Chromium and Cadmium Replacement Options for Advanced Aircraft

Keith Legg

HCAT Program Review, KSC, Nov 2003
**Title:** Chromium and Cadmium Replacement Options for Advanced Aircraft

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**ABSTRACT**
23rd Replacement of Hard Chrome Plating Program Review Meeting, November 18-19, 2003, Cape Canaveral, FL. Sponsored by SERDP/ESTCP.

**LIMITATION OF ABSTRACT**
Same as Report (SAR)

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- **REPORT:** unclassified
- **ABSTRACT:** unclassified
- **THIS PAGE:** unclassified
Chrome replacement
# Summary of best options

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<td>Plasma spray</td>
<td>IDs&gt;3” (&gt; 1.5” with new gun)</td>
<td>ID&gt;1.5” &gt;0.001” thick</td>
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Qualified | In test

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Niche options

- **Ion (Plasma) Nitride**
  - 500°C vacuum heat treat
  - Add oxide for corrosion resistance

- **Electrocomposites**
  - Electroplated Ni or Co with hard particles

- **Laser cladding**
  - Weld surfacing (also laser glazing, LISI, etc.)

- **Electrospark deposition (alloying)**
  - Localized repair and build-up

- **Explosive cladding**
  - Wide area bonding – IDs, gun tubes, etc.
Data available

Large quantity of detailed performance data available from HCAT, including rig and flight tests; also commercial flight experience
HVOF – available data
Reports available

HCAT

- Landing Gear
  - Joint Test Report
  - Cost and Performance Report
  - Final Report (NRL report)

- Propeller Hubs
  - Joint Test Report
  - Cost and Performance Report
  - Final Report (NRL report)

- JSF Reports
  - HVOF as a Cr replacement
  - ID Cr alternatives
  - Repair options for Cr and Cd

- Original DARPA Cr options report

C-HCAT (Landing Gear folder)

- Heroux Devtek
  - Fluid compatibility
  - Grinding
  - NDI
  - Stripping

- DND
  - Coupon testing

- Messier-Dowty
  - F-18 landing gear and drag brace rig tests (available shortly)

- Goodrich (available later)
  - Dash-8 rig test
  - Bend tests

Note: C-HCAT is all WC-CoCr

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Applications - military

Qualified
- Landing gear components approved for HVOF coating at Hill AFB
  - A-10 MLG Piston
  - A-10 NLG Piston
  - B-1 MLG Axle
  - C-130 MLG Piston
  - C-141 MLG Bogie Beam
  - C-141 Outer Cylinder
  - C-5 MLG Roll Pin
  - C-5 MLG Ball Screw
  - C-5 MLG Outer Pitch
  - F-15 Drive Keys
  - KC-135 MLG Axles
- Messier-Dowty
  - CF-18 steering covers, piston heads, MLG hexagon repair
- F-22 (Raptor)
  - F-119 engine, convergent nozzle actuators

Rig and flight test
- NADEP-CP, H-S, WR-ALC
  - EA-6B landing gear (flight)
  - P-3 bomb bay door actuators (flight)
  - E-2C, C-2, P-3, and C-130: prop tailshaft, low pitch stop lever sleeve, rocker land (rig)
- Lockheed
  - P-3 landing gear (rig)
- Messier-Dowty
  - F-18 landing gear (rig)
- TF-33 engine, (P&W)
  - Accelerated Mission Test (AMT)
- NAVAIR PAX, Greene Tweed
  - Hydraulic actuator rig tests

F-35 – Goodrich
WC-CoCr baselined for piston and axle journals

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Applications - commercial

- **Commercial – OEM**
  - Boeing - >100 spot HVOF uses
  - B767-400 HVOF on landing gear (production)
  - Airbus 380 spec’d for HVOF WC-CoCr (Goodrich)
  - GEAE uses for GTE shafts
  - Bombardier flap tracks
  - Messier-Dowty installing HVOF for landing gear

- **Commercial – MRO**
  - Boeing permits HVOF for repair to 0.010”
  - Delta using HVOF landing gear repair in own maintenance shop
    - Similar moves at United and American
  - Flap and slat tracks, various aircraft
# Advantages and Limitations

## Advantages
- Much better wear resistance
- Lower seal wear (with proper superfinish)
- Takes a good finish (superfinish)
- Little or no fatigue debit
- Dry process, no embrittlement
- Easily stripped
- Widely available

## Limitations
- Spalls at high cyclic bending load (close to yield)
- Spalls with high point or line load
- Coating can corrode (different mechanism)
- Cannot coat IDs
- Substrate heating (must control process)
- Must be done in booth (noise and dust, robotic)
Developments needed

- **More ductile HVOF coating**
  - Primarily needed for MRO (thick coatings)
    - Existing material fine for OEM use
  - Avoid spalling at high load
  - Will almost certainly have worse wear (softer)
    - But still better than EHC
  - Use only where high bending or contact stresses
  - May be a layered coating with ductile build and brittle overlay
    - Increased wear rate on breakthrough

- **Same grinding wheel for steel and HVOF**
  - Is being done commercially
  - Hill AFB tests under way – looks readily doable
Summary of HVOF implementation issues

- **Integrity at high stress**
  - Issue only for thick overhaul coatings on carrier-based aircraft
  - Sensitive to cyclic contact stress
    - Not seen in rig tests but should be watched

- **Masking**
  - Can be very personnel-intensive
  - Cannot use tapes
  - Hard masking needed – have to build up mask inventory

- **Grinding**
  - Need Al₂O₃ wheel for metal but diamond wheel for HVOF carbides
  - Machine resetting or different grinding procedures (feeds, speeds, lubricants)
  - Recent testing looks good

- **Corrosion**
  - EHC does not corrode – substrate corrodes and undercuts coating
  - HVOF matrix (Co) can corrode, causing roughening, leakage, but not undercuts coating
    - Slow increases in leakage rather than catastrophic flaking
    - Seen with one operator’s actuators in Europe – probably due to specific fluids or de-icers used only there

- **Embrittlement relief**
  - Hydrogen appears to diffuse slower through HVOF – may need longer H bake after Nital etch

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Electroless Ni

Electroless Ni, being a Ni material, is next against the wall and is on the JSF Restricted Materials List.
Consider as an intermediate coating – a lot better than chrome, but likely to need replacement itself pretty soon.
Applications

- **Wide variety of industrial applications**
- **Aircraft**
  - GTE components – P&W uses Ni-B various parts
    - Compressor blades (erosion, corrosion)
  - Shaft rebuilding
  - Flap tracks
  - Bearing journals
Advantages and limitations

- **Advantages**
  - No electrodes
  - No edge build-up
  - Thin or thick
  - A variety of EN composites available
    - SiC
    - Diamond
    - Teflon

- **Limitations**
  - Adhesion always a concern
  - Requires 300-400°C heat treat for max hardness
  - Hydrogen evolved during deposition
    - Does not seem to cause embrittlement
  - Bath must be dumped periodically
Data available

- Like EHC electroless Ni has been around for so long that little data is available
  - Especially need comparison to EHC
- Some data available from vendors
  - Concern over reliability, accuracy
- Beware – most data will be for heat treated state, but most airframe usage will be as-deposited
  - Wear not as good, corrosion better

- Studies of a number of electroless and electroplated Ni coatings being done by AFRL
  - Work ongoing
  - Typical hardness 700 – 850 HV
  - Good barrier corrosion, but no protection if breached (as with Cr)
  - [http://www.materialoptions.com/w2g/cgi/kmcgi.exe?O=DIR0000000H8I&V=0](http://www.materialoptions.com/w2g/cgi/kmcgi.exe?O=DIR0000000H8I&V=0)
  - joseph.kolek@wpafb.af.mil

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Implementation issues

- Reliable adhesion is biggest production issue cited by aerospace users
- Requirement for heat treating for maximum hardness means that for many applications must be used as-deposited
  - Significantly lower wear resistance
  - Data needed for as-deposited and heat treated state
Nanophase Co-P

New coating developed by Integran of Toronto, Canada
SERDP Project #1152, almost completed
http://www.materialoptions.com/w2g/cgi/kmcqi.exe?O=GRP00000000H8F&V=0
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 coating, right from the substrate interface.

Typical deposition conditions
2ms pulses
125Hz, 25% duty cycle
2 – 3V, 150mA/cm²
# Advantages and limitations

## Advantages
- **Drop-in**
  - Wherever EHC can go Co-P can go
- Better corrosion than EHC
- Little or no embrittlement
  - May work for field repair
- Looks usable to replace EHC, TDC, brush Cr

## Limitations
- **ESOH**
  - OSHA pel for Co (8hr TWA) = 0.1 mg(Co)/m³
  - OSHA pel for metallic Cr (8hr TWA) = 1 mg(Cr)/m³
  - Co not known carcinogen
  - No regs at this time
- Heat treat for best hardness
- Requires pulse power supplies
  - Capital cost

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Data available

Info at
http://www.materialoptions.com/w2g/cgi/kmcgi.exe?O=GRP0000000H8F&V=0
nCo-P structure

Nano Co-P alloy coatings developed under SERDP project PP-1152 as an environmentally-benign replacement for hard Cr coatings for NLOS applications.

Synthesis of Nanocrystalline Co-P Alloys

- Electrodeposition parameters modified to yield deposits with average grain sizes below 100nm
- Pulsed Current Deposition
- Plating Efficiency >90%
- Deposition rate 2-8 mills/hr
- Consumable & nonconsumable anode

Coating Thickness and Integrity of Nano Co 2-3wt%P

Surface Morphology

- Nodular, cauliflower morphology
- No pits, cracks, pores

Cross-Section

- Thickness ~135µm
- No pits, cracks, pores

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Implementation issues

- ESTCP program approved between HCAT, Lockheed, Curtiss-Wright, Smiths Aero, NADEP JAX, OO-ALC to validate for ID EHC and for TDC replacement
  - Will begin January 04
  - Primary issues:
    - Can it work as a TDC alternative?
    - Heat treat requirements to meet TDC requirements
    - Embrittlement – is it really non-embrittling?
    - Long term bath and process stability in depot environment (processing many different items)
Physical Vapor Deposition (PVD)

PVD involves deposition from a solid material source – evaporation, sputtering, arc
Applications

- Limited applications in aerospace
- Major application is TBCs
  - E-beam evaporated ZrO₂
- Wear resistance
  - TiN
  - Bearing races and retainers
- Blade erosion
  - MDS Prad coating
- Fretting
  - AlCu
- Low friction
  - Variations of MoS₂
# Advantages and Limitations

## Advantages
- Very hard, wear resistant
- Reproducible, high quality
- Smooth
  - No finishing needed
- Probably good TDC alternative
- Many vendors
  - Esp. for TiN, DLC

## Limitations
- Cost
- Thin (typically 3µm – 0.0001”)
  - Cannot be used for rebuild
- Lack of specs
- Vacuum requirements
  - Size limitations
  - Substrate temperature typically >250°C
    - Less reliable at low T
  - High cleanliness
  - Line of sight
Data available

- Large amounts of data available for many PVD coatings
  - Most in R&D journals
  - Little or no publicly available data for aerospace production use
Implementation issues

- Best applications for thin wear- or RCF-resistant items for max life (difficult to strip)
  - Items that will not be refurbished
  - Pins, gears, bearings
  - Niche applications
- Need data on wear and seal performance
- Easy to make components into cutting tools, esp with gears
- ID hard coatings under development
  - Marshall Labs, Paradigm Shift Techs
Plasma spray

Plasma spray guns can be small and the stand-off distance (gun-substrate) is much less than with HVOF
Applications

- Already specified for various repairs and build up in GTEs and airframes
  - Often used for same-material dimensional restoration

- In general new applications use HVOF rather than plasma spray
  - Plasma spray cheaper but quality lower

- Good method for coating IDs
  - Most guns only capable of coating >3” ID
  - New Sulzer Metco F-300 gun >1.6”
  - Makes most sense when already use HVOF for OD, so can do ID and OD with same spray booth, robot, etc.
CH-53 helicopter blade damper

- Approved for repair
- T400 plasma spray on ID
- Typical actuator coatings:
  - Rod – HVOF/D-gun WC-Co, WC-CoCr, WC-CrNi
  - Piston – HVOF/D-gun WC-Co, T400
  - ID – plasma spray T400

HVOF/D-gun WC-Co (rod)

Plasma spray Tribaloy 400 (ID, piston)
Advantages and limitations

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Similar to HVOF</td>
<td>Adhesion not as good as HVOF</td>
</tr>
<tr>
<td>Able to coat inside IDs down to 3” ID for most guns, 1.6” for Sulzer F-300 gun</td>
<td>3-7 ksi vs &gt;10 ksi</td>
</tr>
<tr>
<td></td>
<td>Lower porosity than HVOF</td>
</tr>
<tr>
<td></td>
<td>10% vs 1 - 2%</td>
</tr>
<tr>
<td></td>
<td>Can allow leak-by in gas-over-fluid systems</td>
</tr>
<tr>
<td></td>
<td>Requires grind, superfinish</td>
</tr>
<tr>
<td></td>
<td>More difficult for ID than OD</td>
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</table>
Data available

Nowhere near the amount of data available for HVOF. ID coating data available from HCAT ID plasma spray program.

http://www.materialoptions.com/w2g/cgi/kmcgi.exe?O=GRP0000000GOW&V=0
Implementation issues

- May need to be sealed for some hydraulic applications
- Surface finish not well defined – likely to need superfinish
- Design of air sweep to take heat and overspray from ID
- Plunge-grinding specs for OEM pistons
  - Coat piston, then plunge-grind seal groove
Conclusions on Cr replacement options

- **HVOF is the method of choice for most ODs**
  - WC-CoCr wherever possible for better corrosion resistance
  - Where stress is too high we will need a more ductile coating
    - Maybe nCo-P, electro- or electroless Ni, or similar, trading wear life for coating integrity

- **For IDs standard HVOF not viable**
  - Electro- and electroless plating
    - Widest applications, including thin dense and flash Cr replacement
  - ID plasma spray
    - Most cost-effective when using HVOF or other thermal spray for OD
  - **PVD**
    - Niche applications because of cost and complexity
      - Could be broadened with reliable vendors, data, specs, especially for TDC replacement
Cadmium replacement options
Usage

**Steel Components**
- The “cure-all” corrosion coating
- Good salt spray and scribed corrosion protection
- No hydrogen embrittlement or stress corrosion cracking
- ODs and IDs
- Plate steel to protect Al

**Fasteners**
- Correct lubricity (avoid changes to torque-tension specs)
- No hydrogen embrittlement
- Retain thread profile

**Connectors**
- For electrical equipment
- Low contact resistance
- Non-insulating corrosion products
- Solderable a plus

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Galvanic series

- Al and Al alloys
- Zn-Ni
- Al-Mn
- Zn
- Be!!

Mother Nature left us short on options!
Summary of Cd alternative options

Cd alternatives

Vacuum Al alternatives
- IVD aluminum (Ivadizing)
  - ID sputtered Al for IDs

Aqueous electroplated alloys
- Zn-Ni

Non-aqueous electroplates
- Electroplated Al (Alumiplate)
  - Molten salt bath Al-Mn

Niche alternatives
- SermeTel ceramic coatings
  - Metal-filled polymers
    - CVD Al (small IDs)

Alternative base alloys
- New high strength stainless

Al is the only “global” replacement
Almost everything needs chromate conversion

In use  In test  In development

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JSF Cd Alternatives Report

- Requirements
- Alternatives
  - Zn-Ni, Sn-Zn electroplates
  - Alumiplate
  - Al-Mn molten salt bath
  - IVD and CVD Al
  - Sputtered Al
  - Thermal spray
  - SermeTels
  - Filled polymers
  - High strength stainless steel

http://www.materialoptions.com/w2g/cgi/kmci.exe?O=DIR0000000GK&P&V=0
Joint Test Report

- Cd alternatives report for low strength steels (<220 ksi)
  - Boeing, JGPP
  - Sn-Zn
  - Acid Zn-Ni (Boeing)
  - Alkaline Zn-Ni
  - IVD Al

http://www.materialoptions.com/w2g/cgi/kmcgi.exe?O=DIR000000016D&V=0

Engineering and Technical Services for Joint Group on Pollution Prevention (JG-PP) Projects

Joint Test Report
BD-R-1-1

for Validation of Alternatives to Electrodeposited Cadmium for Corrosion Protection and Threaded Part Lubricity Applications

October 1, 2002

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IVD Al

Vacuum PVD process
Fully qualified and quite widely used by OEMs and depots
Spec MIL-C-83488 for Al coating does not define deposition method
Applications

- **Military**
  - F-4
  - F-14
  - F-15
  - F-16
  - F-18
  - AV-8B
  - A-12
  - V-22
  - Apache

- **Commercial**
  - Boeing 737, 747, 757, 767
  - McDonnell-Douglas DC9, 10, MD-80, 90, 11
  - Bombardier Dash 7, 8
  - Airbus A300, A310
Advantages and limitations

**Advantages**
- Qualified commercial process
  - Commercial coating shops
  - IVD-coated fasteners available commercially
- Clean and safe
- Good performance
- No H embrittlement

**Limitations**
- Vacuum process
  - Expensive
  - Awkward
- Poor quality coating as-deposited
  - Peen and chromate
- Poor throwing power
- Soft and easily damaged
  - Cannot easily be repaired
- Dissolves in alkaline cleaners
  - MRO users may have to change cleaning process
Data available

Data available from Boeing, JGPP report
http://www.materialoptions.com/w2g/cgi/kmcgi.exe?O=DIR000000016D&V=0
PVD Al for IDs – sputtered Al

- Marshall Labs Plug and Coat
  - Works inside IVD chamber
  - Makes it possible to coat OD and ID simultaneously Plug & Coat
    - Add-on to existing IVD chamber
- Status
  - Being installed at Hill AFB
  - Commercially available
  - Meets MIL Spec.
- Note: All Al coatings require use of proper aqueous cleaners (avoid alkaline cleaners)
Developments needed

- Some additional environmental embrittlement data needed
- Plug and Coat miniaturization needed for smaller IDs
  - Under way at Marshall Labs
- Porosity and need for peening always an issue
  - Various approaches for better coating quality
    - Higher plasma density
    - Sputtering instead of IVD
    - Pulse biasing
Electroplated Al (Alumiplate™)

Alumiplate, Minneapolis
Deposited from organic solution
Alumiplate description

- **Organic electroplate**
  - Requires enclosed tank and plating line in inert environment
    - Similar to vacuum processing but less
  - Al salts in toluene solution
  - Reasonable throwing power
    - Needs conformal or secondary electrodes for complex shapes, IDs
  - Frequently uses Ni strike for adhesion
  - Recent development uses grit blasting and activation with no Ni strike
    - Equivalent adhesion
  - Metallic strike needed for insulators such as composites
  - Coating thickness 0.0001 – 0.001”
    - Usually 0.0003 – 0.0005”
  - Conversion coat (traditionally chromate) for best corrosion performance (as with all other Cd alternative)
## Advantages and Limitations

### Advantages
- “Drop-in” replacement
- Able to coat complex shapes
- Higher quality coating than as-deposited IVD AL
- Suitable for components, connectors, fasteners (with dry lube)
- Directly compatible with Al skins
- Can be anodized for better wear and abrasion

### Limitations
- Size limited
  - Landing gear about 3’ long
  - Limited by current bath size
  - Appears scalable
- Requires dry lube for threads to prevent galling
- Sole source is Alumiplate, Minneapolis
  - Willing to license, but no current licensees
  - Not yet available in Europe
- High capital cost
- Toluene bath not suitable for DoD depot use
- Cannot brush plate Al repair
  - Can brush plate Sn-Zn to repair Al
Data available

A great deal of data becoming available as a result of ongoing JSF and Army testing. Rowan is currently putting together a report on the technology – available by year’s end.
Electrical connectors

- Meets all tests for qualification on connector shells (MIL-DTL-38999K testing)
  - Al and C-fiber/PEEK composite
  - Corrosion, conductivity stability in salt fog
  - Mate/unmate testing (wear, torque, conductivity)
  - No insulating corrosion products

- Amphenol has now assigned part numbers for commonly-used AlumiPlated aerospace connectors
Other issues

- **Repairability**
  - Al can be repaired by brush plating Sn-Zn after suitable activation (Boeing)
  - Can also be repaired with brush-on SermaTel

- **Anodizing**
  - Can be anodized, leaving Al layer beneath anodize layer
  - Will improve wear and abrasion, but hard coating on soft underlay not a good high load wear surface

- **Any form of Al avoids Cd embrittlement**
  - Very bad form of embrittlement
  - Can occur when aborted takeoff heats brake discs and nearby landing gear components
Developments needed

- Non-toluene solution needed for depot use
  - Present chemistry cannot be used in depots
- Additional sources for plating service
- Additional embrittlement testing
- Well-defined brush plate or other repair
  - Both for OEM and MRO use
Other ways to deposit Al

- **Arc or flame spray**
  - Used on some Bombardier aircraft
  - Thick coating (0.001 – 0.003”)
  - Rough
  - Al-Zn arc spray used on support equipment, radar towers, bombs

- **CVD**
  - Generally high temperature
  - Used for cooling passages in hot section blades
  - AFRL SERDP project approved for FY 04

- **Slurry Al – developed by Liburdi Engineering**
  - High temperature heat treat
  - For hot section turbine blades (oxidation resistance)
SermeTel®

Metal-filled ceramics from SermaTech
SermeTel

- Al flakes in ceramic matrix
- Brush or spray on
- Older formulations contain Cr\(^{6+}\)
- Heat treat 375-700°F
  - Hard, glassy coating
- Grit blast to uncover Al

Figure 17. SermeTel aluminum-ceramic coating cross sections 500x. Left chromate-containing coating; right chromium-free coating.
Applications

- **Used in turbine engines**
  - Cases and discs

- **Landing gear in some older aircraft (commercial)**

- **F-22**
  - Extensive use of SermeTel coatings on landing gear and other systems
  - See Baltimore meeting on Materials Substitution for P2 in Advanced Aircraft (2002)
## Advantages and limitations

### Advantages
- Simple spray or paint
  - Can be used for repair
- Hard coating
  - Abrasion resistant

### Limitations
- Sole source
  - Licensing to major users only (e.g. Goodrich)
  - Others (inc. depots) must send to SermaTech
  - Very high cost
- Requires heat treat
  - Can be low enough T for HSS
- Embrittlement from acids in formulation
  - When using 984/985 HE on A100 for F-22
  - New formulation, not yet tested or approved
- Contains chromates
  - New non-chromate formulations now available

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Note: There are now some other similar coatings on the market

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Data available

Little publicly available data
Zn-Ni electroplate
Applications

- Boeing uses acid Zn-Ni
  - Restricted to UTS<220 ksi because of embrittlement issues
- Oklahoma City ALC
  - Replaced Cd and TiCd with brush Cd, Zn-Ni and IVD in 1991
## Advantages and limitations

### Advantages
- Aqueous electroplate
  - Easier application in open tanks
- Qualified process
- Tank and brush plate

### Limitations
- Alloy chemistry
  - Difficult to ensure reproducibility and uniformity, especially on complex shapes
- Embrittlement
Data available from Boeing, JGPP report

http://www.materialoptions.com/w2g/cgi/kmliği.exe?O=DIR00000016D&V=0
Developments needed

- Extension to high strength steels
  - New JTP for HSS under way – Boeing, JGPP
- Brush plating
  - Is Zn-Ni a good repair for IVD or electroplated Al?
High strength stainless steel

S-53 – new steel developed by QuesTek Innovations LLC
Advantages and limitations

**Advantages**
- No coating to come off
- Eliminates corrosion
  - Primary cause of landing gear overhaul and parts condemnation
- Avoids SCC
  - Primary mechanism for major landing gear failure

**Limitations**
- Cannot be used uncoated against Al
- More expensive than 300M
  - A bit less than cost of A100
Developments needed

- Full validation of properties and performance
- Development of materials database
- Licensing to steel producers so commercially available
  - QuesTek’s intent is licensing to several steel companies (QuesTek is a steel developer, not a producer)
Data available

Extensive data will become available over next 2 years from ESTCP program
HSSS properties

- HT + LN₂ + single temper
- HT + LN₂ + double temper
- HT + longer LN₂ + double temper
- HT + dry ice + double temper
Current status

- Appears to be mechanically equivalent to 300M but much better fracture strength and SCC
- Being tested and validated at Hill AFB
- Work to be complete in 3005
- Will obtain data needed for qualification
  - Not MIL Handbook 5 (requires 10 heats at $300,000/heat)
  - Will do three heats to 20,000 lb
    - Then use AIM method (Accelerated Insertion of Materials) to interpolate between and extend lab data using modeling data
Conclusion on Cd alternatives

- **Al** is the best overall option, but deposition methods are not straight “drop-in”
  - Electroplated Al looking increasingly good for OEMs
  - If adopted broadly, what about depot repair?
    - Non-toluene electroplate? IVD + sputtering?

- **High strength stainless** exciting new development
  - Will be 2 or 3 years before it is fully qualified at Ogden
  - Even then, no MIL Handbook 5 numbers
  - Modeling will tell us more about this steel than we know about most others

There are niche applications for other Cd alternatives