complex shapes like impellers and pressure components.
  - Multi-process advanced gas metal arc (GMA) system
  - High frequency protected - gas tungsten arc or plasma arc DED AM capability
  - Laser DED AM capability
  - Weld vision system and infrared pyrometer for quality and feedback control - future efforts.
  - Other:
    - Capabilities will support training, development, prototyping, and future efforts that will explore adaptive arc DED AM control technologies.
    - Provides unique resource to shipyards for developing and prototyping metal AM structures and components.

# Task 3 - Robotic Arc DED AM – Digital Data Workflow Competencies (all members)

- Background:
  - AM enables designers the ability to build parts directly from CAD files.
    - CAD-to-path manufacturing build process.
    - CAM software to solve AM build plan, prepare machine build file, edit build file, and download machine build parameters and path plans.
  - Robotic DED AM processes are an emerging area for AM. Very few robot companies have mature DED AM CAM software capabilities
    - Range of existing robotic AM CAM software programs (i.e., Robotmaster, Octopuz, Autodesk Powermill, and Seimens NX, etc.)
    - Most AM CAM software are configured for 3- to 5-axis CNC machines
    - Most AM CAM software use G-code, which is standard language for “subtractive” machining industry
    - Robotic CAM, also known as Computer Aided Robotics (CAR) software
    - Robotic CAM is emerging area that provides path planning solvers that post-process 3- to 5-axis (G-code) build models into robot simulation environment, locate the workpiece to maximize build performance of the robot(s), and post-process robotic build trajectories (path plans) for 6- to 12-axis (or more) robotic systems.
    - Powermill was selected by EWI based on the widest user base, especially for machining and allied digital manufacturing processes, and robot-agnostic solvers compatible with most commercial robot systems.

# Task 3 - Robotic Arc DED AM – Digital Data Workflow (DDW) Competencies (all members)

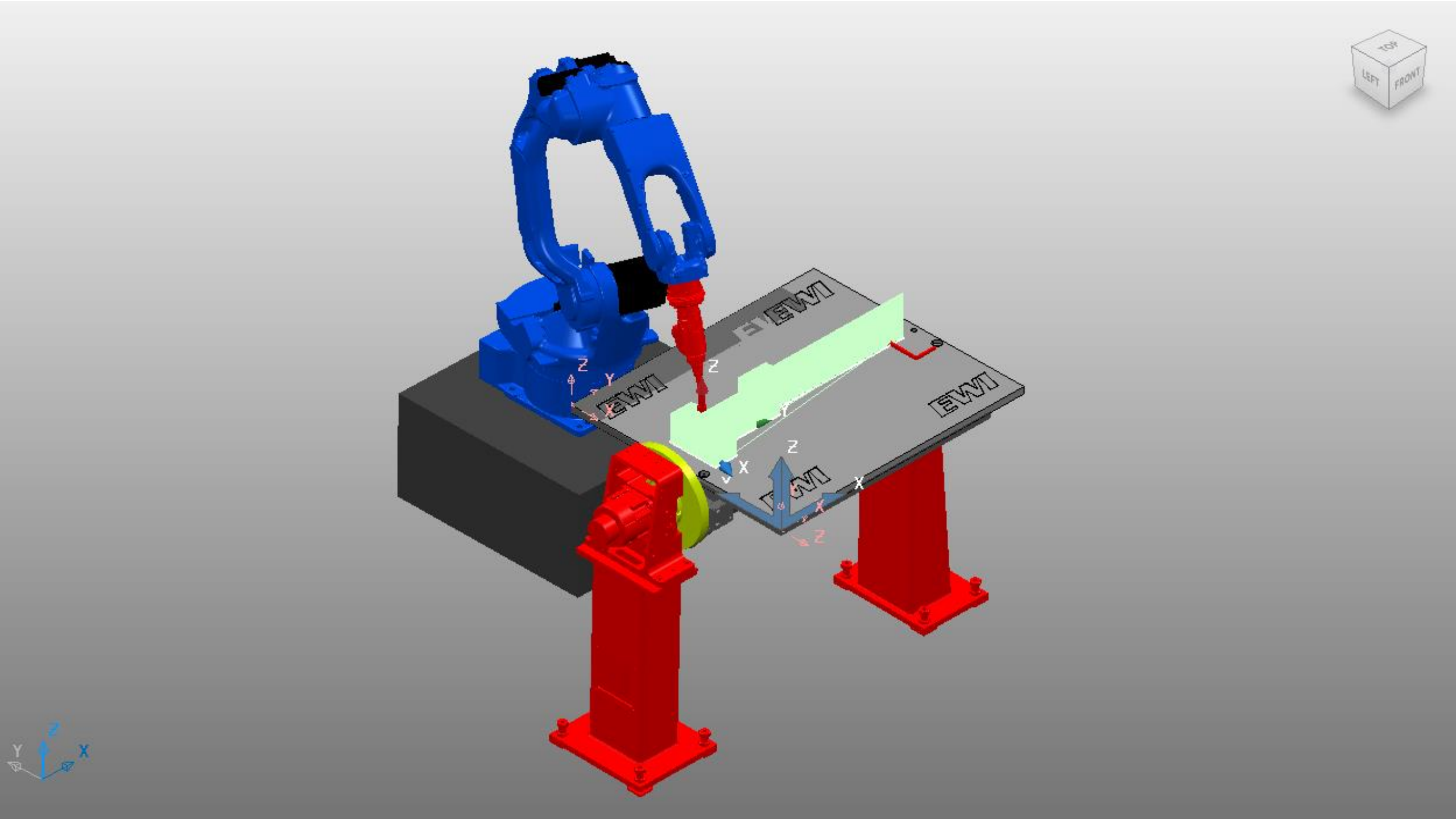
- Involves the following steps:
  - Review/assess CAD geometry (as-designed) for DED AM
  - Modify design for arc DED AM build (add stock, start / stop tabs, build supports to control distortion, etc.)
  - Simulate CNC CAM model of overall build strategy
  - Setup build, simulate robotic DED builds, and determine preferred workpiece position and plan based on simulation analysis
  - Post-process trajectories (multi-axis robot build-plan)
  - Edit trajectories (embed knowledge in robot build plan)
  - Add sequence data for allied processes (deposit, cool, inspect, grind, repeat, etc.)
  - Fabricate shapes using arc DED AM build plan

# Task 3 - Robotic Arc DED AM – DDW Robot Infrastructure for Training

- EWI - Setup Powermill Post-processors on 3 or more existing 6- and/or 8-axis robot cells to establish basic robotic arc DED AM capabilities.
- Multiple robotic DED AM systems are needed to develop technology and support training
  - Prefer small groups for robotic training so participants can gain experience
- EWI already invested and setup post-processors on two robots to build experience prior to project start
  - 7-axis Motoman Arc DED AM System
  - 8-axis Motoman Laser-Blown Powder DED AM System
- Two additional robots were setup for training - 10/7/19
  - 2 – 8-axis OTC Arc DED AM Systems
- Two additional post-processors are planned
  - 9-axis Cloos Arc DED AM System
  - 11-axis Navus ABB Arc DED Gantry System

**EWI invested in a Powermill basic training programs that consisted of two weeks**

- **One week learning machining functions**
- **One week at EWI learning Powermill robotic & AM;**
- **This approach is being combined into one week for robotic arc DED AM**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# Task 3 - Basic Powermill Robotic Arc DED AM Training Program Development

- Powermill Robotic Arc DED AM training for metal manufacturers / shipbuilding
  - Every installation has been a custom combination of training content and approaches
- Develop Basic Powermill Training program for robotic arc DED AM
  - Learn wide range of functions for machining, robotics, and additive
  - Real applications used and simulations can be “posted” for builds in future
  - Pre-planned build demos using post-processor are planned for basic shapes;
- Training led by Autodesk Strategic Partner, DSI who has decades of experience with Powermill
  - Shipyard partners can use software within their facilities and start to build DDW competencies
  - EWI and HI-NNS will use this training to support Tasks 4 and 5
- Training lessons learned incorporated into Basic Robotic Arc DED AM training seminar in Task 7

# Task 3 - Advanced Powermill Robotic Arc DED AM Training Program Development

- EWI will host an Advanced Powermill Training program in Year 2.
  - Training will be scheduled once the gantry is installed per Task 6, gantry robotic arc DED AM capabilities established, and advanced feature build capabilities established;
  - Design, model, simulate, and build advanced shapes using up to 11-axes of coordinated motion.
- EWI with project partners' guidance will develop advanced training program / workshop
  - Leverage training above and lessons learned,
  - Develop workshop exercises
  - Host an "alpha" workshop to evaluate and refine training materials
  - Incorporate into Advanced Powermil Robotic Arc DED AM Training Workshop per Task 7

# Task 4 - Arc DED AM Process Models for Shipyard Applications (EWI, HII-NNS)

- This Task will select two advanced GMA process & consumable applications
  - Stainless steel, high strength steel, nickel-aluminum bronze, and/or aluminum, based on consensus from the shipyard partners for parametric process modeling.
  - Develop Additive Manufacturing Procedure Specifications (AMPS) for two materials
- EWI will use AMPS to build a range of features using Powermill tools.
- Robotic arc DED AM cells at EWI and HII-NNS will be used to test the models, evaluate a range of basic shapes, and build digital and hands-on competencies.
  - Robotic dry-run simulations will be used to validate machine calibration, build plan performance, and readiness for builds.
  - Basic shapes will be limited to 10- to 20-lb builds and demonstrate a range of shipbuilding structural features using the different DED AM consumables
  - The builds will be visually examined for soundness and sectioned as needed to examine metallographic structure and soundness. Several tensile specimens will be removed from test builds for each material to examine properties.

# Task 5 - Feature-Process-Property Data (Representative Qualifications) (EWI, NSWCCD, HII-NNS, ABS Technology)

- Background:
  - Both EWI and NSWCCD are active in American AM standards.
  - EWI is leading two consortia:
    - The EWI Additive Manufacturing Consortium
    - ASTM International Center of Excellence
  - NSWCCD (with support from EWI) is leading a separate initiative to develop an arc DED metal AM standard (Technical Publication) for U.S. Navy.
  - In addition, HII-NNS completed a significant panel project, "Development of a Requirements Framework for the Fabrication and Inspection of Naval Parts using Additive Manufacturing (2005-341A-050)", and proposed a qualification and inspection framework for shipbuilding AM.
  - Leverage NSRP panel project recommendations and concurrent initiative at NSWCCD.

# Task 5 - Feature-Process-Property Data (EWI, NSWCCD, HII-NNS, ABS Technology)

- Based on concurrence from NSWCCD; EWI and HII-NNS will fabricate "standard qualification builds" for a range of features to establish process-feature-properties for one consumable used in Task 4.
  - Compare results (round-robin testing) and used to demonstrate reproducibility.
  - An example qualification scheme may involve minimum and maximum bead size for a range of features, or just test one bead size based on HII-NNS allowances
  - For estimating purposes, it is assumed that two standard qualification builds / location will be produced for the selected process – consumable combination.
  - Both radiographic and ultrasonic nondestructive testing will be used to evaluate soundness of standard qualification builds.
  - Property specimens (tensile, bend, metallographic) will be removed from the builds using the testing scheme of the pending Navy standard.

# Task 5 - Feature-Process-Property Data – ABS Role (EWI, NSWCCD, HII-NNS, ABS Technology)

- Per NSRP Guidance Letter, ABS Technology was added to the project
- ABS is global standards and certification body for shipbuilding.
- For the project, ABS will:
  - Assess the qualification scheme(s) being developed by NSWCCD and tested in this task
  - Provide an overview of ABS's guidance document for additive manufacturing.
- ABS has committed to start draft - ABS Guide for metal AM
  - Seek to harmonize requirements with the Navy Technical Publication were possible

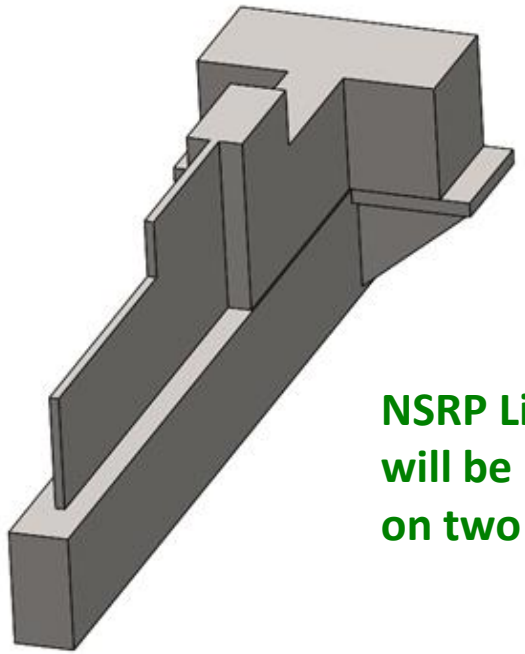
# NSWCCD Process Qualification Scheme Development for Technical Publication Initiative – Arc Directed Energy Metal Additive Manufacturing

## Objectives:

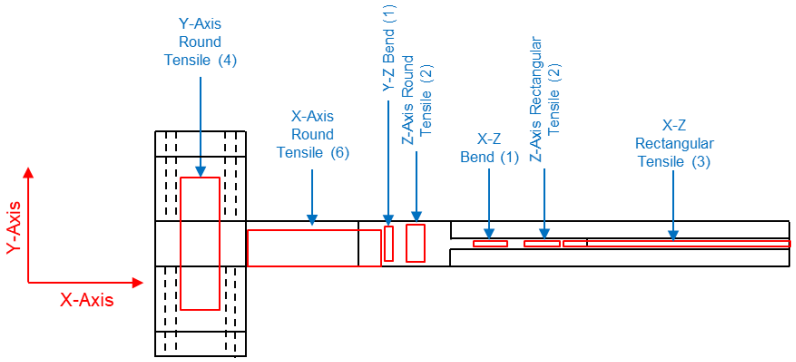
- Develop, evaluate, and recommend preferred process qualification build schemes for arc DED processes.
- Phase 1 - Develop material property data for 304L (ER308L consumable) stainless steel using arc DED processes.
- Provide input - NSWCCD for Tech Pub for arc DED metal AM

## Project Team:

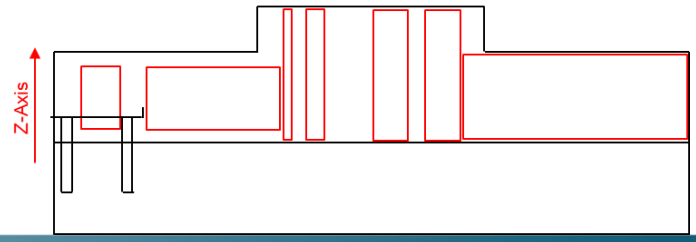

Dennis Harwig, EWI – Project PI
Bill Mohr, EWI
Mike Carney, EWI
Susan Hovanec, NSWCCD;
Justin M. Rettaliata, Technical Warrant Holder
- Additive Manufacturing NAVSEA 05T

| | |
|---|---|
| A – B | 4 Tensile specimens (Y-axis) |
| B – C | 6 Tensile specimens (X-axis) |
| C – D | 1 Bend specimen (Y-Z plane) |
| D – E | Not Used |
| E – F | 2 Tensile specimens (Z-axis) |
| F – G | Not Used |
| G – H | 1 Bend specimen (X-Z plane) |
| H – I | Not Used |
| I – J | 2 Tensile specimens (Z-Axis) |
| J – K | 3 Tensile specimens (X-Z plane) |




**NSRP Link - The Qualification Scheme will be used to demonstrate properties on two or more process conditions**



# NSWCCD Tech Pub Project Background

- Metal AM technology is rapidly maturing.
- AM impact limited by the availability of standards
- Many standard organizations developing standards
  - ASTM, AWS, ASME, API, etc
- AWS D20.1/D20.1M:2019 - Specification for Fabrication of Metal Components using Additive Manufacturing
  - AWS standard provides framework for manufacturers and suppliers to implement AM (Framework similar to other AWS D Codes)
    - Comprehensive, however, scheme not prescriptive for process application qualifications
    - Engineer has to define wide range of requirements (example to follow)
- Navy developing prescriptive material and application requirements for new Technical Publications

# AWS D20 - Engineer shall define……

(1) Classification – Class A, B, or C

(2) Component and design requirements

(3) Essential process controls

(4) Feedstock specification requirements

(5) Material and component property data

(6) Design of witness specimens

(7) Product definition data set

(8) Tensile specimen removal plan for pre-production test builds

(9) Determination of acceptability of in-process correction

(10) Method of dimensional examination

(11) Approval - visual and dimensional examination plans

(12) Surface inspection in any condition other than fully machined

(13) Alternate method for examining builds that cannot be completely inspected by RT

(14) Sampling plan for Class B builds (8.2.5.2 and

(15) Location of tension test specimens within witness specimens

(16) Chemical analysis test method

(17) Acceptance criteria for tensile testing

(18) Disposition of components not meeting the requirements

(19) Acceptance criteria for metallographic testing

(20) Acceptance criteria for chemical analysis

(21) Acceptance criteria for density testing

(22) All Engineer's responsibilities listed in subsequent sections of this document

(23) All additional requirements, identified by the Engineer, that are not specifically addressed in this standard

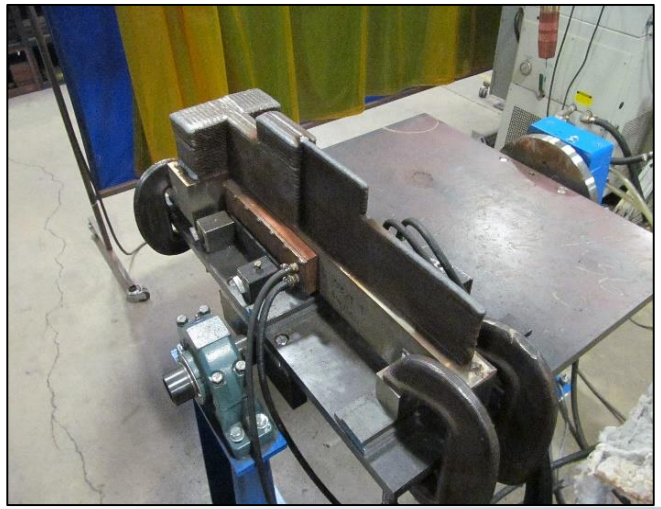
**This can add months or years to implementation opportunities - Need to maximize detailed requirements**

# NSWCCD Tech Pub Objectives

- NSWCCD drafting US Navy Technical Publication - Arc Directed Energy Deposition Metal Additive Manufacturing
  - Separate Tech Pub for powder bed metal AM processes
  - Separate Tech Pubs for Laser DED metal AM processes
  - Leverage large body of proven welding standards & Tech Pubs
    - **Develop prescriptive requirements where possible**
    - **Leverage equivalent (wrought, casting, forging, filler, etc) material properties for (tensile, impact, hardness, etc) criteria**
- Qual. Scheme - Develop preferred standard qualification build(s) and specimen matrix for common arc DED metal AM process applications
  - Austenitic, Ferritic, Advanced materials
  - Single-sided with & without integrated build platform
  - Double-sided with integrated build platform

# Qualification Build Parameters & Examples

| GMA-P Paramters | | | | | |
|---|---|---|---|---|---|
| **Build#** | **WFS (ipm)** | **TS (ipm)** | **I (amps)** | **V (volts)** | **# BEADS** |
| **15L** | 305 | 20 | 226 | 24.1 | 1452 |
| **15H** | 305 | 20 | 226 | 24.1 | 1589 |
| **30L** | 250 | 8 | 186 | 22.1 | 788 |
| **30H** | 250 | 8 | 186 | 22.1 | 793 |



# Qualification Scheme – Next Steps

- Develop qualification build geometries & specimen plans for:
  - Advanced steels, nickel aluminum bronze, Inconel, stainless steels, etc.
  - Integrated build plate test requirements (single- or double-sided)
  - Laser DED process (hot wire & blown powder)

**NSRP Link - Qualification Scheme(s) will be validated in project and a future service for shipbuilders and industry.**

- Develop UT & RT calibration blocks
- Provide input to draft Tech Pub.
  - Manage risk to drive affordability, properties and quality
  - Leverage large body of welding standards for Arc DED AM

# Task 6 - Robotic Arc Gantry DED AM System Integration and Build Trials (Navus, EWI)

- Navus will integrate, simulate, and integrate new test-bed gantry system
  - Install the new system at EWI (Columbus HQ), calibrate the system, test functionality, and prepare for arc DED AM trials.
- Gantry ready for Phase 2 – June 2020
- Develop gantry robot system simulation model and post-processor in Powermill
  - Basic parts tests for machine calibration, and machine qualification

# Task 7 - Robotic Arc DED AM DDW Seminar and Workshop Demos (Project Participants)

- Background: EWI will host training events in both Year 1 and Year 2.
  - EWI's facility in Columbus, Ohio.
- At end of Year 1, host:
- **Basic Robotic Arc DED AM Training Seminar & Workshop**
  - Review/assess CAD geometry (as-designed) for DED AM
  - Modify design for arc DED AM build (add stock, start / stop tabs, build supports to control distortion, etc.)
  - Simulate CNC CAM model of overall build strategy
  - Setup build, simulate robotic DED builds, and determine preferred workpiece position and plan per simulation analysis
  - Post-process trajectories (multi-axis robot build-plan)
  - Edit trajectories (embed knowledge in robot build plan)
  - Add sequence data for allied processes (deposit, cool, inspect, grind, repeat, etc.)
  - Use shapes for arc DED AM builds in workshop
- At end of Year 2, host:
  - **Advanced Robotic Arc DED AM Training Workshop**

# Task 8 - Shipyard Implementation Opportunities and Metrics (HII-NNS, Austal)

- Background: There are many opportunities for metal AM to impact shipbuilding and large structure manufacturing.
- Arc DED AM can be used as an alternative to castings, build forging preforms, add features to structure, conformal clad structures, fabricate tooling and attachments, and repair, to name a few.
- In this task:
  - Austal USA will explore application opportunities, prioritize which application and materials offer impact, and provide a short report at end of year 1 and 2 describing next-step recommendations for their yard.
  - NNS, PHNS, PNS, and PSNS will be surveyed to explore robotic arc DED AM capabilities in Naval shipyards for sustainment applications

# NSRP Project Benefits

- Standardized ‘big-area’ gantry
  - Maximize flexibility / lower system costs
  - Access to test-bed control platform
- Accelerate Transition
  - Powermill digital data workflow competencies & training
  - DED AM process qualification scheme
  - Additive Mfg. Procedures Specs (AMPS)
  - Develop technology for:
    - High quality DED AM builds & properties
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  - Beta test site for Basic and Advanced Powermill DED AM


NATIONAL SHIPBUILDING
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RESEARCH PROGRAM