Channel Wall Nozzle Manufacturing and Hot-Fire Testing using a Laser Wire Direct Closeout Technique for Liquid Rocket Engines

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Motivation for Channel Wall Nozzle (CWN) Technology

- Channel wall nozzles have been evaluated as a cost savings technology for current and future missions for a variety of engine programs.
- NASA has evaluated and worked with vendors and contractors on fabrication of “traditional” large scale channel wall nozzles (CWN) on several programs over the last few decades.
- Recent CWN manufacturing technology has been limited based on minimal investments and scale to mature technology:
  - Current State of the art focused on brazing technology
  - GKN (formally Volvo) evolved the laser welded sandwich wall technology
  - Other domestic technology has limited public data available

Goal:
Evaluate alternate manufacturing techniques to reduce fabrication cycle (and subsequent costs) and improve performance for large scale channel wall nozzles.
What about using Selective Laser Melting for Nozzles?

Although new additive manufacturing machines are being introduced, current state of the art is limited in size...

**Engine**

- SSME/RS-25
- RL-10A-4
- J-2X, Regen Only
- RD-180

**Nozzle Exit Dia.**

- 90”
- 46”
- 70”
- 56”

Ref: Gradl, P.R., Brandsmeier, W. Alberts, D., Walker, B., Schneider, J.A. Manufacturing Process Developments for Large Scale Regeneratively-cooled Channel Wall Rocket Nozzles

Paper presented at 63nd JANNAF Propulsion Meeting/9th Liquid Propulsion Subcommittee, December 5-9, 2016. Phoenix, AZ.
Overview of Techniques

- 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

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

- 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

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

Deposition Techniques for Forming Liner
Directed Energy Deposition (DED)

Arc-based Deposition
Metal Direct Digital Manufacturing (MDDM)

- Provides high deposition rate (20+ lbs/hr) using wire-based arc welding techniques; near net shape deposition
Water Jet Milling

- Abrasive blind Water Jet Milling technique to form coolant channels (*akin to slotting*)
  - Low load technique, reduced wall thicknesses
  - Allows for easy milling of difficult materials in a variety of geometries
  - Current development to “mimic” features of slotting

- Ability to hold +/- 0.001” in subscale applications
- Rougher surface finish that traditional machining, but acceptable during hot-fire and flow testing

Traditionally Slotted, notice deformation of hotwall
Water Jet Milling, 25% thinner hotwall, no deformation
Closeout – Laser Wire Direct Closeout

- Laser Wire Direct Closeout (LWDC) is an additive technique that locally bonds a wire to the channel ribs and provides a structural jacket in place
  - Freeform welding process without need for filler
- Uses laser energy source and off-axis wire
- Complete bond at ribs and previously deposited layers
- No material “drop-thru” into channels
Closeout – Laser Wire Direct Closeout

- Demonstrated on a variety of materials including Inco 625, SS347, Bimetallic (Cu-Inco), Al-6061
- Allows for interim starts-stops and real-time inspection
# CWN Techniques Hot-fire Tested

<table>
<thead>
<tr>
<th>Nozzle #1</th>
<th>Nozzle #2</th>
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<tr>
<td><strong>CRES 347 Forging</strong></td>
<td><strong>Inconel 625 Arc-Deposited Liner</strong></td>
</tr>
<tr>
<td>Water Jet Milled Channels</td>
<td>Water Jet Milled Channels, Thin-wall</td>
</tr>
<tr>
<td>SS247 Laser Wire Direct Closeout (LWDC)</td>
<td>Inco 625 Laser Wire Direct Closeout (LWDC)</td>
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</tbody>
</table>
Fabrication Process for LWDC Nozzles

- Process for fabrication of Inco 625 Nozzle #2 shown
- Near net-shape deposition of liner and LWDC closeout significantly reduced machining required

1. Deposit Liner
   - Perform using Arc-Deposition
2. Solution Heat Treatment of Liner
3. Final Machine
   - IML and OML
   - Surfaces
4. Water Jet Milling of Channels

- Closeout of Channels
  - using Freeform Wire Laser Deposition
- Final Machine Forward and Aft Manifolds

- Deposition of Manifold Weld Lands
- Machine Weld
  - Preparations and Groove for Aft Channel Flow
- Electron Beam Welding of Manifolds
- Final Machining of Forward Interface
- Welding of Inlet and Outlet Ports
- Final Inspections and Proof Testing

Solution Heat Treatment of Liner

Deposit Liner

Perform using Arc-Deposition

Closeout of Channels

using Freeform Wire Laser Deposition

Deposition of Manifold Weld Lands

Machine Weld

Preparations and Groove for Aft Channel Flow

Electron Beam Welding of Manifolds

Final Machining of Forward Interface

Welding of Inlet and Outlet Ports

Final Inspections and Proof Testing
Nozzle #2 – Inco 625 LWDC

- Abrasive Water Jet Milling
- Liner Formed using Arc-Deposition Additive
- Traditionally machined manifolds
- Laser Wire Direct Closeout
CWN Supporting Test Hardware
All-Additive Thrust Chamber Assembly

Additive SLM Injector
GRCop-84 SLM Chamber
LWDC Nozzle

LOX/GH2
Hot-Fire Testing of LWDC and DED Nozzles

- Completed hot-fire testing at MSFC TS115, November 2017 (PH034)
- LOX/GH2, Pc=800 psig and MR = 5.6 – 6.7 (1,200-1,500 lb thrust)
- Completed 13 hot-fire tests

<table>
<thead>
<tr>
<th>Nozzle Identifier and Technique</th>
<th>Starts</th>
<th>Accumulated Time (seconds)</th>
</tr>
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<tbody>
<tr>
<td>Nozzle #1 - LWDC SS347</td>
<td>4</td>
<td>160</td>
</tr>
<tr>
<td>Nozzle #2 - LWDC Inco 625, Fully AM</td>
<td>9</td>
<td>880</td>
</tr>
</tbody>
</table>

Nozzle #1 - SS347

Nozzle #2 - Inco 625, Fully Additive
Results of Hot-fire Testing

✔ No issues observed with arc-based deposited liner, material behaved as-expected at elevated temperatures and strain ranges
✔ Pressure-drop measured during hot-fire testing using water jet milled channels met predictions
✔ LWDC closeout performed as-expected during startup and steady state hot-fire loads

Nozzle #2, LWDC with Arc-based Additive Liner
Video of Hot-Fire Test
Conclusions

• New manufacturing technologies have been developed and advanced for use in channel wall nozzle applications
  – Deposition techniques offer alternatives for rapid forming liners
    • Material properties confirmed in mechanical test and hot-fire
  – Water Jet Milling offers an alternative to slotting for difficult to machine materials
    • Met pressure drop expectations
  – Laser Wire Direct Closeout (LWDC) offers a new method for closeout of nozzle and chambers
    • Demonstrated subscale hardware and process for fabrication
• NASA is continuing to invest in these technologies through Project Funding, IRAD, Space Act Agreements, SBIR/STTR programs and fabricating larger-scale hardware for testing
• The process is continued to be scaled up and hardware being developed
• Alternate materials being investigated including bimetallic hardware
• Data on techniques and vendors available to industry
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