Rapid Fabrication Techniques for Liquid Rocket Channel Wall Nozzles

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Overview of Briefing

- Motivation for Technology Development
- Background and History
- Overview of Techniques
- Liner Forming
- Liner Waterjet Milling Techniques for Channels
- Liner Closeout Techniques
  - Freeform Laser Deposition Closeout
  - Explosive Bonding Closeouts
  - Liquid Cold Spray Closeout
- Conclusions
Channel Wall Nozzle Large Scale Development

- Channel wall nozzles have been evaluated as a cost savings for current and future missions for a variety of engine programs.
- NASA has evaluated and worked with vendors and contractors on fabrication of large scale channel wall nozzles (CWN) on several programs over the last few decades.
- Recently NASA has been advancing powder-bed fusion Additive Manufacturing (AM) techniques for chambers and nozzles, but size is very limited for single-piece nozzles.
- Closeout of the coolant channels is the most challenging manufacturing process. Previous studies and development work on mature processes for CWN:
  - Pressure Assisted Brazing (HIP) or Vacuum Compression Brazing (VCB)
  - Vacuum Plasma Spray
  - Laser Welded Sandwich Wall

**Goal:** Evaluate alternate manufacturing techniques to reduce fabrication cycle (and subsequent costs) and improve performance for large scale channel wall nozzles.
Channel Wall Terminology

- Braze Bond or Closeout Interface
- Closeout and/or Jacket (Coldwall)
- Coolant Channels
- Lands
- Fluid
- Hotwall
- Inner Liner

Vacuum Compression Brazed Closeout Sample
Overview of Techniques

- Fabrication techniques and sequences vary, but rolled into four (4) categories: Liner, Slotting, Closeouts, Manifolds

### Liner Forming
- Forging
- Spin Forming
- Shear Forming
- Powder Metallurgy
- Freeform AM Deposition
  - Powder-based Laser
  - Wire-based Laser
  - Arc-based Wire
- Multi-Piece SLM
- Platelets
- Coldspray
- Casting
- Vacuum Plasma Spray

### Slotting
- Slitting Saw
- End Milling
- Water Jet Milling
- Electro or Photochemical
- Plunge EDM
- Multi-Piece SLM
- Platelets
- Freeform AM Deposition

### Closeout and Jackets
- Pressure Assisted Braze
- Standard Atmosphere Braze
- Multi-Piece SLM
- Vacuum Plasma Spray
- Electroplating
- Coldspray
- Freeform AM Deposition
  - Wire-based Laser
  - Powder-based Laser
  - Arc-based Wire
- Explosive Bonding
- Ultrasonic
- Laser Welding
- Diffusion Bonding
- Platelets
- Casting
- Composite Overwrap

### Manifolds
- Wrought and Machined
- Freeform AM Deposition
  - Wire-based Laser
  - Powder-based Laser
  - Arc-based Wire
- Multi-Piece SLM
- Platelets
- Casting
- Molded Composites
Liner Forming

- NASA has researched a variety of large scale liner forming techniques and completed demonstrations on a few techniques
  - Blown Powder Deposition *(LENS, LFMT, DMD)*
  - Wire-based Freeform Deposition *(LMD, LDT)*
  - Arc-based wire deposition *(MDDM, Arc-DED)*
  - Electron Beam Freeform Deposition *(EBF^3)*
- Completed mechanical property and materials evaluations
Slotting using Blind Abrasive Waterjet Milling

- Waterjet milling has been demonstrated on a variety of materials for forming complex channels and also reduced slotting time for hard to machine materials.
Completed series of measurements to inspect channel depth and subsequent hotwall thickness

- Trades well with traditional slotting techniques
Channel Wall Closeout Techniques

• NASA advancing techniques for low-cost and rapid fabrication of high-integrity closeout bonds
• Eliminate or simplify plating and brazing processes
• Conducted a variety of experiments on flat plate sample hardware and down selected the following techniques for further development
  – Freeform Laser Deposition, Large Scale Additive Manufactured
  – Explosive Bonding (or welding) Closeout
  – Liquid Cold Spray Closeout
Freeform Deposition Closeouts

• Developed a wire-based freeform deposition process to closeout channel wall nozzles with a variety of materials
  – 300-series Stainless, Aluminum Alloys, Inconel 625, Bimetallic
• Completed without filler in the coolant channels
• Additional development work being completed to mature and optimize process
• Several advantages including Real-time inspection of joint

Covered under MFS-33232-1
Freeform Deposition Closeouts

Inconel 625 to C-18150 Copper

300 Series Stainless

Aluminum 6061
Explosive Bonding Closeouts

- Explosive welding (EXW) offers a solid state bond and has been demonstrated in a variety of materials including bi-metallic
  - Building on previous research on channel wall closeouts from Apollo program
- Requires a filler material in the channels
  - MSFC investigating a variety of metallic and non-metallic fillers
    - Metallic fillers require significant chemical milling
    - Non-metals offer significant advantages for removal
- Low cost tooling and explosive bonding operation compared to traditional techniques

Stainless to C-18150 Copper
Explosive Bonding Closeouts

- Completed 24" dia liner with Explosive Bonding Process
  - Inconel 625 Closeout shell to Inconel 625 liner
Summary

- MSFC has evaluated a series of techniques for channel wall rocket nozzles to decrease fabrication build schedules and associated costs
  - Large Scale Freeform Additive Manufacturing Deposition for Liners
    - Demonstrate >50% material and machining reduction
    - Significant decrease in liner machining schedule
  - Waterjet Milling for Channel Slotting
    - Reduced hotwall thicknesses
    - Increased complexity in coolant channels
  - Closeout Techniques
    - Freeform Deposition
    - Explosive Welding
    - Liquid Coldspray
- MSFC to continue evaluation and characterization of these techniques in addition to further scale-up
  - Completing a series of subscale optimization experiments, NDE and destructive evaluation and hotfire testing
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Liquid Cold Spray

- Evaluated Liquid Cold Spray Technique to build copper onto mandrel, complete machining and closeout of coolant channels
  - Completed fabrication demos and mechanical and metallography test specimens

Rapid Build Up ➔ Machine ➔ Channel Milling ➔ Filler Medium

Closeout using Liquid Cold Spray
Optical Inspection Techniques Supporting Fabrication

- Inspection is integral to fabrication of nozzles and large scale components
- MSFC has advanced structured light scanning techniques to allow for detailed 3D process evaluations
  - Allows for predictive and adaptive machining
  - Evaluations of thermal processing
  - Digital Assembly
  - Reverse engineering and Quality control
  - Part setup
Predictive Machining Strategy using Scanning

• Example of predictive machining strategy to understand cleanup of large scale additive manufacturing nozzle liner and use of scan data to determine setup on lathe


The plots on the bottom show structured light data and predictions for machining for visual references. The red on the ID contour is the area that is being removed for each pass – process used to help drive machining.
References


References


