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Applied Research Laboratory

Cold Spray Development at the Applied Research Laboratory

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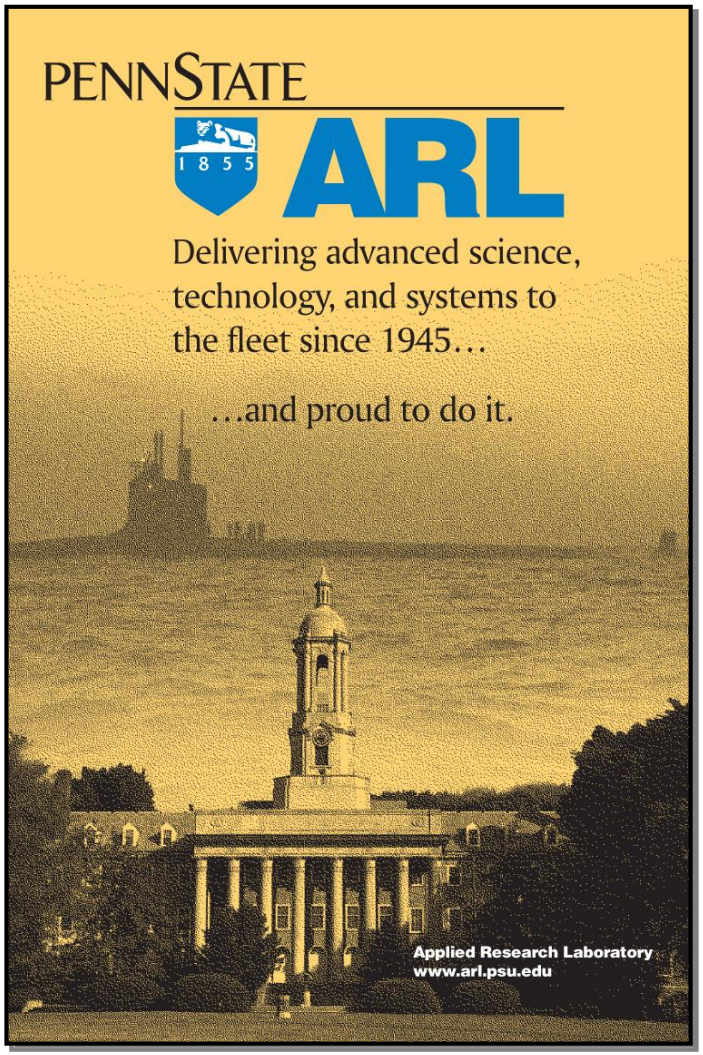
Introduction to the Applied Research Laboratory



- **Established in 1945 by the Navy post WW II**
- **Technology Areas**
  - **Undersea Weapons**
  - **Undersea Vehicles/UUV's**
  - **Hydrodynamics and Structures**
  - **Acoustics & Quieting**
  - **Comms and Information**
  - **Power and Energy**
  - **Navigation**
  - **Materials/ Manufacturing**
- **Largest Interdisciplinary Research Unit at Penn State – 1148 faculty/engineers, staff, students**
- **Designated an University Affiliated Research Center (UARC) by DoD in 1996**

"…maintains a special long-term strategic relationship with DoD for technology development and engineering applications."

Manufacturing Technology Center of Excellence
ManTech COE – ONR Funded

- Execute projects; manage project teams
- Serve as corporate expertise in technological areas
- Collaborate with acquisition program offices / industry to identify and resolve manufacturing issues
- Develop and demonstrate manufacturing technology solutions for identified Navy requirements
- Facilitate transfer of developed technologies

Repair Technology REPTECH

- Addresses repair, overhaul and sustainment functions that emphasize manufacturing processes and advancing technology
- Target fielded weapon systems and provide the process and equipment technology needed to repair and maintain fleet assets
- Implement projects at naval depots, shipyards, Marine Corps logistics bases, intermediate maintenance activities and contractor facilities responsible for the overhaul and maintenance of fleet hardware

Approach to Material Solutions

Develop Long Term Strategic Relationships

UNDERSTAND REQUIREMENTS

- Performance
- Operating Environment
- Material Compatibility
- Maintenance
- Cost
- Life Cycle

SOLUTION DEVELOPMENT

- Select Materials
- Select Optimal Technology
- Develop Material, Coating or Manufacturing Process
- Validate/Qualify Solution
- Transition Technology

TECHNOLOGIES/CAPABILITIES

Metals and Ceramics Processing

- Coatings/Cold Spray
- Material Consolidation
- Materials Characterization and Testing

High Pressure Test Facility

- CIP
- High Pressure Testing (up to 20,000 psi)

Advanced Coatings

- Electron Beam Physical Vapor Deposition (EB-PVD)
- Cathodic Arc/ Sputtering
- Ion Beam Assisted Deposition (IBAD)

Electronic Materials and Devices

- Crystal Growth
- Devise/Sensor Fabrication
- Material/Device Characterization

Drive Train Center/Gear Research Institute

- Manufacturing
- Materials Characterization
- Metrology
- Mechanisms

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REPTECH Project
Cold Spray Repair of Shipboard Components

Technology Development

- Puget Sound Naval Shipyard (PSNS) and the Intermediate Maintenance Facility (IMF) identified a number of candidate components for Cold Spray Repair
  - Repair of corrosion damage and material restoration
- Four components were selected
  - Hydraulic Actuators/Controllers (Al-6061)
  - Electric Motor End Bell Bore Repair (Steel and Cast Iron)
  - Swing Check Valve (70/30 CuNi)
  - Seawater Pump Components (Bronze)
- Develop, qualify and transition repairs
- Navy Repair Procedures for repairs
  - General Cold Spray Procedure
  - Specific Repair UIPI – Universal Industrial Process Instruction
- Navy wide teleconference to provide updates
  - Provide updates on Cold Spray Technology
  - Master list of components being repair
  - Forum for discussion

REPTECH Approach

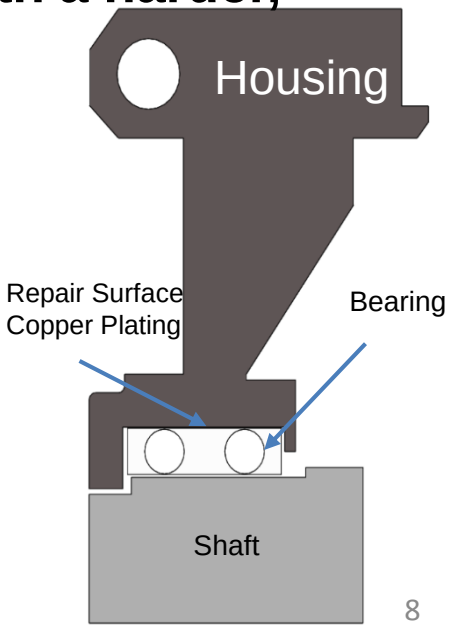
Project Update

- Repairs have been developed using high pressure Cold Spray systems
- Formed team to leverage capabilities
  - PSNS & IMF
  - ARL/Penn State
  - Army Research Laboratory
  - VRC Metals
  - UTRC
  - Moog
- TD -63 and TD-16, the Al-6061 have been repair and granted limited use status
- CVN #1 Main Circulating Water Pump Casing (bronze) has been give major temporary approval for unrestricted operations
- Repairs in progress
  - Electric Motor End Bell Bore Repair (Steel and Cast Iron)
  - Swing Check Valve (70/30 CuNi)

Copper Plating Replacement

Bell Housing Repair

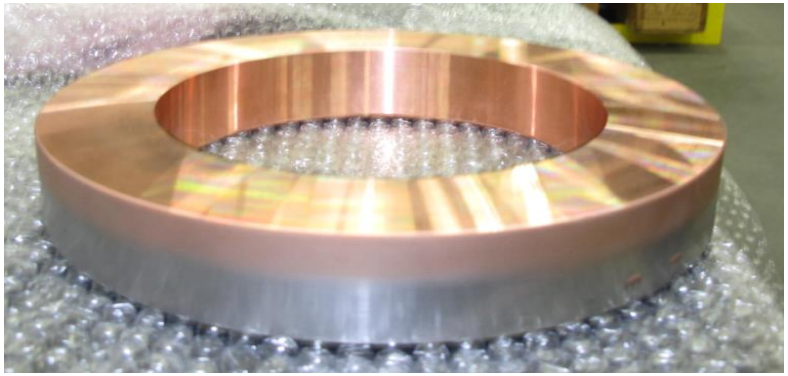
- Motor end bell wears/deforms at the bearing/housing interface which causes the shaft to vibrate
  - Current Solution: Copper plating of steel or cast iron
    - Machine worn area to remove damage
    - Surface Preparation
    - Restore surface to original dimension
  - Desired Solution: Replace copper plating with a harder, more durable coating
  - A minimum thickness of 0.030 inches
  - Develop repair process
    - Material selection
      - Copper
      - Nickel
      - Nickel Chrome- Chrome Carbide



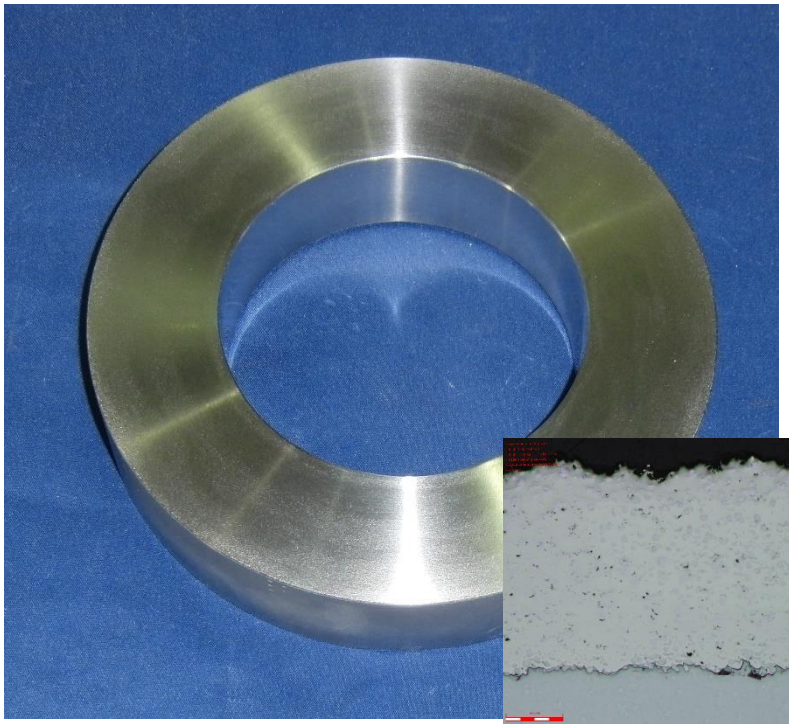
Copper Plating Replacement

Bell Housing Repair

- Copper Plating
  - Excellent machinability
  - Adhesion Strength
    - 8.5 ksi
- Nickel
  - Excellent machinability
  - Adhesion Strength
    - > 11 ksi
- Nickel chrome – chrome carbide
  - Excellent machinability
  - Adhesion Strength
    - > 11 ksi
  - Hardness 42-45 HRC
- Mockups completed
- Repair Motor End Bell Housing



Copper Coated Steel Ring



NiCr-Cr3C2 Coated Steel Ring

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Porous Coating Development

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Engineering Science and Mechanics
The Pennsylvania State University

Pro. Bill Cheung
Mechanical Engineering
The Pennsylvania State University

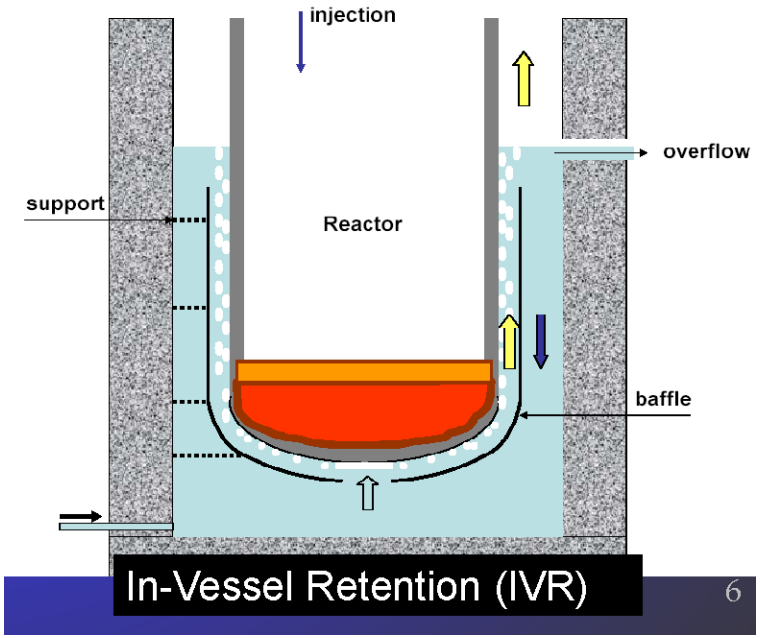
Porous Coating Development

Objective

- **Create tailored micro-porous coatings for reactor head to enhance downward facing boiling heat-transfer during emergency flooding:**
  - **Eliminate boiling crisis caused by the vapor layer**
  - **Increase critical heat flux (CHF)**
  - **Contain or slow down release of molten core**

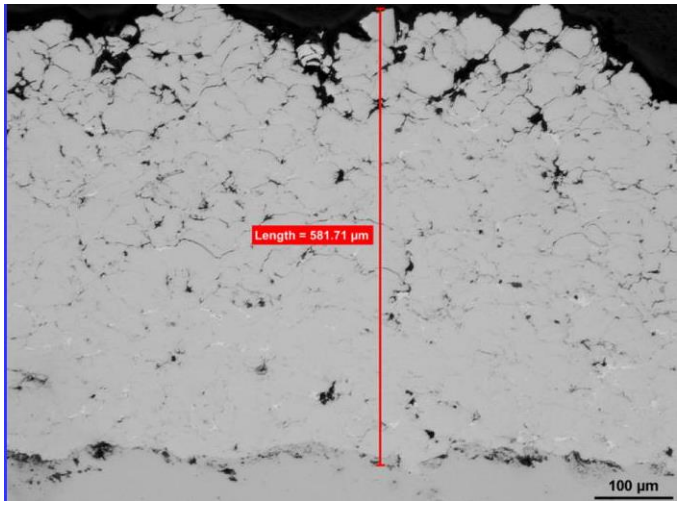
Solution

- **Cold spray coating**
  - **Interconnected Porosity**
  - **Good Adhesion to steel**

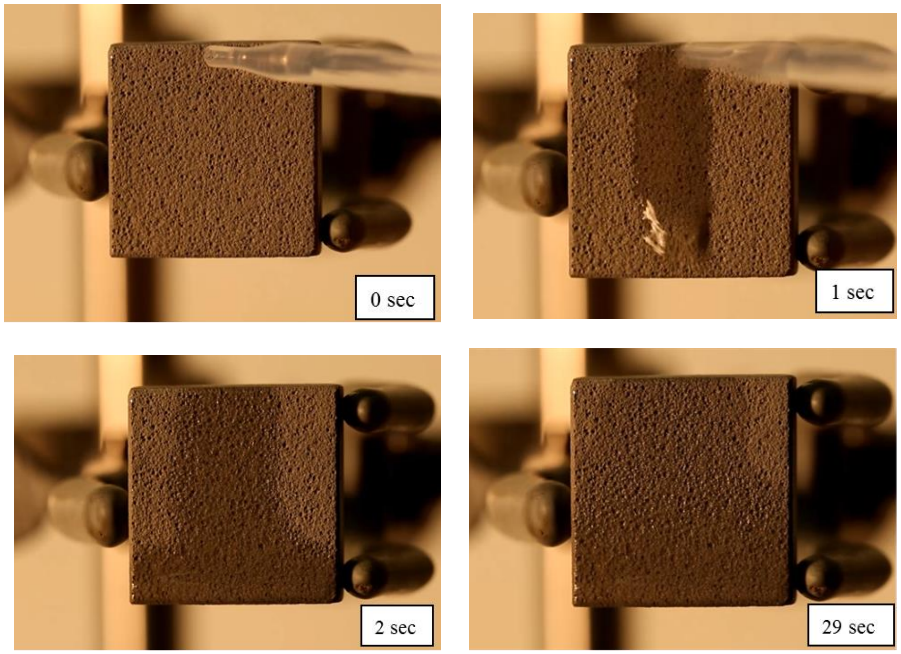


Results

- Developed porous stainless steel coating
- Tested in a subscale high heat flux/ high flow test loop
- Excellent results in lab-scale high heat flux testing



Porous Coating - ~3% porosity

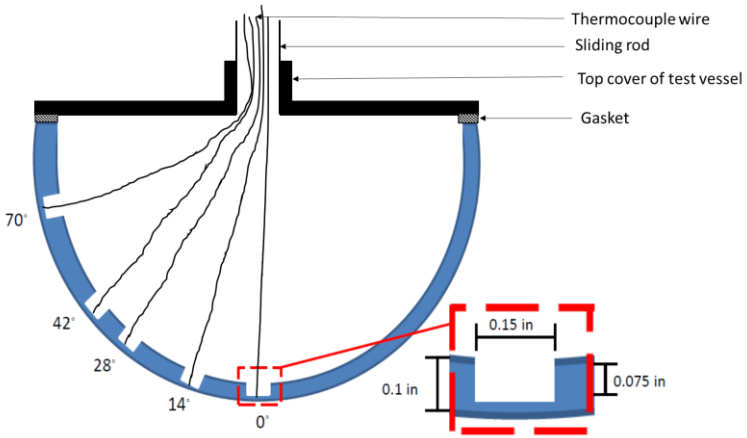


Water Absorption Testing

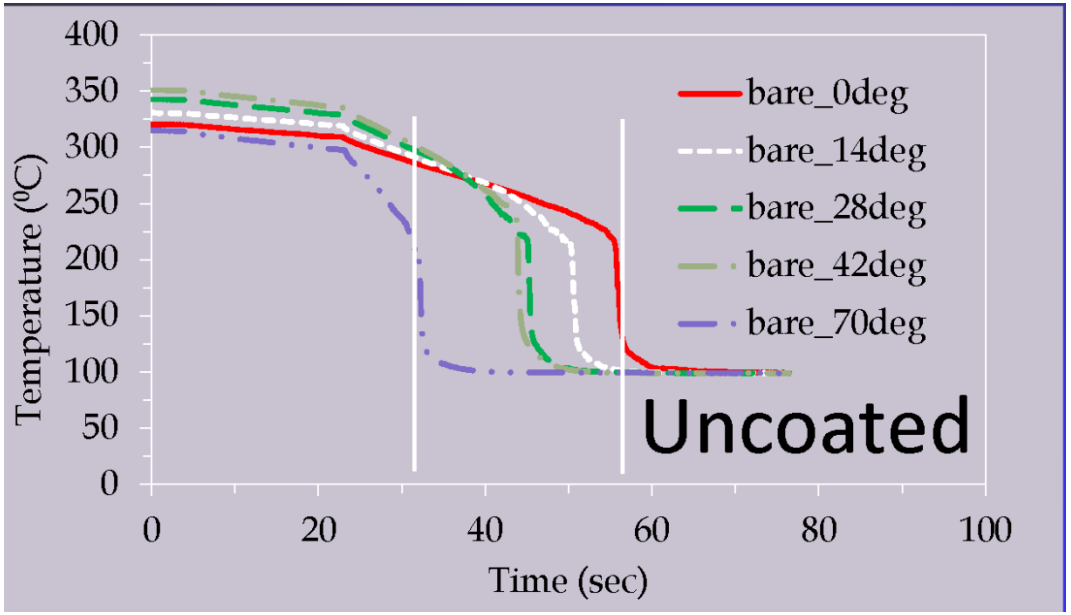
Test Section

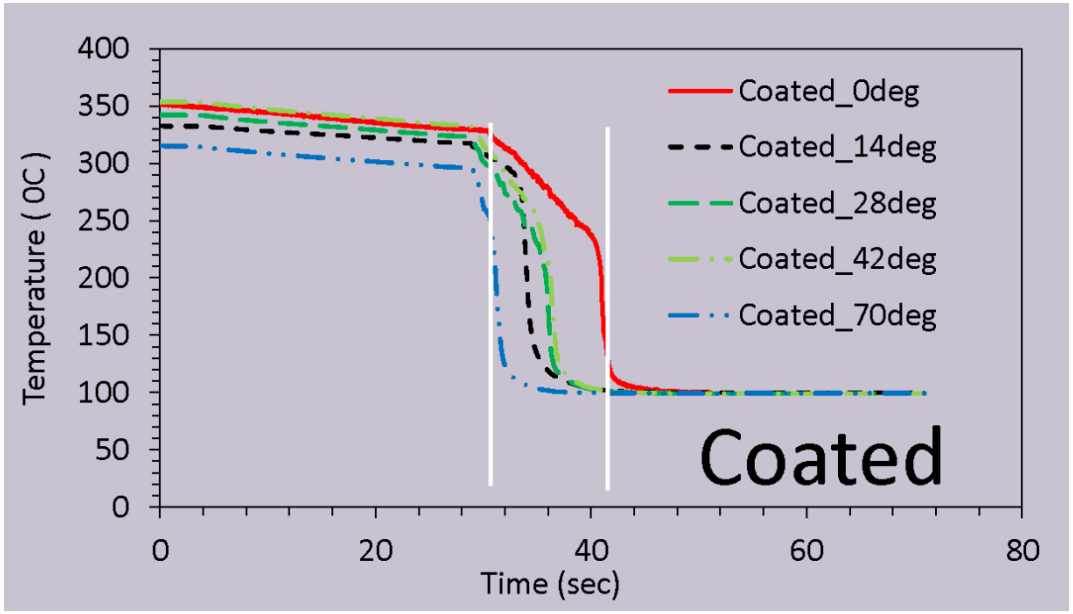
Enhanced Heat Transfer

Heated sphere to 365º C
Immersed in 100º C Water



Schematic of test hemisphere

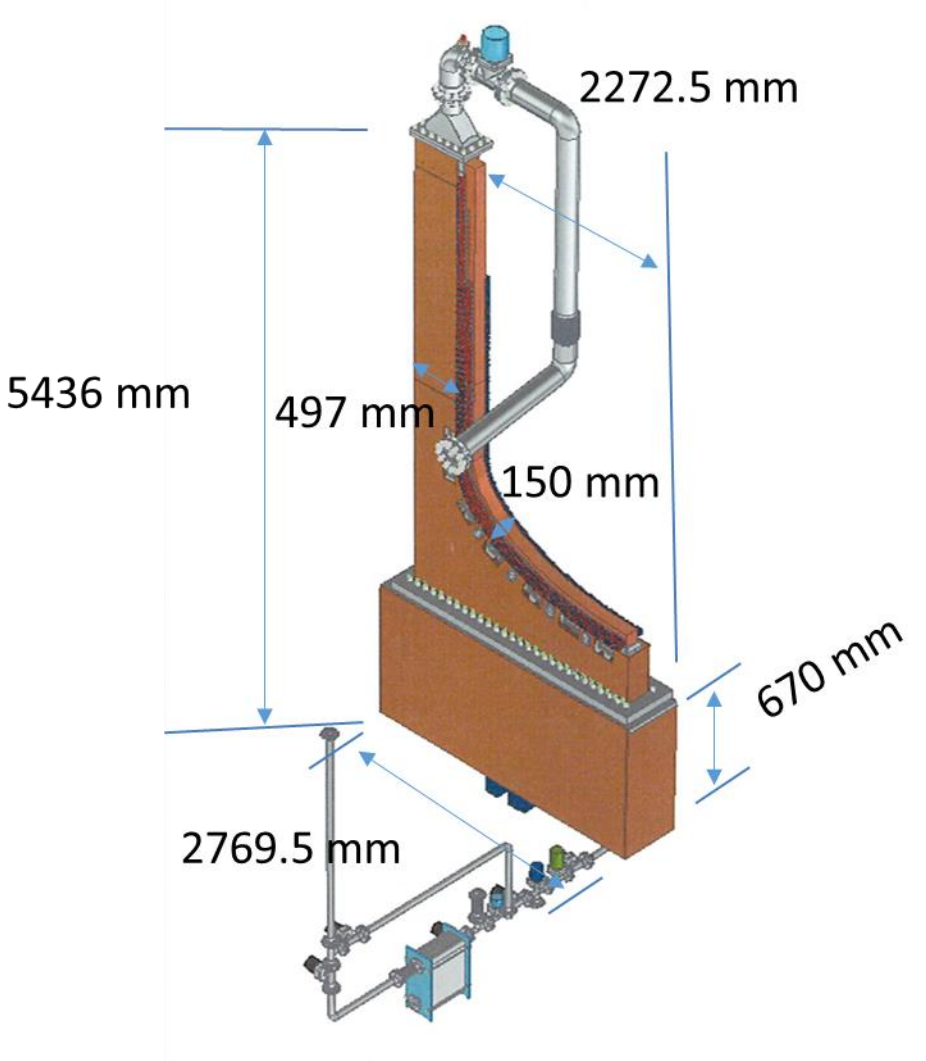




Porous Coating Development

Future Work

- Build large scale test section
- Coat test section
- Evaluate coating performance
- Demonstrate deposition process
- Develop process for full scale reactors



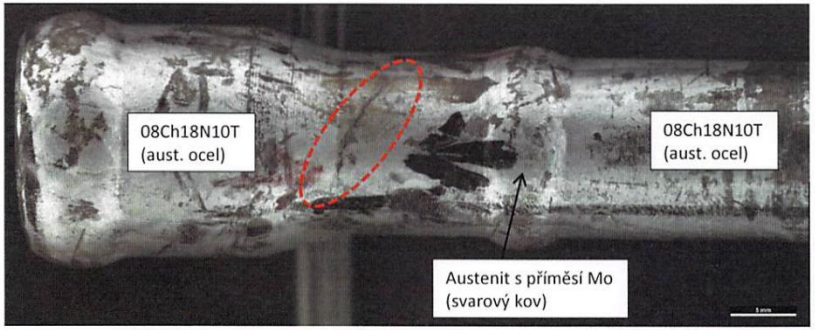
Impulse Tube Repair

Material

- Czech Standard CSN 411418
- Tensile Strength: 410-530 MPA
- Yield Stress: 265 MPA
- Elongation 23%
- Hardness
- Base Material: 141-145 VHN
- Heat Affected Zone: 161-260 VHN
- Weld: 251-250 VHN

Steam Leak

- Tube cracked during operation



Stream Impulse Tube

Crack in Stream Impulse Tube

Impulse Tube Repair

Repair

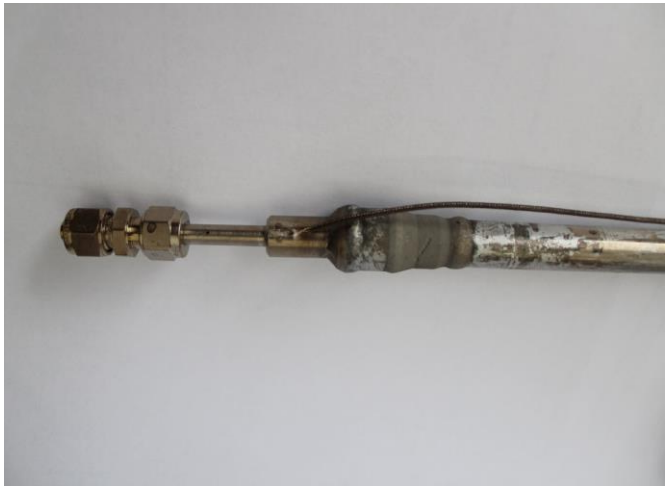
- **Cold Spray using the VRC Gen III**
- **VRC performed the repair**
  - **NiCr-Cr_3C_2**
  - **He**

Testing

- **Pressure Testing**
- **18.6 MPa (2740 psi), 25ºC**
- **18.6 MPa, 325ºC (617ºC)**
- **1 hours**
- **Next Step – cyclic testing**

Steam Impulse Tube with Cold Spray Repair

Test Step



Test fixture for Steam Impulse Tube

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Development of Cold Spray Bonding Model

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Prof. Ivi Smid & Tim Eden
Engineering Science and Mechanics
The Pennsylvania State University

Vic Champagne
Army Research Laboratory

Strain Energy Bonding Model

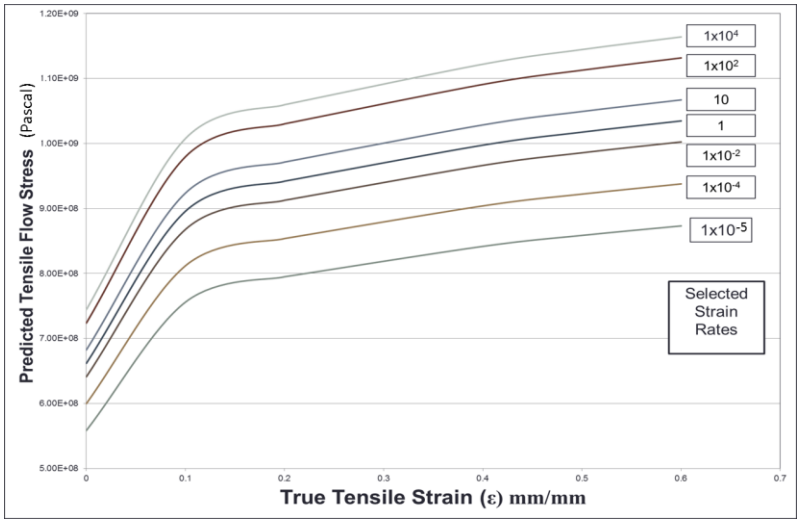
- Army Research Laboratory Modeling Effort
- Develop a comprehensive model of the bonding mechanism in the cold spray process
- Implement the Preston-Tonks-Wallace high strain rate plasticity model
- Compare results with experiments
- Develop a strain based bonding/debonding criteria
- Transition from single particle to multiparticle impact
- Compare results with bulk adhesion data

Johnson-Cook Constitutive Material Model

- **Empirically based material model that relies on five material parameters to predict flow stress.**
- **Without strain-rate corrections, only valid for strain-rates from quasi-static to 10^4/sec.**

$$\sigma_y = \left[A + B\varepsilon_p^n\right]\left[1 + C ln\dot{\varepsilon}_p\right]\left[1 - T_H^m\right]$$

A = quasi-static yield strength
B = power law pre-exponential factor
C = strain rate pre-exponential factor
n = strain hardening exponent
m = thermal softening exponent



Flow stress prediction for AISI 4340 steel using Johnson-Cook Equation at various strain-rates [J. Schreiber].

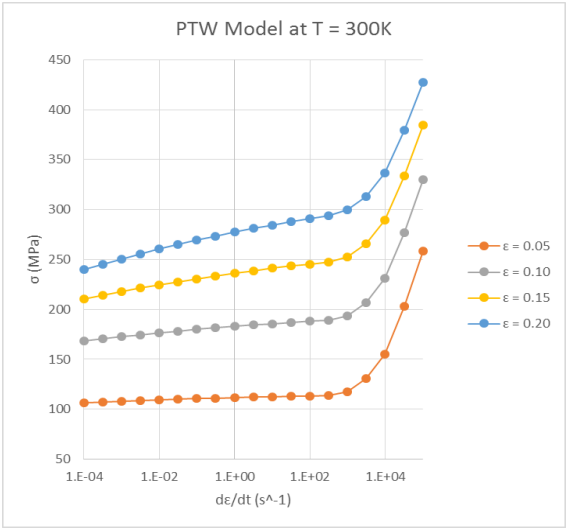
Preston-Tonks-Wallace Material Model

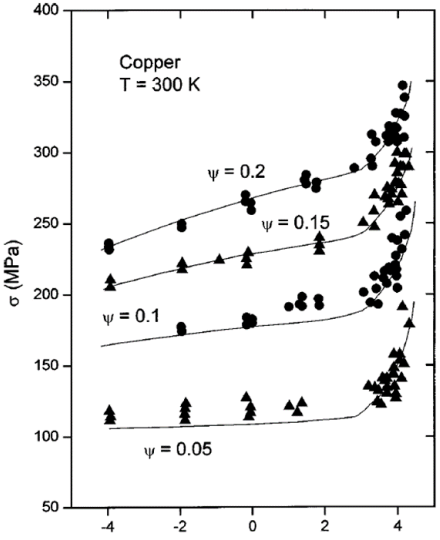
- Physics based materials model that is capable of predicting yield stresses at strain-rates ranging from 10^{-3} to 10^{12} 1/sec
- Relies on three dimensionless variables that are based on:
  - Flow stress
  - Temperature
  - Strain-rate

$$\hat{\tau} = \hat{\tau}_s + \frac{1}{p}(s_0 - \hat{\tau}_y) ln\left[1 - \left[1 - exp\left(-p\frac{\hat{\tau}_s - \hat{\tau}_y}{s_0 - \hat{\tau}_y}\right)\right] * exp\left\{-\frac{p\theta\psi}{\left(s_0 - \hat{\tau}_y\right)\left[exp\left(p\frac{\hat{\tau}_s - \hat{\tau}_y}{s_0 - \hat{\tau}_y}\right) - 1\right]}\right\}\right]$$

$\hat{\tau}_s$ - normalized work hardening stress (how the model accounts for strain hardening)
s_0- saturation shear stress at 0K
$\hat{\tau}_y$ - Normalized yield stress (at low strain rates), saturation stress (at high strain rates)
p – hardening parameter
θ – hardening constant
ψ – scaled equivalent plastic strain rate value

Finite element subroutine prediction agrees with experimental data

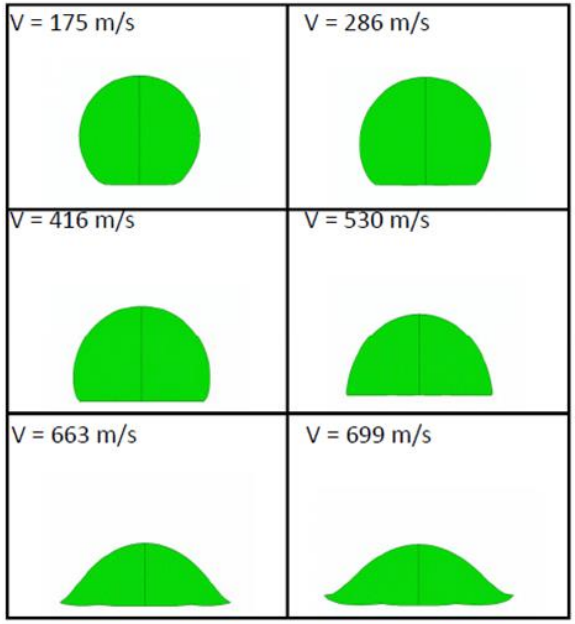




D.L. Preston, D.L. Tonks, D.C. Wallace, Model of plastic deformation for extreme loading conditions, J. Appl. Phys. 93 (2003) 211. doi:10.1063/1.1524706.

Single Particle Impact Modeling

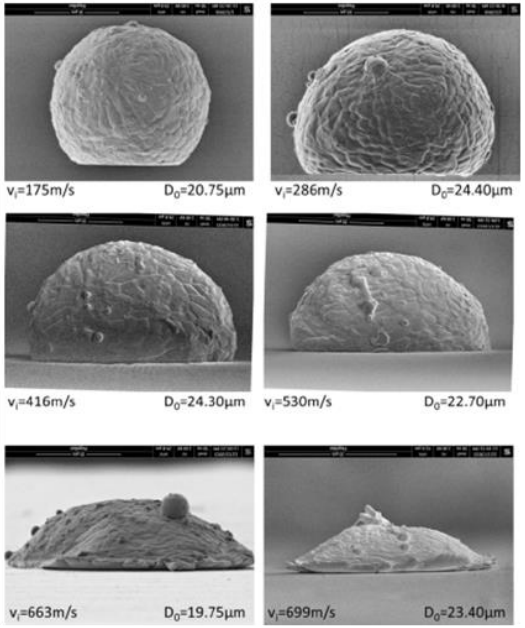
Bilinear Johnson-Cook



A. Alizadeh & S. Muftu, Northeastern Univ.

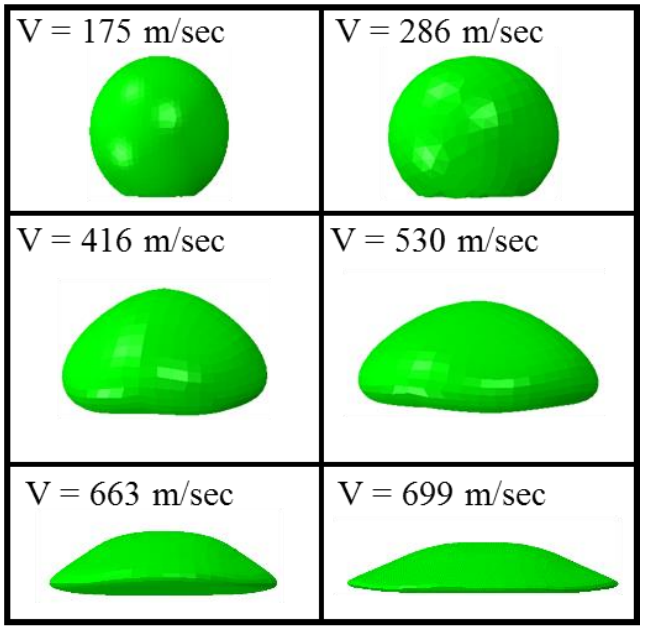
2 sets of Johnson-Cook parameters required to create a 2 region curve fit that is strain-rate dependent

Experimental Results



W. Xie, J.-H. Lee, UMASS

Initial PTW Results



J. Schreiber, T. Eden, I. Smid – Penn State

No parameter changes are required during analysis for PTW model.

WPI is calculating material properties using thermodynamic databases and experiments

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Bond Model Development

VUINTER Subroutine Development

VUINTER is currently used in cutting tool modeling applications, where contact definitions currently do not exist as built-in options.

After an extensive search, there has been no evidence of this subroutine being used for any impact bonding applications in the open literature.

However, this subroutine is fully customizable and is compatible with other subroutines in Abaqus (This is important to note, since we are using VUHARD as the input method for the Preston-Tonks-Wallace plasticity model)

Advantages

- **Can be used to define mechanical/thermal interaction between two surfaces**
- **Can update solution dependent variables (possibly to allow separation under tension)**

Disadvantages

- **Very complex subroutine, for advanced users only (according to Abaqus help)**
- **Overrides all built-in contact definitions (must describe every contact definition in the subroutine)**
- **Only capable of using penalty contact constraint method (not a direct issue for impact analysis)**

"Soft Contact" Normal Behavior Development

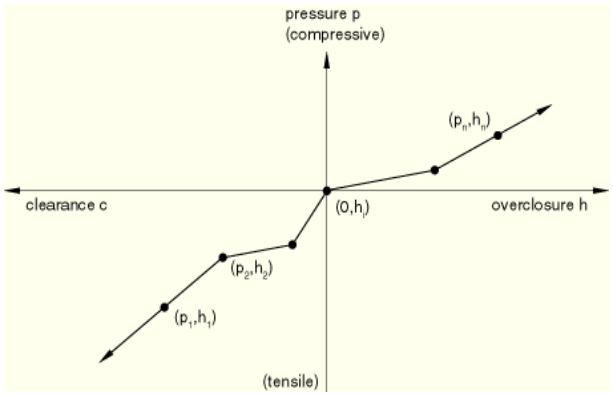
- **Simplistic method for introducing bonding between two or more bodies**
- **Relies on contact pressure to begin bonding process**
- **Unlike the "Hard Contact" model, soft contact will allow for de-bonding under a tensile load**

Advantages

- **No subroutine needed**
- **Tabular data controls the bonding and debonding process**

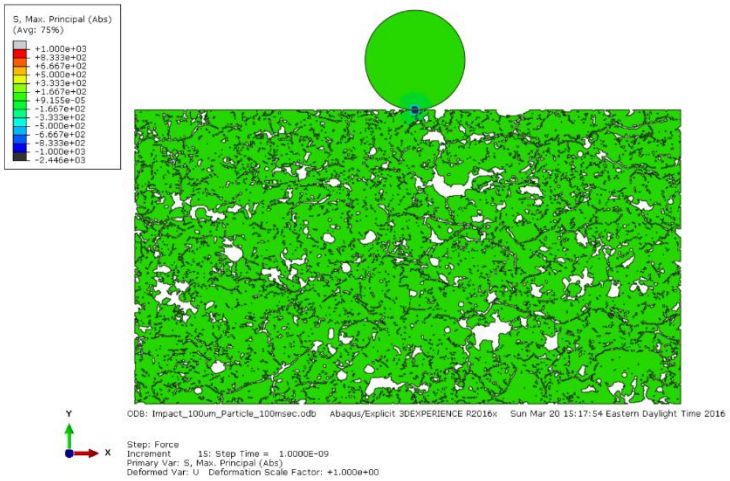
Disadvantages

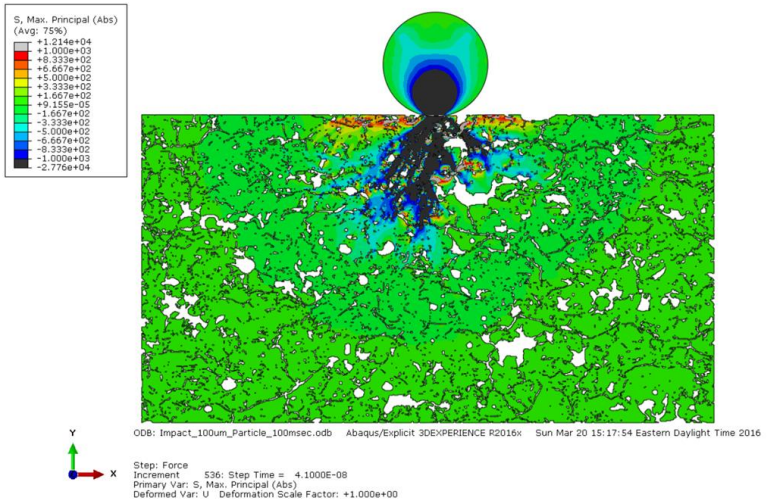
- **Is a pressure only based bonding model**
- **Uses tabular data rather than in-situ strain energy values**

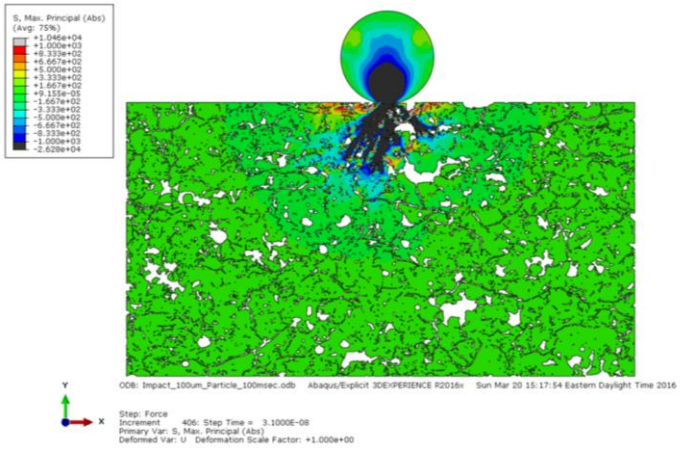


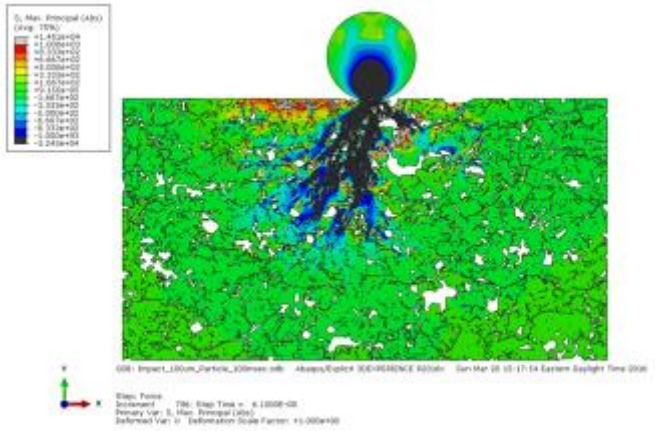
Example of the tabular data required for bonding and de-bonding

Ceramic Substrate Model Development









- **NIST OOF2 Finite Element Analysis of Microstructures**
- **SEM images of microstructure**
- **Abaqus Finite Element Code**
- **0, 31, 41 and 61 ns**

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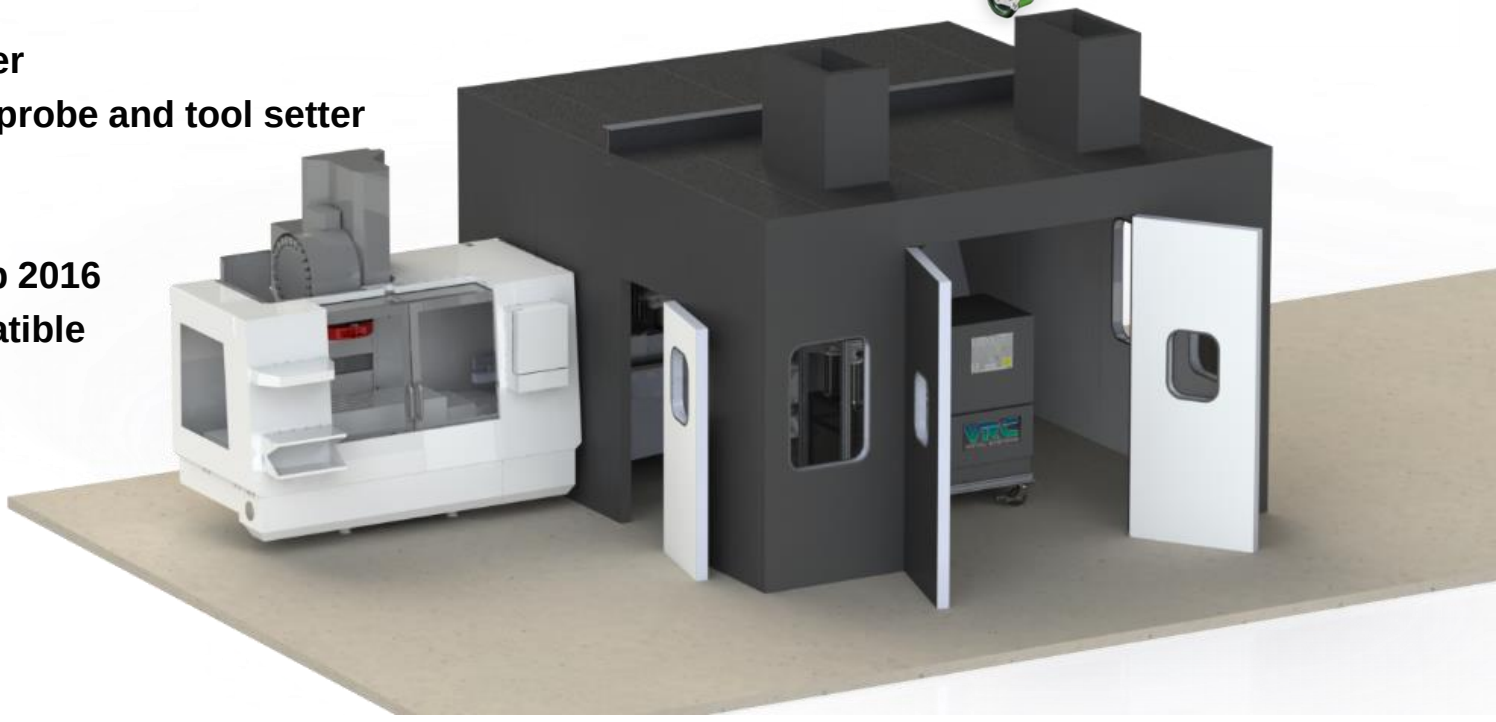
Additive-Subtractive Cold Spray Based Manufacturing Station

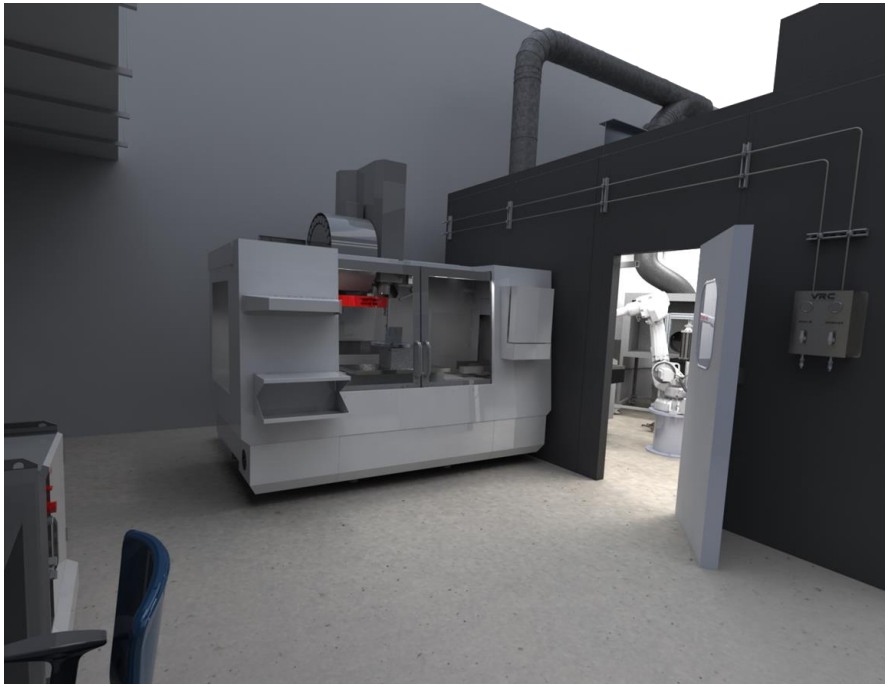
ONR Defense University Research Instrumentation Program

DURIP

- VRC Gen III Cold Spray System
  - Max Gas Pressure 6.9 bar
  - Max Gas Temp at gun 750º C
  - Max Heater Powder 45 kw
  - Deposition rate 7 kg/hr
  - Data logging and storage
- HAAS VF-3 CNC Mill
  - Rotary Table
  - Pallet Changer
  - Dimensional probe and tool setter
- ABB Robot
- Cold Spray booth
- Operational in Sep 2016
- Solidworks compatible
- Touch Probe
- Fully integrated



Future



- Apply portable high pressure cold spray
  - Dock/Ship side repair
  - Hatchable
- RepTech Program
  - Navy
  - Marines
  - Complete modeling