

National Aeronautics and
Space Administration



Rapid Fabrication Techniques for Liquid Rocket Channel Wall Nozzles

AIAA-2016-4771

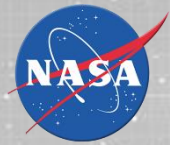
Paul Gradl

NASA MSFC
256.544.2455
Paul.R.Gradl@nasa.gov

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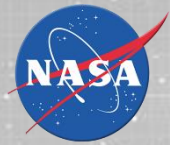


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Overview of Briefing

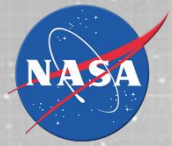
- Motivation for Technology Development
- Background and History
- Overview of Techniques
- Liner Forming
- Liner Waterjet Milling Techniques for Channels
- Liner Closeout Techniques
 - Freeform Laser Deposition Closeout
 - Explosive Bonding Closeouts
 - Liquid Cold Spray Closeout
- Conclusions



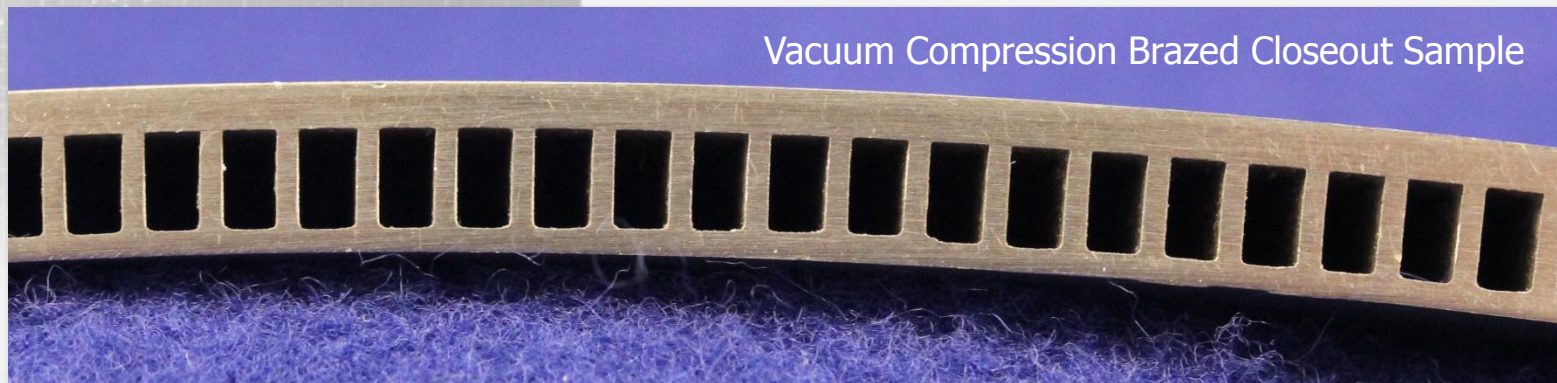
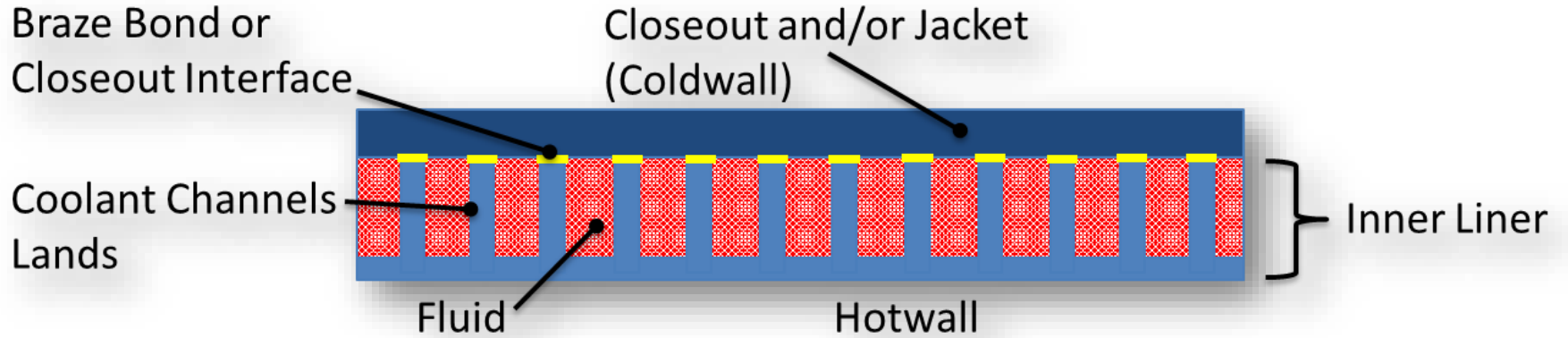
Channel Wall Nozzle Large Scale Development

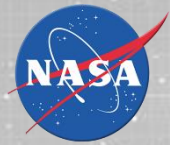
- Channel wall nozzles have been evaluated as a cost savings for current and future missions for a variety of engine programs
- NASA has evaluated and worked with vendors and contractors on fabrication of large scale channel wall nozzles (CWN) on several programs over the last few decades
- Recently 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





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
- Explosive Forming
- **Coldspray**
- Casting
- Vacuum Plasma Spray

Slotting

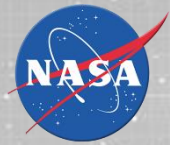
- Slitting Saw
- End Milling
- **Water Jet Milling**
- Electro or Photochemical
- Plunge EDM
- Multi-Piece SLM
- Platelets
- Freeform AM Deposition

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

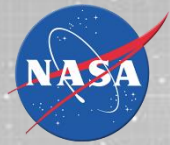
- Wrought and Machined
- Freeform AM Deposition
 - Wire-based Laser
 - Powder-based Laser
 - Arc-based Wire
- Multi-Piece SLM
- Platelets
- Casting
- Molded Composites



Liner Forming

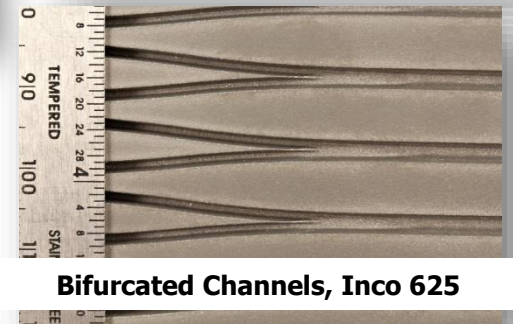
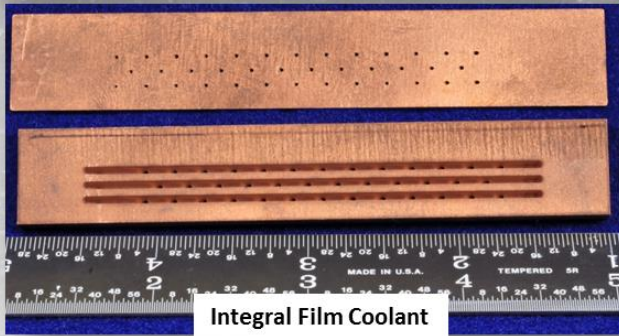
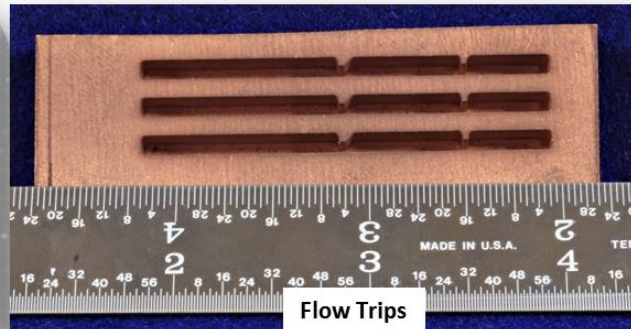
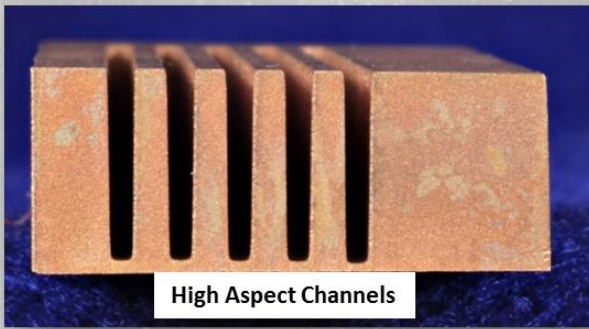
- NASA has researched a variety of large scale liner forming techniques and completed demonstrations on a few techniques
 - Blown Powder Deposition (*LENS, LFMT, DMD*)
 - Wire-based Freeform Deposition (*LMD, LDT*)
 - Arc-based wire deposition (*MDDM, Arc-DED*)
 - Electron Beam Freeform Deposition (*EBF³*)
- Completed mechanical property and materials evaluations

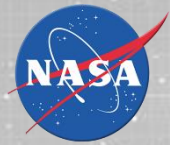




Slotting using Blind Abrasive Waterjet Milling

- Waterjet milling has been demonstrated on a variety of materials for forming complex channels and also reduced slotting time for hard to machine materials





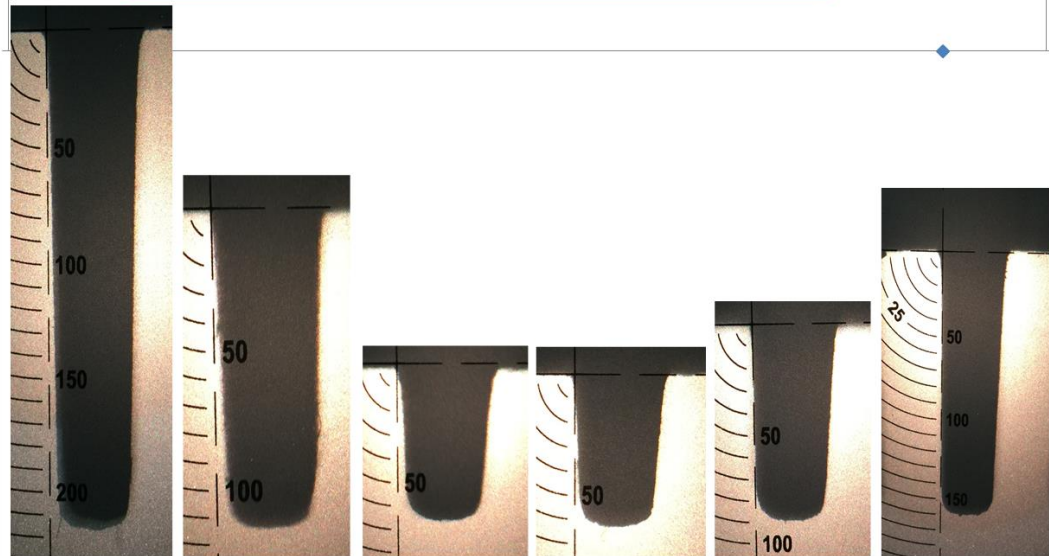
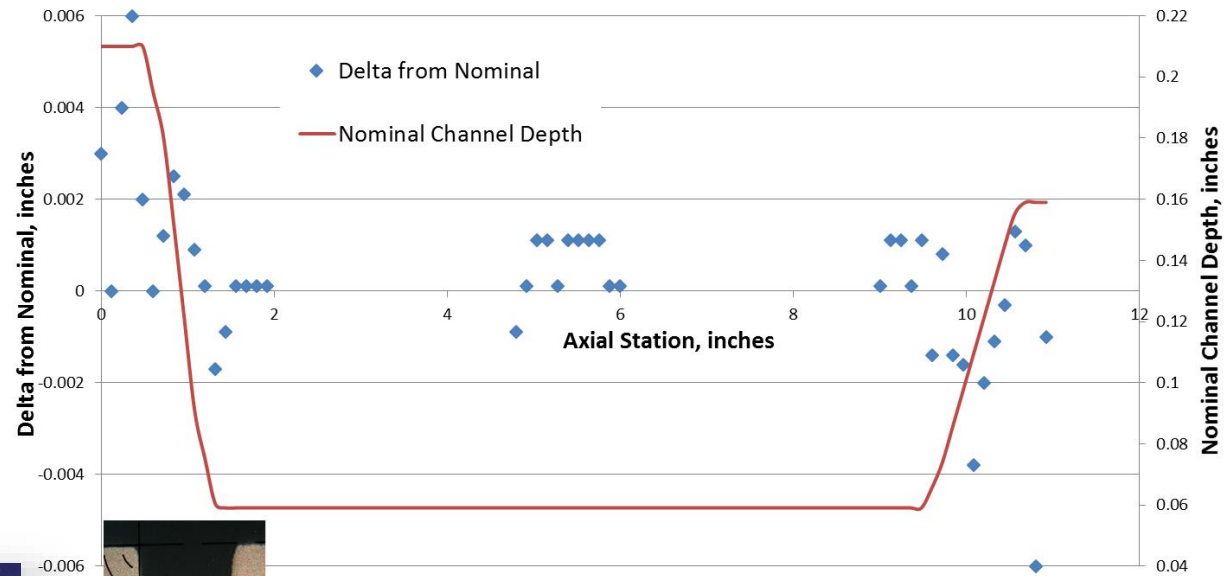
Process Repeatability, Waterjet Milling

Completed series of measurements to inspect channel depth and subsequent hotwall thickness

- Trades well with traditional slotting techniques



Depth Error Along Axial Stations of Liner 2D Cross Section



X = 0.25" from aft
0.206" deep

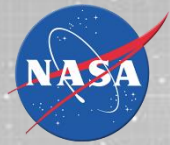
X = 1" from aft
0.109" deep

X = 2" from aft
0.059" deep

X = 7.92" from aft
0.059" deep

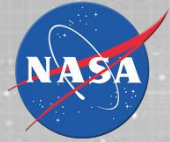
X = 9.92" from aft
0.092" deep

X = 10.67" from aft
0.158" deep



Channel Wall Closeout Techniques

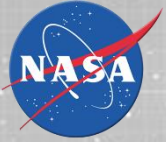
- NASA advancing techniques for low-cost and rapid fabrication of high-integrity closeout bonds
- Eliminate or simplify plating and brazing processes
- Conducted a variety of experiments on flat plate sample hardware and down selected the following techniques for further development
 - Freeform Laser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



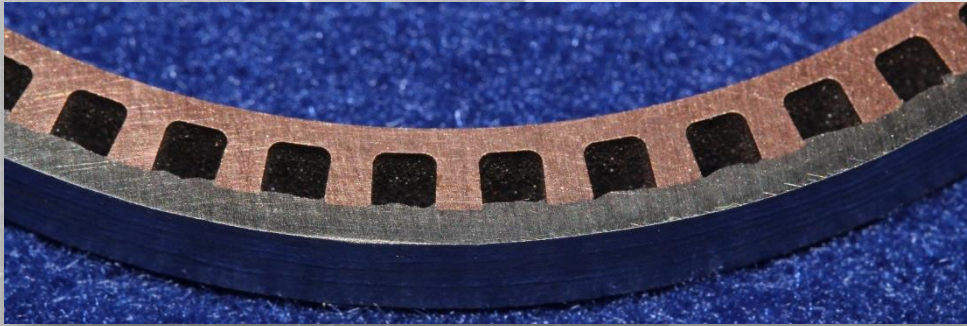
Freeform Deposition Closeouts

- 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





Freeform Deposition Closeouts



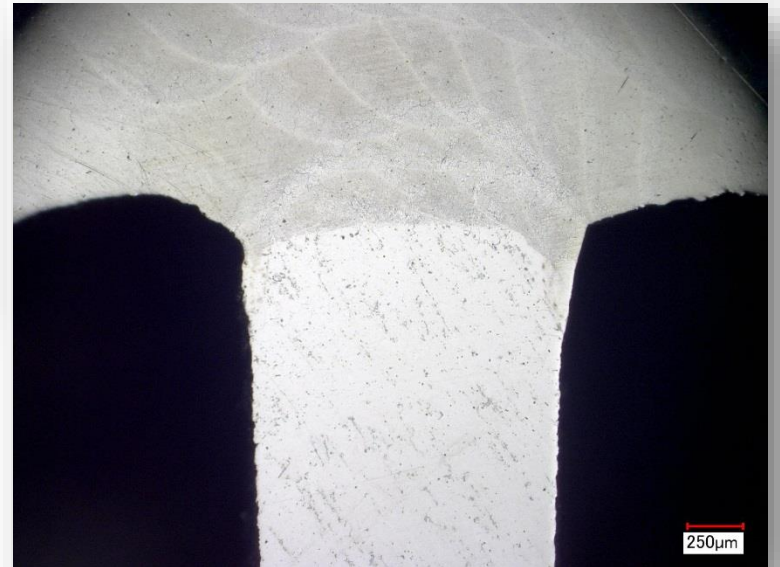
Inconel 625 to C-18150 Copper

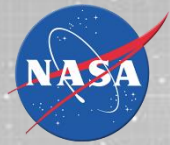


Aluminum 6061



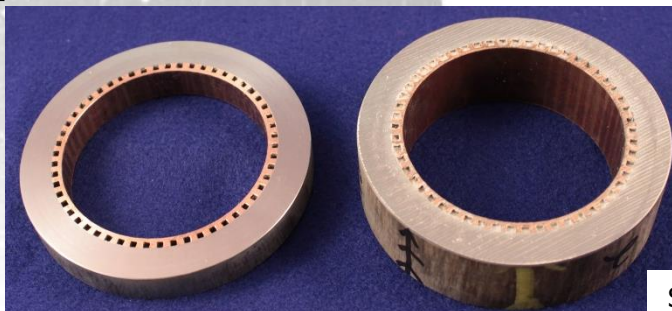
300 Series Stainless



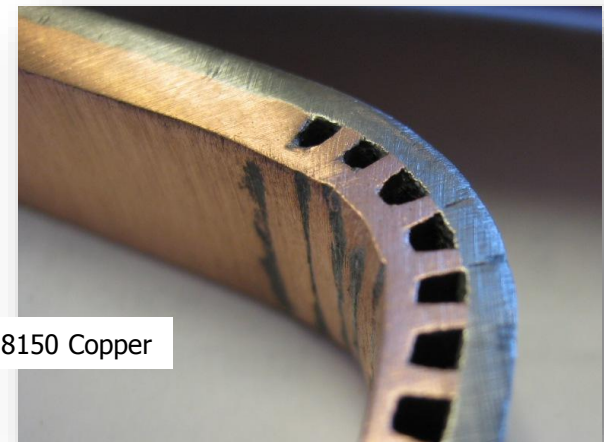


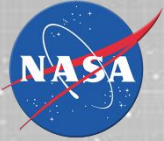
Explosive Bonding Closeouts

- 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-metallics offer significant advantages for removal
- Low cost tooling and explosive bonding operation compared to traditional techniques



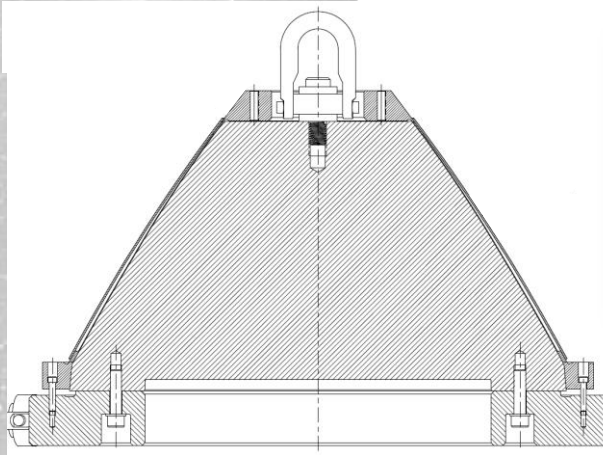
Stainless to C-18150 Copper





Explosive Bonding Closeouts

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



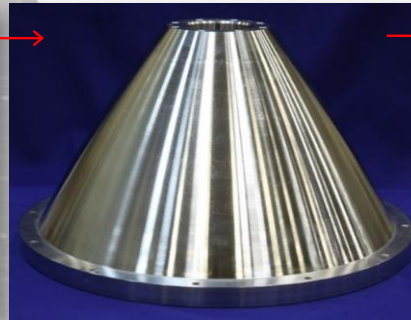
Closeout Shell



Final Explosive Bonded Assembly



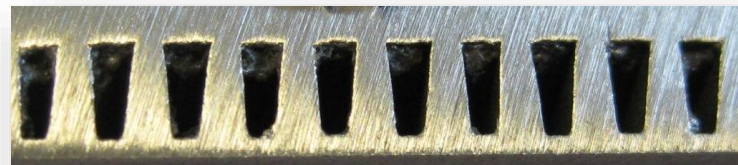
Freeform Deposition Liner

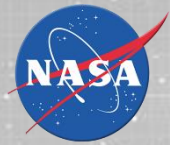


Final Machined Liner



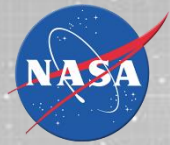
Water Jet Milled Channels





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



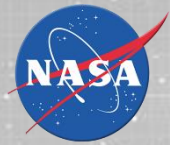
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- Judy Schneider / UAH
- Jeff Clouch
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- CDA Techs
- Brad Perkins
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Contact: Paul Gradl
NASA MSFC
256.544.2455
Paul.R.Gradl@nasa.gov

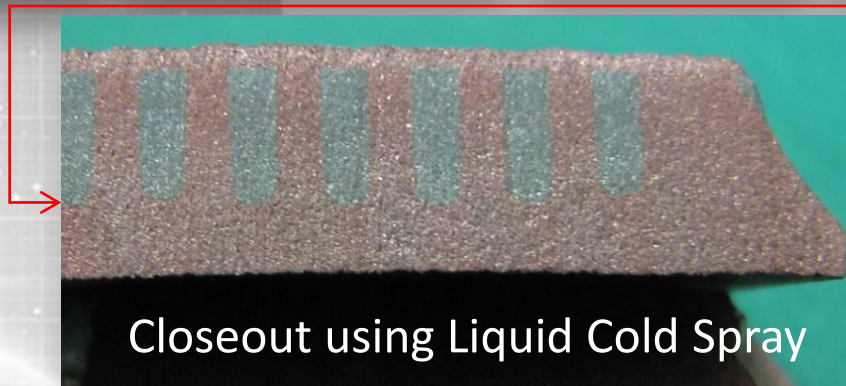
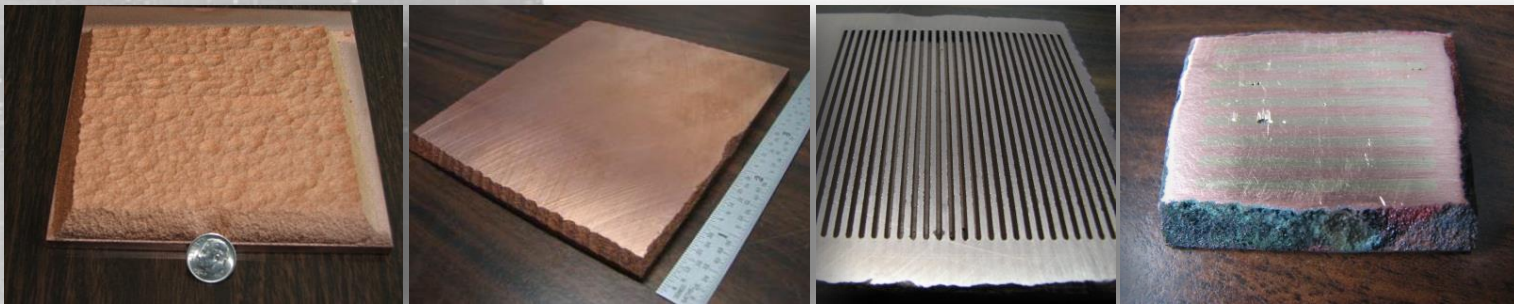
BACKUP

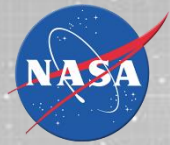


Liquid Cold Spray

- 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

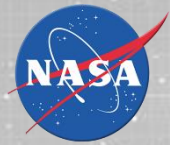
Rapid Build Up → Machine → Channel Milling → Filler Medium





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

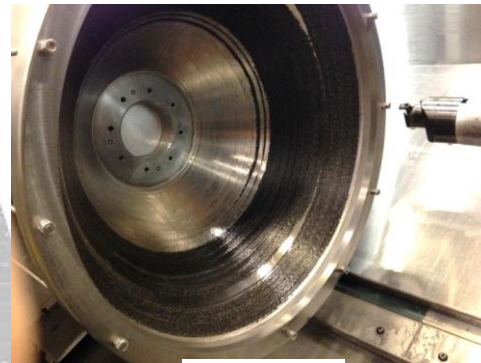


Predictive Machining Strategy using Scanning

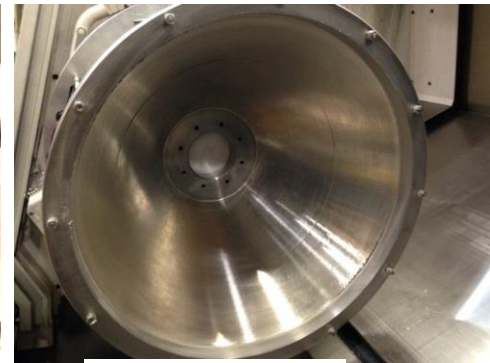
- Example of predictive machining strategy to understand cleanup of large scale additive manufacturing nozzle liner and use of scan data to determine setup on lathe
- Ref: Gradl, P.R. "Application of Optical Measurement Techniques during Fabrication and Testing of Liquid Rocket Nozzles." Paper presented at 62nd JANNAF Propulsion Meeting/8th Liquid Propulsion Subcommittee, June 1, 2015. Nashville, TN.



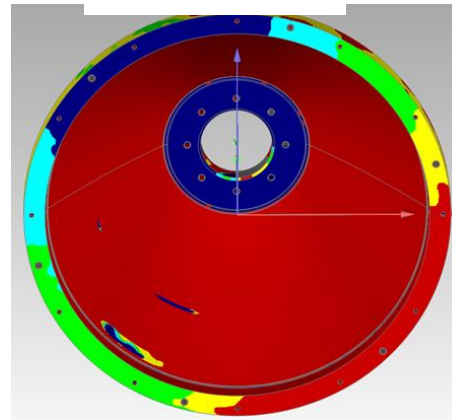
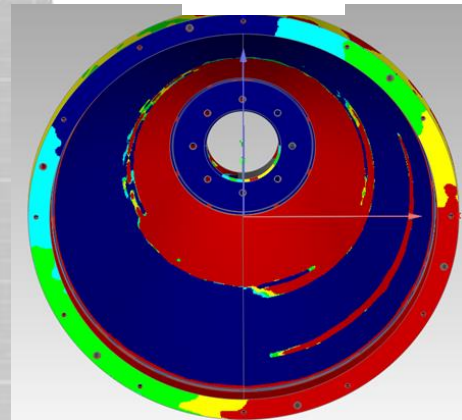
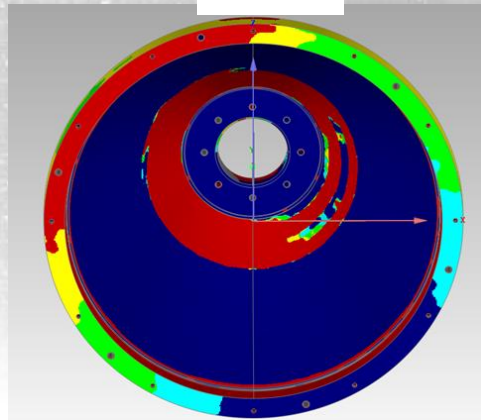
1st Pass



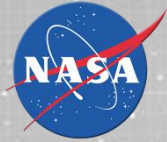
2nd Pass



Within 20 mils

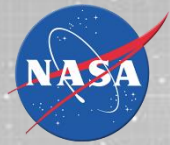


The plots on the bottom show structured light data and predictions for machining for visual references. The red on the ID contour is the area that is being removed for each pass – process used to help drive machining.



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