Impact of Surface Finishing/Texture on Low and High Cycle Fatigue Performance of L-PBF GRCop-42

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1. REM Surface Engineering
2. NASA – Marshall Space Flight Center (MSFC)
REM: Who We Are

• Experts in Isotropic Superfinishing
• Founded in 1965
• Family owned and operated
• 63 Employees

• Locations:
  – Southington, CT, USA
  – Brenham, TX, USA
  – Merrillville, IN, USA
  – St. Neots, Cambridgeshire, UK

REM: What We Do

PROCESS INSTALLATION

Install REM’s Technology at Your Facility
- Work with REM to specify the right equipment solution for your needs
- REM installs the equipment at your facility and provides the initial process setup and training
- REM provides ongoing supply of process consumables and tooling

Process Design

Process Equipment

Process Consumables

Process Support
REM: Outsourced Processing

Outsourced Processing Expertise

Utilize REM's Outsourced Processing Capabilities
- Send your pre-production or production parts to REM
- REM's expert technicians process your components
- Available as an ongoing production solution or a bridge to installation
**REM: AM => The Challenges of Implementation**

- Component failure due to complex surface conditions
  - Partially sintered/melted powders
  - High surface roughness
  - Significant surface waviness
  - Surface and near surface defects/porosity

- No prior/existing surface finishing technology could adequately remediate all above surface condition defects while maintaining component integrity and geometry
  - Traditional machining/abrasive methods are less effective on new surfaces/alloys and complex geometries/limited by line of sight access
  - Traditional chemically accelerated mechanical finishing methods are less effective due to new superalloys/chemical resistance
Effects of Surface/Near Surface Defects

- Particle shedding/cleanliness
- Reduced dynamic fatigue life
- Reduced corrosion resistance
- Problematic thermal concentrations
- Increased pressure drop/poor flow properties
Can be used individually or in combination

**Chemical Polishing Characteristics:**
- “Fast” (removes ~0.001”/25 µm every 1 – 10 minutes)
- Removes all loose and partially melted/sintered powder
- Can remove/aid in the removal of supports
- Can polishing long/narrow channels and lattices

**Chemical Mechanical Polishing Characteristics:**
- “Gentle” (removes ~0.001”/25 µm every 1 – 10 hours)
- Planarizes (flattens) the surface
- Maintains existing geometry
- Can produce a bright or matte finish as desired
REM: The Extreme ISF® Process

– Suite of chemical & chemical-mechanical process technologies
  • Compatible with complex geometries
  • Removes all surface & near surface defects
  • Increases part cleanliness & performance
  • Increases dynamic/bending fatigue performance

– Generates isotropic surface textures

– Applicable AM build styles:
  • E-PBF/EBM
  • L-PBF
  • Binder Jet
  • Metal FDM/FFF
  • DED
Alloy Experience

- Titanium Alloys
  - Examples: Ti 6Al - 4V, CP Ti

- Stainless Steel Alloys
  - Examples: 17-4 PH, 15-5 PH, 316/316L

- Carbon Steel Alloys
  - Examples: SAE 4140, SAE 4340, 16MnCr5, Ferrium® C64

- Maraging and Tool Steels
  - Examples: A2, L40, M300, H13

- Copper Alloys
  - Examples: GrCOP-42, GrCOP-84, CP Cu

- Nickel-Chrome Superalloys
  - Examples: IN-718, IN-625, HX

- Iron-Nickel Superalloys
  - Examples: JBK-75, NASA HR-1

- Nickel Alloys
  - Examples: Invar 36, Permalloy, Moly Permalloys

- Aluminum Alloys
  - Examples: AlSi10Mg, AS7, F357 Scalmalloy®, A6061 RAM2, A205/A20X
Extreme ISF® Process: Benefits

- Remove Support Structures
  - Weaken and/or dissolve supports

- Remove Powder
  - From channels, lattices, etc.

- Reduce Roughness/Waviness
  - Eliminate granular surface texture
  - Flatten as-printed surface texture

- Remove Oxide Layers
  - From HIP and other heat treatments

- Controlled wall thickness reduction
  - For thermal properties, weight reduction, etc.

- Increase Tensile Strength
  - Improve thin-wall tensile strength behavior

- Increase Fatigue Life
  - Eliminate surface initiation sites & near surface defects

- Improve Flow
  - Reduce turbulence and pressure drop from surface texture

- Increase Corrosion Resistance
  - Remove surface initiation sites & increase passivation

- Improve Part Cleanliness
  - For industrial, aerospace/space, and biomedical applications

EP and Chem Milled was performed by a third party
Relevant Examples

Project, Awards, Applications
REM: NASA LLAMA Program

- Surface Finishing of NTA by the Extreme ISF® Process: Combustion Chambers GRCop-42 and GRCop-84

GRCop-42 is a high conductivity, high-strength dispersion strengthened copper-alloy for use in high heat flux applications such as liquid rocket engine combustion devices.

GRCop-84 is a copper-based alloy with excellent elevated temperature strength, good creep resistance, long low-cycle fatigue (LCF) lives and enhanced oxidation resistance.

<table>
<thead>
<tr>
<th>Element</th>
<th>GRCop-42 Wt %</th>
<th>GRCop-84 Wt %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cr</td>
<td>3.1 – 3.4</td>
<td>6.2 – 6.8</td>
</tr>
<tr>
<td>Nb</td>
<td>2.7 – 3.0</td>
<td>5.4 – 6.0</td>
</tr>
<tr>
<td>Fe</td>
<td>Target &lt;50 ppm</td>
<td>Target &lt;50 ppm</td>
</tr>
<tr>
<td>O</td>
<td>Target &lt;400 ppm</td>
<td>Target &lt;400 ppm</td>
</tr>
<tr>
<td>Al</td>
<td>&lt;50 ppm</td>
<td>&lt;50 ppm</td>
</tr>
<tr>
<td>Si</td>
<td>&lt;50 ppm</td>
<td>&lt;50 ppm</td>
</tr>
<tr>
<td>Cu</td>
<td>Balance</td>
<td>Balance</td>
</tr>
</tbody>
</table>

Cr:Nb Ratio: 1.12 – 1.15

REM: NASA & Commercial Space

– NASA MSFC RAMPT Project Team Member

• Nozzles & Combustion Chambers
  – Hotwall thickness reduction
  – Hotwall roughness reduction
  – Cooling channel roughness reduction

• Alloys: IN-625, JBK-75, NASA HR-1, GrCOP-42, GrCOP-84

Hot fire testing of REM processed Thrust Chamber Assembly (7K LLAMA)
Images courtesy of NASA MSFC
Surface Finishing of NTA by the Extreme ISF® Process: Combustion Chambers

Case study: GrCop-42 and GrCop-84

Additively Manufactured L-PBF of GrCop-42 Liners in its as-print condition.*

GrCop-42 Surface Finished by Extreme ISF®

GrCop-42 and GrCop-84 Surface Finished by Extreme ISF®

REM: GRCop-42 As-Built Surfaces

- Partially Closed Internal Channels
- HIP Oxide Layer
- Highly Granular Surface
REM: GRCop-42 Chemical Polishing

<table>
<thead>
<tr>
<th>SMR (µm)</th>
<th>Ra (µm)</th>
<th>Sa (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>18</td>
<td>11</td>
</tr>
<tr>
<td>140</td>
<td>8.0</td>
<td>6.0</td>
</tr>
<tr>
<td>225</td>
<td>3.9</td>
<td>1.6</td>
</tr>
<tr>
<td>275</td>
<td>1.3</td>
<td>1.4</td>
</tr>
<tr>
<td>375</td>
<td>1.3</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Graph showing Ra and Sa values against SMR (µm).
REM: GRCop-42 Chemical Mechanical Polishing

SMR = 0
Ra = 18 µm
Sa = 17 µm

SMR = 112 µm
Ra = 8.0 µm
Sa = 8.5 µm

SMR = 150 µm
Ra = 6.0 µm
Sa = 5.0 µm

SMR = 285 µm
Ra = 2.7 µm
Sa = 1.4 µm

SMR = 467 µm
Ra = 0.8 µm
Sa = 0.9 µm

Graph showing the relationship between SMR (µm) and Ra/Sa (µm)
REM: GRCop-42 CP + CMP

Ra/Sa (µm)

CP |

CMP

SMR (µm)

Ra

Sa
REM: Combustion Chamber Testing

– NASA MSFC Combustion Chamber Testing

• Cooling Channel Pressure Drop Testing
  – As-Built vs. REM Processed 1.2K Chamber
    » 75 µm Surface Material Removal from cooling channels → 71% Pressure Drop Reduction

• Heat Load Testing
  – As-Built vs. REM Processed 1.2K Chamber
    » 75 µm Surface Material Removal from Hot Wall → 28% Reduction in Total Heat Load

There was significant variation on the LCF results at room temperature.

Polished samples seem to improved fatigue life compared to as-built and machined samples.

However, there was not statistically significant differences \((p < 0.05)\) between any of the sample.
There was significant variation on the LCF results at different temperatures for the polished specimens.

However, the polished samples show a trend of having a higher fatigue life from -196 °C to 200 °C before decreasing up to 800 °C.
Conclusions

• Additively Manufactured new non-standard alloys are being employed in the space industry to meet the extreme specifications and environments for space exploration.

• The surface finishing of metal additively manufactured components is possible with a two step process involving chemical polishing followed by chemical mechanical polishing, obtaining Ra values under 0.5 µm on exterior, interior, and internal surfaces.

• A 75 µm of surface material removal from internal of a 1.2K combustion chamber cooling channels caused a 71% pressure drop reduction and 28% reduction in total heat load.

• The LCF experiments suggest a trend of better performance for the surface finished experiment, but due to the significant spreading of the data no statistically relevant conclusions could be achieved.
**REM: SBIR Acknowledgements**

**Phase I**
- “Internal/External Surface Finishing of Additively Manufactured IN-625” (80NSSC18P2192)

**Phase II & Phase II-E**:  
- “Post-Process Optimizing of Additive-Manufactured Nickel-Based Superalloys” (80NSSC19C0211)

**Phase III**:  
- “Surface Enhancement using ISF of Additively Manufactured Hardware” (80NSSC20C0080)

* Denotes currently active SBIR’s

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**AFWERX, OO-ALC, AFLCMC/EBW**

**Phase I**:  
- “Internal/External Surface Finishing of Additively Manufactured Aluminum-6061-RAM2 Components” (FA864920P0930)

**Phase I**:  
- “Internal Channel Polishing for GRCop-42 Additively Manufactured Regeneratively Cooled Liquid Rocket Engine Applications” (FA864922P0396)

**Phase II**:  
- “Internal/External Surface Finishing of Additively Manufactured Aluminum-Based Components” (FA864921P0815)

**Phase II (direct)**:  

**Phase II (direct)**:  
- Additively Manufactured Heat Exchanger and Channel Fabrication Optimization via Chemical Powder Blockage Removal, Surface Roughness Reduction, and Wall Thickness Optimization/Component Lightweighting (FA864922P0969)
REM: Relevant Publications


Questions???

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REM: GRCop-42 Chemical Polishing
REM: GRCop-42 Chemical Mechanical Polishing

The graph illustrates the relationship between Ra/Sa (µm) and SMR (µm). Points on the graph represent the experimental data for Ra and Sa, with error bars indicating the variability. The dotted lines with exponents indicate the theoretical curves for Ra and Sa, showing how theoretical predictions align with the experimental data.
REM: Combustion Chamber Testing

- GRCop-42 L-PBF Channel Specimens
  - Optimize CP formulation developed
  - Complete HIP oxide layer removal
  - Significant roughness reduction

AF SBIR Phase 1: “Internal Channel Polishing for GRCop-42 Additively Manufactured Regeneratively Cooled Liquid Rocket Engine Applications” (FA864922P0396)
Case study: CuCrZr

Copper alloy CuCrZr has a favorable combination of electrical and thermal conductivity accompanied with good mechanical properties. This alloy reaches its good properties during heat treatment.

AMCM M 4K-4

Large scale, high productivity system for demanding AM applications. 1 meter building height with up to $4 \times 1.000$ W laser power.

Credits: Launcher and AMCM

https://amcm.com/machines/amcm-m4k