Metal Matrix Composite LOX Turbopump Housing Via Novel Tool-Less Net-Shape Pressure Infiltration Casting Technology

AMPET 2002
Huntsville, AL 35812

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WHY METAL MATRIX COMPOSITE FOR PROPULSION COMPONENTS

- **PERFORMANCE**
  - High Specific Strength & Specific Stiffness = Weight Savings
  - Compatibility With H₂ and O₂ -- Better Than PMC/CMC
  - Low Thermal Coefficient of Expansion
  - Higher Electrical & Thermal Conductivity than PMC
  - Ductility & Toughness From Metal Matrix
  - Particulate MMC’s behavior More Like Metallic Alloys

- **AFFORDABILITY**
  - Complex Parts Can be Produced by Low Cost Casting
  - MMC Cost per Pound Comparatively Less Than PMC/CMC
  - Many Commercial & DoD Applications Now in Service
METAL MATRIX COMPOSITE TURBOPUMP HOUSING
JOINT REDESIGN EFFORT

- Metal Matrix Cast Composites, Inc.,
  - Phase II SBIR Award
  - Develop Materials And Manufacturing Process.
  - Cast 3 Full Scale “Redesigned” “Hybrid” Al MMC LOX Compatible Turbopump Housings

- NASA MSFC Space Transportation Team
  - Internal NRA Award
  - Re-analyze and Re-design Al MMC Pump Housing

- NASA To Provide New Pump Housing Design To MMCC. Inc.

Redesign Objectives – 40% weight Savings
BASELINE PUMP DESIGN AND ANALYSIS
BASELINE PUMP HOUSING DESIGN AND STRESS ANALYSIS

Discharge Flange (EO1)
IP/Lox Interface
Cutwater
Volute
Inlet Flange (ME1)
BASELINE PUMP HOUSING DESIGN AND STRESS ANALYSIS - Continued

Material: Microcast Inconel 718

E = 29.6 Msi, ν = 0.29, d = 0.297 pci UTS = 140 Ksi, YS = 110 Ksi

Safety Factor: 1.4 on UTS

PEAK STRESSES IN CUTWATER LOCATION

Baseline Deformation Plot

Baseline Stress Plot
TOOL-LESS ADVANCED PRESSURE INFILTRATION CASTING PROCESS
TOOL-LESS ADVANCED PRESSURE INFILTRATION CASTING PROCESS

VACUUM ATMOSPHERE

Molten Alloy

Preform

Tooling

Pressure

MMC

Header containing reservoir of molten alloy

Pre heated-pre evacuated mold vessel containing preforms

Autoclave for pressure infiltration

Two cubic foot casting being transferred to autoclave for pressure infiltration and directional solidification
TOOL-LESS ADVANCED PRESSURE INFILTRATION
CASTING PROCESS: 3 Dimensional Printing (3DP) of Ceramic Preform

Novel 3D-Printing Technology

Advantages: From CAD file to preform with no tools; uniform defect-free preform

MMCC, Inc. 101 Clematis Ave Waltham, MA www.mmccinc.com
TOOL-LESS ADVANCED PRESSURE INFILTRATION
CASTING PROCESS: Tool-Less Mold Process

3DP + ToolLess™ Mold = Breakthrough

MMCC, Inc. 101 Clematis Ave Waltham, MA www.mmccinc.com
TOOL-LESS ADVANCED PRESSURE INFILTRATION CASTING PROCESS: Mechanical Properties and Microstructure Optimization

- **3DP Ceramic Reinforcement particle Size and Volume used**

<table>
<thead>
<tr>
<th>Reinforcement Type</th>
<th>Particulate Size</th>
<th>Particulate Vf in final MMC Composite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al2O3</td>
<td>(17 + 20% of 2.7) micron</td>
<td>35 - 38 %</td>
</tr>
<tr>
<td>Al2O3</td>
<td>17 micron</td>
<td>37 - 41 %</td>
</tr>
<tr>
<td>SiC</td>
<td>(17 + 20% of 2.7) micron</td>
<td>31 - 35 %</td>
</tr>
</tbody>
</table>

- **Typical microstructure of 3DP composite:**
  - isotropic in X-Y plane, anisotropic in X-Z plane
3DP sintered alumina Al alloy composites: Strength, toughness vs alloy composition and particle size
SUBSCALE PUMP HOUSING: Pressure Infiltration Casting Demonstration
PREFORM SPLICING AND JOINING FOR LARGE COMPONENTS SUCH AS PUMP HOUSING
## 3DP- Al₂O₃ Particulate Preform Joining Study- Conclusions:

1. Tensile properties relatively insensitive to joint design
2. Components can be printed as parts and joined after sintering
3. These results lead to processing flexibility

### Joint type

<table>
<thead>
<tr>
<th>Joint type</th>
<th>Sintered</th>
<th>UTS</th>
<th>Std. Dev. Sintering</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Connection</td>
<td>UTS</td>
<td>Std. Dev.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ksi</td>
<td>mPa</td>
</tr>
<tr>
<td># 1) Butt</td>
<td>yes</td>
<td>53.4</td>
<td>368</td>
</tr>
<tr>
<td></td>
<td>no</td>
<td>59.0</td>
<td>406.8</td>
</tr>
<tr>
<td># 2) V-Joint</td>
<td>yes</td>
<td>62.1</td>
<td>428.1</td>
</tr>
<tr>
<td></td>
<td>no</td>
<td>56.6</td>
<td>390.5</td>
</tr>
<tr>
<td></td>
<td>no</td>
<td>51.1</td>
<td>352</td>
</tr>
<tr>
<td># 3) 45 Degree</td>
<td>yes</td>
<td>67.9</td>
<td>468.4</td>
</tr>
<tr>
<td></td>
<td>yes</td>
<td>57.0</td>
<td>392.8</td>
</tr>
<tr>
<td></td>
<td>no</td>
<td>62.6</td>
<td>431.6</td>
</tr>
<tr>
<td></td>
<td>no</td>
<td>62.1</td>
<td>428.1</td>
</tr>
<tr>
<td>#4) Tongue &amp; Grove</td>
<td>yes</td>
<td>55.6</td>
<td>383.0</td>
</tr>
<tr>
<td></td>
<td>no</td>
<td>64.5</td>
<td>444.8</td>
</tr>
<tr>
<td></td>
<td>no</td>
<td>59.4</td>
<td>409.4</td>
</tr>
</tbody>
</table>

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### 3D Printing is Limited in Size

Requiring splicing and joining of large part preforms.

1. 3DP Print Preforms
2. Join Preforms
3. Sinter Together
4. Infiltrate
5. Heat Treat
6. Tensile Test Coupon

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### 3D Printing Process Flow

1. 3DP Print Preforms
2. Join Preforms
3. Sinter Together
4. Infiltrate
5. Heat Treat
6. Tensile Test Coupon
FULLSCALE PUMP HOUSING REDESIGN
Objective: Redesign the pump housing to reduce the maximum stress yet keeping the 40% weight savings.

Full Scale Manufacturing

Positive Margin in Design
FULLSCALE PUMP HOUSING REDESIGN - Manufacturing Design Options Considered

Hybrid: Wrap fibers around volute in cutwater area
   Alloy not suitable for hybrid reinforcement
   manufacturing complexity

Inconel718 insert in cutwater area
   Manufacturing complexity
   Cost and Schedule

Al particulate MMC with gussets in volute
   Selected for Manufacturing Demonstration

Hybrid: Sic Fiber stiffened gussets in volute
   Cracking in Fiber/particulate interface in subscale specimen. Need to match CTE.
FULLSCALE PUMP HOUSING REDESIGN - FEM Analysis

FEM Analysis Particulate Al MMC Properties Used:  Linear Isotropic Material

\[ E = 22 \text{ Msi}, \quad UTS = 58\text{Ksi}, \quad YS = 50\text{Ksi}, \quad \nu = 0.3, \quad \delta = 0.111 \text{ pci}, \]

Factor of Safety = 2.0 on UTS  
Allowable Max Stress = 29 Ksi

Margin of Safety = (actual safety factor/required safety factor) – 1

<table>
<thead>
<tr>
<th>AI Particulate MMC Design Options Analyzed</th>
<th>Weight Lbs</th>
<th>Margin of Safety ***</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline - Inconel 718</td>
<td>25.95</td>
<td>0.0</td>
</tr>
<tr>
<td>Baseline - MMC</td>
<td>9.70</td>
<td>-0.606</td>
</tr>
<tr>
<td>Baseline + Thicker Volute</td>
<td>10.71</td>
<td>-0.518</td>
</tr>
<tr>
<td>Baseline + Thicker Volute + Larger Cutwater Radius</td>
<td>10.70</td>
<td>-0.471</td>
</tr>
<tr>
<td>Baseline + 3 Radial Gussets Added to Volute</td>
<td>10.56</td>
<td>-0.455</td>
</tr>
<tr>
<td>Baseline + Deeper Radial Gussets, Larger Cutwater Radius</td>
<td>10.84</td>
<td>-0.372</td>
</tr>
<tr>
<td>Baseline + 4-ply SiC Fiber Reinforced Gussets</td>
<td>10.84</td>
<td>-0.371</td>
</tr>
</tbody>
</table>

*** MOS using a Factor of Safety = 2.0 and not 1.4
FULLSCALE PUMP HOUSING PREFORM - Spliced, Joined and Sintered Preform

Housing after sintering but prior to application of Soft-Shell™ Tool-Less Mold compound-

(Note stainless steel threaded inserts in bolt circle)
FULLSCALE PUMP HOUSING - Casting

- Inserts for threaded mechanical joint
- Holes for Bolted Joints
FULLSCALE PUMP HOUSING –
Lessons Learned

- Alloy composition needs further development for a hybrid design.

- Cracking at SiC fiber/particulate interface.

- 3 Dimensional printing of large preform sections resulted in sagging and loss of dimensional control of the preform.

- Obtaining surface finish with tool-less mold process needs more development. Surface finish is determined by perform technology, not by tool-less mold technology.
SUGGESTED FUTURE DEVELOPMENTS

- For 100% particulate housing, the alloy can be optimized to produce higher strength MMC.
- Sagging can be avoided by printing thinner sections of 3DP preforms. Subsequently, preform joining technique can be used to obtain a complete part.
- Preform volume fraction limited to ~35-40%. Slurry/slip casting, an alternative to 3DP preforms can raise the volume fraction to 55%.
- Surface finish of MMC component is totally dependent upon surface of preform. Improve the surface of the preform prior to casting.
- CTE differences between SiC fibers and particulate composite that leads to cracking at fiber interface could be avoided or reduced by using Nextel fibers.