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**U.S. Air Force Reduction of Hexavalent Chromium on Landing Gear Components via Implementation of HVOF Tungsten Carbide Coatings**

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Standard Form 298 (Rev. 8-98)
Prepared by ANSI Std Z99-18
Overview

- HVOF Implementation process
- HVOF Implementation progress
- Other engineering services
HVOF Implementation Process

- All line-of-site Chrome plated high strength steel components are targeted
- **3-Step Component Approval:**
  - 3D Modeling
  - Stress Analysis
  - System Safety Evaluation (SSE)
- **6-Step Part Conversion:**
  - HVOF Fixture Design
  - HVOF Fixture Fabrication
  - HVOF Spray prototype
  - Grind Prototype
  - Process Order Digital Display System (PODDS)
  - Technical Documentation:
    - Technical Order Update
    - Engineering Change Orders (ECO)
HVOF Implementation Process

- **Step 1 of 3 - 3D Modeling:**
  - Used for component stress analysis (later used for fixture design)
  - Generated from original prints
  - Pro-E or Solidworks

- **Step 2 of 3 - Stress Analysis:**
  - Each component must go through a stress analysis at coating location
  - Performed using limit loads to ensure function under normal stress conditions
  - Not all components identified are suitable for HVOF conversion
    - High stress thin walled (spallation)
HVOF Implementation Process

- **Step 3 of 3 - System Safety Evaluation (SSE):**
  - An SSE must be performed on each component
    - Formal review of safety related changes to original part configuration
  - Separated into two separate cases:
    - General case SSE:
      - Limit stress are below material yield or 226 KSI and at least one of the following:
        - HVOF and EHC finished thickness are equal
        - HVOF is replacing an existing flame spray repair
        - HVOF is specified by the OEM
    - Special case SSE:
      - All others not defined by the General case
HVOF Implementation Process

• **Step 1 of 6 - HVOF Fixture Design:**
  • Uses previously generated 3D model
  • Fixtures are designed with consideration of booth(s) to be used including:
    • Movement restrictions and limitations.
    • Cost effective manufacturing methods
    • Ease of overspray stripping
    • Ease of operator use

• **Step 2 of 6 - HVOF Fixture Fabrication:**
  • Fixture validation:
    • Dimensional inspection
    • Fit check on actual component
  • Fixture delivery:
    • Custom container including all hardware, fixture blueprints, tolerance stack and run out sheets
    • Recommended spare parts lists
    • Instruction manual
HVOF Implementation Process

- **Step 3 of 6 - HVOF Spray Prototype:**
  - Prototyping ensures:
    - Application program incorporates all optimized coating methods
    - Ensures part cooling cycles are correct
    - Verifies actual part processing times
    - Verifies tolerances

- **Step 4 of 6 - HVOF Grind Prototype:**
  - Prototyped component is diamond ground
  - Ensures final dimensional and surface finish attributes are achievable within optimized grinding parameters
  - Grinding accomplished per Air Force drawing 200310642
HVOF Implementation Process

- **Step 5 of 6 - Process Order Digital Display System (PODDS):**
  - Process Orders are the detailed, step-by-step instructions for operators to use to ensure process repeatability
  - The digital instruction database is available on line for all operators

- **Step 6 of 6 – Technical Documentation:**
  - Technical Orders updated
  - Engineering Change Orders:
    - Ensures new procurement using HVOF WC/Co in lieu of EHC
    - Converting components ensures future use of EHC will be reduced, thus lowering hexavalent chrome volume and related exposure issues
HVOF Implementation Progress

- A-10
- T-38
- F-15
- F-16
- C-5
- KC-135
- E-3
- C-130
- B-1
- B-52

# PARTS CONVERTED
# PARTS IN PROCESS
# PARTS IDENTIFIED
Other Engineering Services

- Duplex Coating

- **Finishing Methods:**
  - Diamond Grinding
  - Superfinishing
  - Diamond Belt Finishing

- **Stripping Methods:**
  - Rochelle Salt
  - Pulsed Water Jet

- **WC/Co Alternatives**

- **WC/Co & WC/Co/Cr Qualification**
**Duplex Coating**

- The optimized HVOF WC/Co coatings are currently limited to 0.003”-0.015”
- Coatings thicker than 0.015” are periodically needed
- Duplex coating enables application up to 0.030” while maintaining all mechanical properties
- Phase I complete and working on Phase II

### Table 5: Experiment Design Candidates Summary

<table>
<thead>
<tr>
<th>Experiment Design Candidates</th>
<th>Replicated/Mixed Factor</th>
<th>Randomized</th>
<th>Randomized/Six Non-Linear</th>
<th>Six Factor Central Composite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design</td>
<td>4</td>
<td>4</td>
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<tr>
<td>Runs</td>
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<td>138</td>
<td>72</td>
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<tr>
<td>Included replications</td>
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<tr>
<td>Highest order interactions able to detect quantity</td>
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<tr>
<td>Duplicates system curvature (non-linear)</td>
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<td>Y</td>
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<td>Quantity model curvature?</td>
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<td>Quantity inherent system variation replicability?</td>
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<td>Generates mathematical system model?</td>
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<td>Predict multi-output optimal response?</td>
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<tr>
<td>DDC mitigates influence of unknown extraneous factors?</td>
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<tr>
<td>Study length control of extraneous factors employed?</td>
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<tr>
<td>Total change-over time (minutes)</td>
<td>1,920</td>
<td>72</td>
<td>72</td>
<td>72</td>
</tr>
</tbody>
</table>

* No replicates on corner and axial points. Multiple replicates, however, placed on center point.
**Phase I:**
- Identified initial group of coating chemistries
- Tested per Air Force drawing 200310641
- Down-selected to 4 chemistries
- Generated a coating model tool using a Design of Experiment (DOE) method
  - DOE input parameters:
    - Oxygen Flow Rate
    - Fuel Flow Rate
    - Powder Flow Rate
    - Stand-off Distance
- Coating model tool predicts coating bond strength, ductility, porosity and hardness given changes in the input variables
  - Significantly reduces Phase II testing
Duplex Coating (Phase II)

- Phase II:
  - 4-point bend integrity testing:
    - 0.020” and 0.030” total coating thickness with 0.003” inch WC-Co cap
    - 0.017” and 0.027” total coating thickness without WC-Co cap
    - 5 cycles at 190ksi, 210ksi and 230ksi stress levels or until failure (spallation)
  - Corrosion testing of duplex system to chrome and WC-Co
    - Per ASTM B117
  - Coating integrity (large bar) testing of 2 best chemistries
Phased Coating (Phase II)

- Phase II Coating Integrity Testing Results:
  - The optimized build coat performed worse than expected
  - Adding WC-Co cap to build coat failed coupons at lower than predicted stress levels
  - Important observations:
    - The bond strength of WC-Co to build coat was very high
    - The bond strength of build coat to substrate was low
    - Possibly WC-Co bond coat followed by build coat could improve overall bond
  - Integrity testing with WC-Co bond coat:
    - Much better results (at 230 ksi):
      - No spallation at 0.027 without WC-Co top coat
      - No spallation at 0.030 from 3 of 4 chemistries with WC-Co top coat
Duplex Coating (Phase II)

WC/Co Bond-0.027 Build-0.003 WC/Co Top @ 230 ksi
Finishing Methods

• **Diamond Grinding of 300M:**
  - Air Force drawing 200310642:
    - Cylindrical, Face (contoured) and Surface grinding techniques were optimized to reduce/eliminate grinding burns

• **Superfinishing:**
  - Seal surfaces containing HVOF applied WC/Co coatings must be Superfinished after diamond grinding has been completed
  - Superfinishing methods were optimized and written into AF Drawing 200310642

• **Diamond Belt Finishing:**
  - The initial results of testing indicate an increase of processing efficiency by 3-5 times over standard diamond wheel grinding
  - HAFB long bed grinder has been retrofitted with belt attachment
  - Optimization testing will begin this year, specification to follow.
Stripping Methods

- **Rochelle Salt Stripping:**
  - Industry standard for removing HVOF applied WC/Co materials
  - Electrolytic method under controlled temperature and pH to break down the binder (Co) in the HVOF applied coating
  - Parameters identified within Air Force HVOF application specification-200310641

- **Forced Pulse Water Jet:**
  - Optimized for HVOF WC/Co and WC/Co/Cr stripping
  - Environmentally friendly
  - Fast, very efficient
WC-Co Alternatives

• **WC/Co Alternatives:**

  • Currently, HVOF WC/Co & WC/Co/Cr is the only approved Landing Gear coating
  
  • These coating are expensive and have fatigue and spallation concerns

  • It is desirable to qualify alternative coatings which provide:
    • As good as or better than chrome performance characteristics
    • More cost effective
    • Conventionally finished

  • Landing Gear Thermal Spray Specification
    • Requirements which will enable the Air Force to qualify other thermal spray chemistries
    • Modeled after the Landing Gear HCAT JTP
WC/Co & WC/Co/Cr Qualification

- WC/Co & WC/Co/Cr Qualification:
  - Enables the USAF to qualify vendors for HVOF WC application on OEM components
  - Qualification based on coatings passing standard metallurgical and performance baselines
  - Specification completed and signed off on 28 July 2009 (200925098)
  - Located at www.fbo.gov
Conclusion

- **Benefits:**
  - Improved wear performance
  - Removing a known embrittling process
  - Component longevity
  - Reduction in hexavalent chrome waste stream
  - Greatly reduced rework
  - Faster processing of parts

- **Issues:**
  - Solid infrastructure for EHC
  - Momentum change