Qualification Testing of Electroformed Nanostructured Cobalt-Alloy Bushings

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Project Team

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Problem Statement

The Benefits of Copper Beryllium
- Copper-Beryllium (CuBe) is the hardest and strongest of any copper alloy and is a preferred high-strength bushing material, used in many aerospace applications, due to its high strength and excellent wear properties (low friction, high galling resistance).
- Other advantageous properties include: non-sparking, nonmagnetic, good high temperature and corrosion resistance.

The Drawbacks of Copper Beryllium
- Exposure to Be results in a range of diseases including lung cancer and Chronic Beryllium Disease (CBD).
- EPA classifies Beryllium powder as a hazardous waste material (40 CFR Section 261.33).
- DoD employees are exposed to Be dust and fumes as a result of the wearing of Be-containing alloys during operation and during machining and other fabrication operations. The manufacturing process for CuBe bushing also results in a large amount of hazardous waste material being generated.

A less environmentally hazardous alternative is needed.
Alternative to Cu-Be Bushings

- Nanovate, a nanostructured electroformed Cobalt alloy, exhibits favorable properties as an alternative bushing material.
Alternative to Cu-Be Bushings

- Suitable for fabrication of large diameter bushings
Nanostructured Materials

Hall-Petch relation describes increase in strength of metals with decreasing grain size. Grain boundaries act as pinning points impeding further dislocation propagation.

### Decreasing Grain Size Dramatically Improves Hardness and Strength

<table>
<thead>
<tr>
<th>Property</th>
<th>Units</th>
<th>Conventional Ni (20 um)</th>
<th>Nanovate Ni (100 nm)</th>
<th>Nanovate Ni (10 nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield Strength</td>
<td>MPa</td>
<td>100</td>
<td>700</td>
<td>900</td>
</tr>
<tr>
<td>Ult. Tensile Strength</td>
<td>MPa</td>
<td>400</td>
<td>850</td>
<td>1400</td>
</tr>
<tr>
<td>Vickers Hardness</td>
<td>kg/mm²</td>
<td>140</td>
<td>320</td>
<td>450</td>
</tr>
</tbody>
</table>
Pulse Plating favors nucleation of new grains over growth of existing grains, resulting in an ultra-fine grain structure throughout the entire thickness of the material deposit.

Pulsed Electrodeposition from Aqueous solutions results in the deposition of fully dense metal with a nanocrystalline grain size. At no point in the fabrication process are nanosized powders produced.
Technology Maturity

- Nanocrystalline plating technology is a fairly well established technology.
- A successful Dem/Val for Nano-CoP as a hard chrome alternative was completed.
- Pulse plating tanks are in place at Integran and at FRC-SE.
- Electroforming process represents an extension of this technology.

- 650 gallon plating tank at Integran
- 250 gallon tank at FRC-SE
Technology Maturity

- In SERDP WP-2137, Integran demonstrated that nanostructured Cobalt-based alloys had material properties that made them ideal for bushing applications.
- Two distinct electroformed alloys were developed that showed promise as replacement bushing materials: a nano Co-P alloy and pure nano-Cobalt.
- Compression and ultimate tensile strength of the nano-Co materials exceeds that of conventional bushing materials.

These Nanostructured alloys are formed using advanced electroforming techniques. The process allows for near net shape formation of such alloys. No nanopowder material is produced in the process, thus avoiding the associated hazards to personnel with handling such materials.
Comparison of Bushing Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Compression Strength ksi (MPa)</th>
<th>Yield Strength (Tensile) ksi (MPa)</th>
<th>Ultimate Tensile Strength ksi (MPa)</th>
<th>Modulus of Elasticity (Tensile) GPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nanostructured Cobalt Alloy</td>
<td>285 ksi (1967 MPa)</td>
<td>225 ksi (1550 MPa)</td>
<td>290 ksi (2000 MPa)</td>
<td>18855 ksi (130 GPa)</td>
</tr>
<tr>
<td>Nanostructured Pure Cobalt</td>
<td>222 ksi (1533 MPa)</td>
<td>147 ksi (1016 MPa)</td>
<td>242 ksi (1670 MPa)</td>
<td>18420 ksi (127 GPa)</td>
</tr>
<tr>
<td>Copper Beryllium (C17200-TH04)</td>
<td>142 ksi (973 MPa)</td>
<td>172 ksi (1185 MPa)</td>
<td>190 ksi (1310 MPa)</td>
<td>18855 ksi (130 GPa)</td>
</tr>
<tr>
<td>Nickel Aluminum Bronze (C63000)</td>
<td>110 ksi (760 MPa)</td>
<td>68 ksi (470 MPa)</td>
<td>110 ksi (760 MPa)</td>
<td>16700 ksi (115 GPa)</td>
</tr>
<tr>
<td>15-5PH Stainless (SS15500 H900)</td>
<td>N/A</td>
<td>185 ksi (1275 MPa)</td>
<td>200 ksi (1380 MPa)</td>
<td>29000 ksi (200 GPa)</td>
</tr>
<tr>
<td>Toughmet T3 AT120</td>
<td>N/A</td>
<td>120 ksi (827 MPa)</td>
<td>135 ksi (931 MPa)</td>
<td>18500 ksi (128 GPa)</td>
</tr>
<tr>
<td>Nitronic 60 (level 5 CW)</td>
<td>N/A</td>
<td>180 ksi (1241 MPa)</td>
<td>200 ksi (1379 MPa)</td>
<td>26000 ksi (179 GPa)</td>
</tr>
<tr>
<td>BioDur CCM</td>
<td>N/A</td>
<td>135 ksi (930 MPa)</td>
<td>190 ksi (1310 MPa)</td>
<td>N/A</td>
</tr>
</tbody>
</table>
Mechanical Strength in Tension

- Uniaxial Tension Testing (ASTM E8)

Tensile performance of Integran’s Nanovate cobalt-based and nickel-cobalt metals is superior to copper beryllium (peak hardness);
Pin-on-Disk Sliding Wear Testing (ASTM G99)

- Pin-on-disk testing indicated that the nanostructured cobalt alloys have a low coefficient of friction.

<table>
<thead>
<tr>
<th>Bushing /Mating Material</th>
<th>Hard Chrome coated HSS</th>
<th>HVOF (CoCr-WC) coated HSS</th>
<th>Nano Cobalt coated HSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nanostructured Cobalt Alloy</td>
<td>0.42</td>
<td>0.46</td>
<td>0.36</td>
</tr>
<tr>
<td>Copper Beryllium (C17200-TH04)</td>
<td>0.73</td>
<td>N/A</td>
<td>0.65</td>
</tr>
<tr>
<td>Nickel Aluminum Bronze (C63000)</td>
<td>0.48</td>
<td>0.45</td>
<td>0.45</td>
</tr>
</tbody>
</table>

*COF obtained from Pin-on-disk testing per ASTM G99
Subscale Bushing Testing

- Sub-scale bushing tests were performed on various nano Cobalt-alloy bushings using MIL-B-81820 (LHM-010)
- Test involves applying a normal load to the bushing ID / pin OD interface and rotating through ±25° steady rotation while under load.

Sub-scale Bushing Testing

- Nano-Co alloy bushings performed well:
  - Excellent alloy strength; Low bushing noise; Low bushing temperature increase (10,000lbs = ~50ksi bearing stress)

- Nano-Co alloy bushings exhibit minimal deformation
  - Less than 0.001” wear and no measurable wall flattening
Sub-scale Bushing Testing

Nanovate bushings perform favorably to CuBe

CuBe bushing
MP 35N Pin
1,725 cycles total
125 cycles at 10,000 lbs

Nano Co Alloy bushing
440C Pin
2,000 cycles total
400 cycles at 10,000 lbs
Galvanic Compatibility

- Nano-Co alloys have better galvanic compatibility with typical aluminum aircraft alloys than stainless steel alternatives
  - Expected to result in less galvanic corrosion - fewer maintenance issues

![Graph showing galvanic current measurements](image)
Technical Approach

Current Program is a three year effort with Integran and NAVAIR as the primary performers

Five primary tasks:

1. Manufacturing Process Definition / Demonstration
2. Property and Performance Testing
3. Depot Evaluation and Insertion
4. Cost and Environmental Analysis
5. Material Qualification
Technical Approach

Several factors remain to be fully investigated in order to bring the technology into depot and OEM production:

- Determine optimal process conditions for volume manufacturing of Alloy blanks
- Develop test protocol and perform detailed testing of alloys
- Transfer of electroforming process to the depot environment
- Investigate machinability of alloys in depot environment
- Generate demonstration / validation test parts and articles
- Field testing of Dem/Val Components
Manufacturing Process Definition / Demonstration

- Scale-up and optimize the electroforming process for the nano-Co alloy blanks
  a) cost-effectively manufacture the material
  b) optimize the process for volume manufacturing, and
  c) verify the process through multiple lots of material
    • *New dedicated tank being stood up at Integran*

- Identify/design a suitable permanent/re-useable mandrel for electroforming
  • *Designs being evaluated*

- Assess the effect of various heat-treatments on the bulk structural properties of the electroformed material nano CoP and pure nano Cobalt
**Manufacturing Process Definition / Demonstration**

- Near Net Shape Manufacturing Process with high ‘buy-to-fly’ ratio
- Cost effective due to less material waste during machining

<table>
<thead>
<tr>
<th><strong>Step 1</strong> - Electroform desired thickness onto temporary mandrel</th>
<th><strong>Step 2</strong> - Remove mandrel</th>
<th><strong>Step 3</strong> - Machine Bushings</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Step 1 Diagram" /></td>
<td><img src="image2" alt="Step 2 Diagram" /></td>
<td><img src="image3" alt="Step 3 Diagram" /></td>
</tr>
</tbody>
</table>

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Property and Performance Testing

- Currently developing Joint Test Protocol, to include:
  1. Bulk mechanical property testing in compression and tension
  2. Galvanic corrosion compatibility
  3. Wear testing
  4. Subscale Bushing Testing

- Testing will be performed at Integran, NAVAIR (PAX and FRC-SE) and at independent test laboratories
Dem/Val Component: Bushings for T-45 Arresting Tail Hook

- T-45 Goshawk and F/A18 Hornet/Super Hornet FST Engineering Offices have indicated interest in evaluating the new materials
  - First Dem/Val will be with the T-45
Dem/Val Components

- Integran to supply FRC-SE with blank material in order to evaluate the machinability and to prepare prototype bushings for Dem/Val work

- Suitable NDI techniques for assessing any defects that might be present in the electroformed bushing blanks

- Installation trials to be performed by FRC-SE and PAX personnel to ensure that current installation methods will work with the new Nano Co-alloy bushings
  - Overall objective of this task will be to perform sufficient hands-on evaluation of the material to initiate DoD approval processes.
Cost and Environmental Analysis

- Cost analysis will consider the basic manufacturing cost assessment as well as the implementation cost, full “cradle-to-grave” life cycle cost, and environmental waste reduction costs.
- Additive manufacturing approach significantly reduces material waste and cost.

Assumptions – CuBe bushing machined from solid rod to 0.25” wall thickness, 12” rod length, Cost of CuBe: 12$/lb, Cost of electroformed nCo: 3-10x base metal cost (36-120$/lb)

<table>
<thead>
<tr>
<th>Material</th>
<th>Bushing Diameter</th>
<th>Material Required (lbs)</th>
<th>Material Cost ($)</th>
<th>Material Waste (lbs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CuBe</td>
<td>2”</td>
<td>10.3</td>
<td>$124</td>
<td>86%</td>
</tr>
<tr>
<td></td>
<td>3”</td>
<td>23.2</td>
<td>$279</td>
<td>90%</td>
</tr>
<tr>
<td></td>
<td>4”</td>
<td>41.3</td>
<td>$496</td>
<td>93%</td>
</tr>
<tr>
<td>nCo-alloy (Additive Manufacturing)</td>
<td>2”</td>
<td>1.4</td>
<td>$52 to $173</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>3”</td>
<td>2.3</td>
<td>$81 to $271</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>4”</td>
<td>3.1</td>
<td>$111 to $369</td>
<td>-</td>
</tr>
</tbody>
</table>

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Cost and Environmental Analysis

- Existing FRC issues with Beryllium will be reviewed and updated with respect to costs and other impacts
- Coordinate with other users/working groups to identify ESOH issues related to grinding dust and machining wastes
  - It is anticipated that the nanostructured materials will have similar issues to related alloys with conventional grain size
- Evaluate the option of performing in-situ particle emission sampling of the grinding dusts during machining and/or grinding of the nano CoP materials
Material Qualification

- Draft Aerospace Materials (AMS) and Military (MIL) specifications will be prepared for the bulk Nano-Co material
  - JTP will identify the necessary data requirements for draft specifications
- Once a military or commercial specification is in place, the data will be submitted for approval to include in the Metallic Material Properties Development and Standardization Handbook (MM-PDS).
Possible DoD Benefits

- Significant reduction in the use of toxic Beryllium-containing bushing alloys for low-frequency, rotational wear applications.
  - Subsequent reduction in the exposure of DoD workers to Be through fines and dusts produced during machining/grinding processes or through exposure to wear products during routine

- Performance advantages of the nano Co-alloy bushing material compared to CuBe and other alternatives are expected to lead to enhanced product lifetime, and reduced operating costs.
  - Superior mechanical and tribological properties compared to Copper-Beryllium, steel and alternative bushing materials, resulting in longer life and ability to handle higher loads
  - Better galvanic compatibility with aluminum structures, resulting in less corrosion

- Near net shape manufacturing- very little material waste (high buy-to-fly ratio).

- Allows for rapid depot level fabrication of Bushings on an as-needed basis with reduced turn around time (TAT).

- Applicable to all DoD aircraft where CuBe bushings are the current material of choice.
Thank you for your attention

Questions?
Backup Slides
Summary of n-CoP as a Replacement Bushing Material

- Nanostructured Co-alloy shows excellent potential as a high strength bushing material
  - High tensile strength
  - High compression strength (twice that of CuBe)
  - Good galling resistance / Low friction
  - Excellent sub-scale bushing wear test results
  - Good galvanic compatibility with Al aircraft alloys
  - Cost effective / low waste manufacturing process
Mechanical Strength in Compression

- Uniaxial Compression Testing (ASTM E9)

<table>
<thead>
<tr>
<th>Material</th>
<th>0.2% Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>CuBe TF00</td>
<td>973 ± 42 MPa</td>
</tr>
<tr>
<td>nNiCo</td>
<td>1508 ± 14 MPa</td>
</tr>
<tr>
<td>nNiCo ML1</td>
<td>1640 ± 40 MPa</td>
</tr>
<tr>
<td>nNiCo ML2</td>
<td>1373 ± 23 MPa</td>
</tr>
<tr>
<td>nCo-based</td>
<td>1967 ± 76 MPa</td>
</tr>
<tr>
<td>Cu (pyro)</td>
<td>&lt;&lt; CuBe TF00</td>
</tr>
<tr>
<td>nCuNi</td>
<td>1493 ± 61 MPa</td>
</tr>
</tbody>
</table>

All Nanometals investigated (except pure Cu) had significantly higher compression strength than CuBe.
Galling Testing (ASTM G98)

- The nanostructured cobalt alloy possesses much higher galling resistance than nanostructured Ni-alloys.
- Also compares favorably against other bushing materials:
  - C17200 (CuBe) >50ksi
  - ACUBE >20ksi
How will the Success of the Project be assessed?

- **Performance** – Nano Co-alloy must meet or exceed the performance of current bushing materials in critical bushing performance tests (bushing wear, compression strength, fatigue, corrosion, etc.), and provide superior galvanic compatibility compared to current bushing materials.

- **Producibility/Manufacturability** – The nano Co-alloy material technology must fit with standard bushing machining practices as defined by the DoD and be cost-competitive against the incumbent and emerging materials.
How will the Success of the Project be assessed?

- **Producibility/Manufacturability (cont.)** The manufacturing process must be demonstrated to be stable and robust enough to produce sufficient lots of material to qualify for applying for a MIL-Spec and/or AMS standard certification.

- **Cost** – The net present value, ROI, and payback period must be acceptable to all stakeholders

- **Environmental Benefits** - Elimination of large amounts of Be-containing waste from manufacturing process. Less exposure of Be fumes and dusts to depot personnel.
Technical Objectives

- To demonstrate both the cost effective manufacturing and the performance characteristics of the nanostructured Co-alloy bushings to the stage where they are fully qualified on OEM components as well as demonstrated, validated, and ready for depot implementation.

**Required Activities:**
- Establish and troubleshoot manufacturing process and demonstrate material consistency
- Acquire bushing property performance data
- Validate bushing performance on a range of components from the depot workload;
- Validation of bushing performance in rig tests, where possible;
- Develop military and commercial specifications; and
- Initiate DoD approval processes.

**Platforms for Demonstration and Evaluation (DEM/VAL) within NAVAIR to include:**
- T-45 Goshawk
- F/A-18 Hornet/Super Hornet