Chromium and Cadmium Replacement Options for Advanced Aircraft

Keith Legg

HCAT Program Review, KSC, Nov 2003

ROWAN TECHNOLOGY GROUP
Linking Global Technologies with Markets

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Prescribed by ANSI Std Z39-18

Chrome replacement

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Summary of best options

Technology	Applications	Limitations
Thermal spray (HVOF)	Landing gear, hydraulics, flap tracks	>0.001” thick Not IDs
Electroless Ni (Ni-P, Ni-B)	IDs, other NLOS, TDC alt.	Adhesion, build-up, heat treat
Nano Co-P electroplate	IDs, TDC alt., carrier LG?	Heat treat
PVD	Gun barrel IDs, small components	Cost <0.001” thickness
Plasma spray	IDs>3” (> 1.5” with new gun)	ID>1.5” >0.001” thick

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.

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Data available

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

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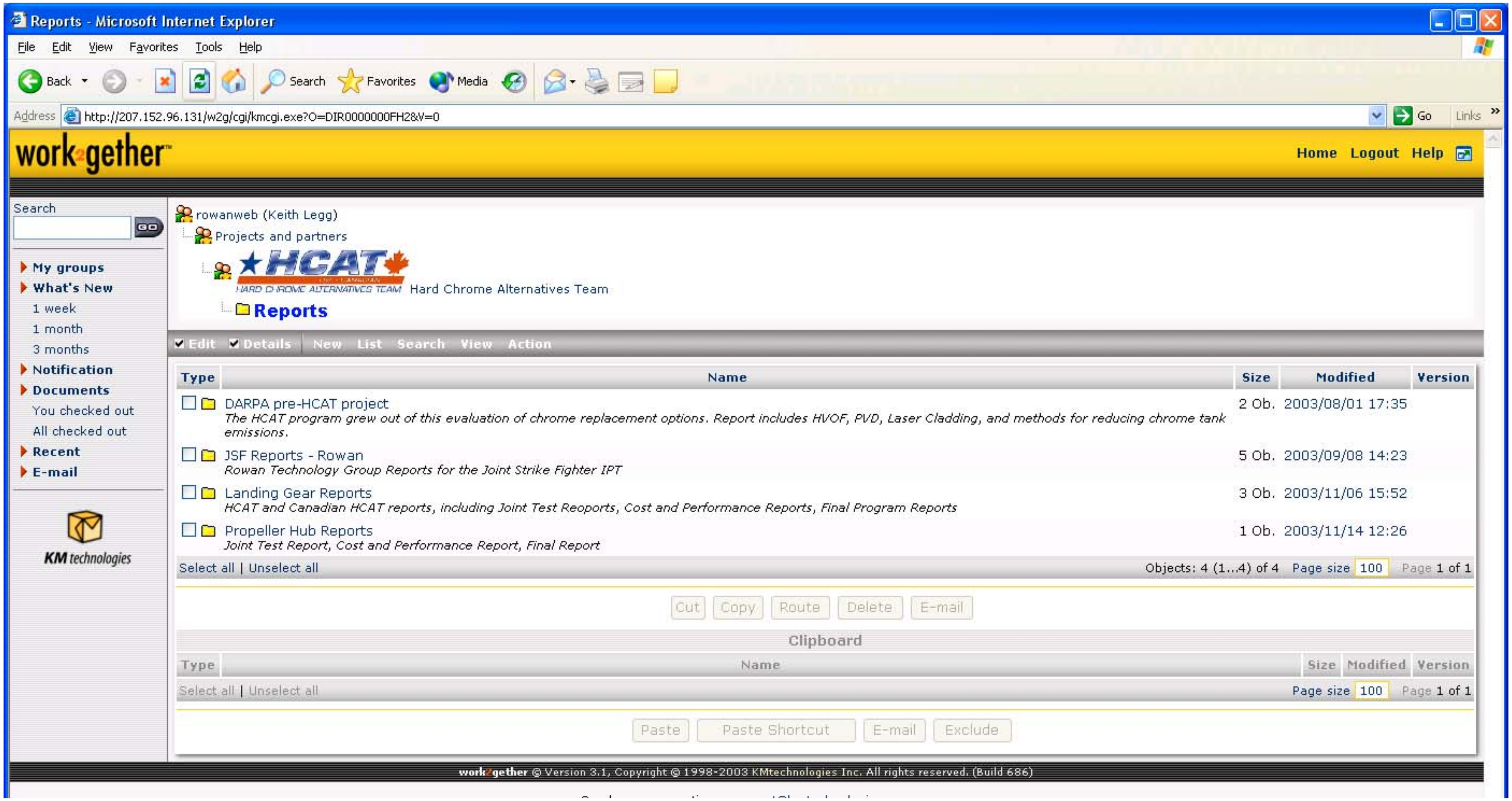
HVOF – available data



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)

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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 Al_2O_3 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 undercutting
    - 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.

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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

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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

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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
  - 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

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Nanophase Co-P

New coating developed by Integran of Toronto, Canada

SERDP Project #1152, almost completed

http://www.materialoptions.com/w2g/cgi/kmcgi.exe?O=GRP0000000H8F&V=0

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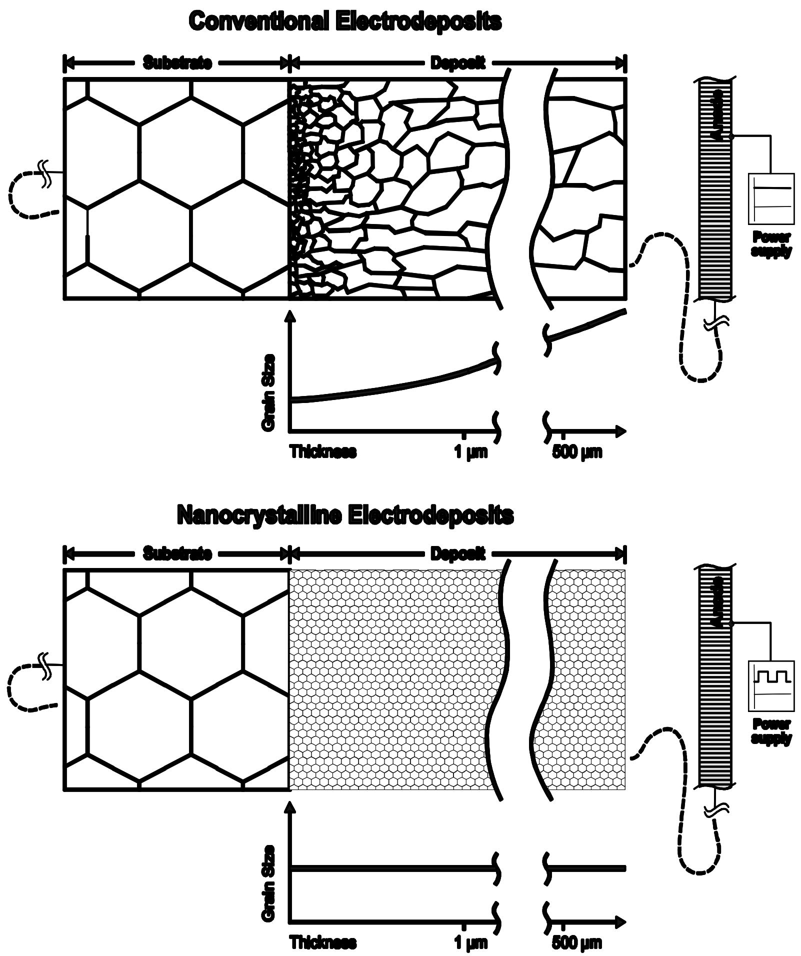
Description



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/cm^2

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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)/m^3
  - OSHA pel for metallic Cr (8hr TWA) = 1 mg(Cr)/m^3
  - 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

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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.

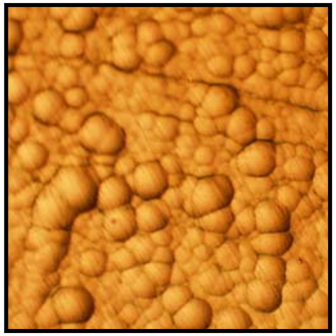
Synthesis of Nanocrystalline Co-P Alloys

- 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

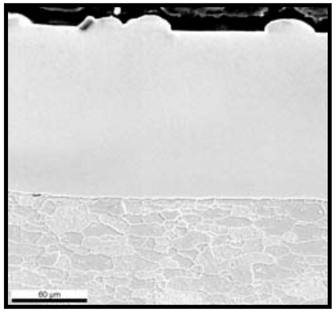
Surface Morphology

- ▷ 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)

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Physical Vapor Deposition (PVD)

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

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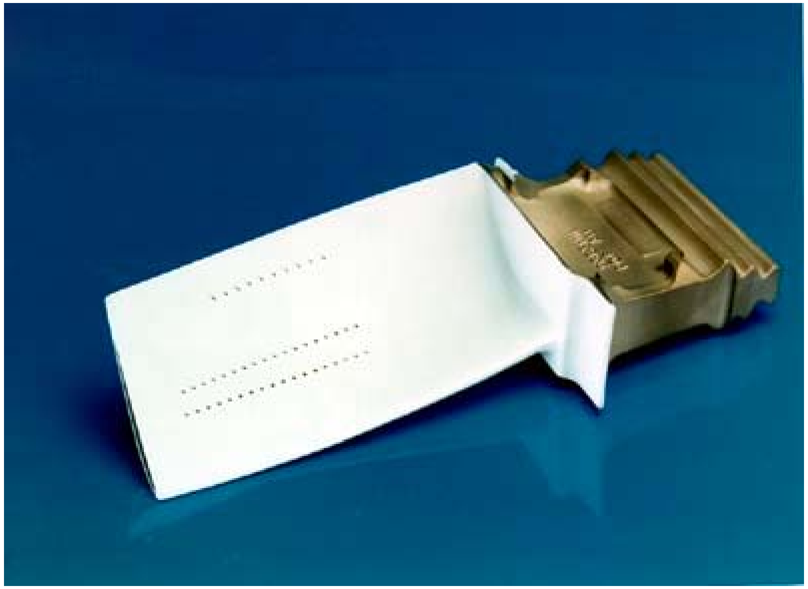
Applications

- Limited applications in aerospace
- Major application is TBCs
  - E-beam evaporated ZrO_2
- Wear resistance
  - TiN
  - Bearing races and retainers
- Blade erosion
  - MDS Prad coating
- Fretting
  - AlCu
- Low friction
  - Variations of MoS_2



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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

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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

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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

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HARD CHROME ALTERNATIVES TEAM

Plasma spray

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

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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.

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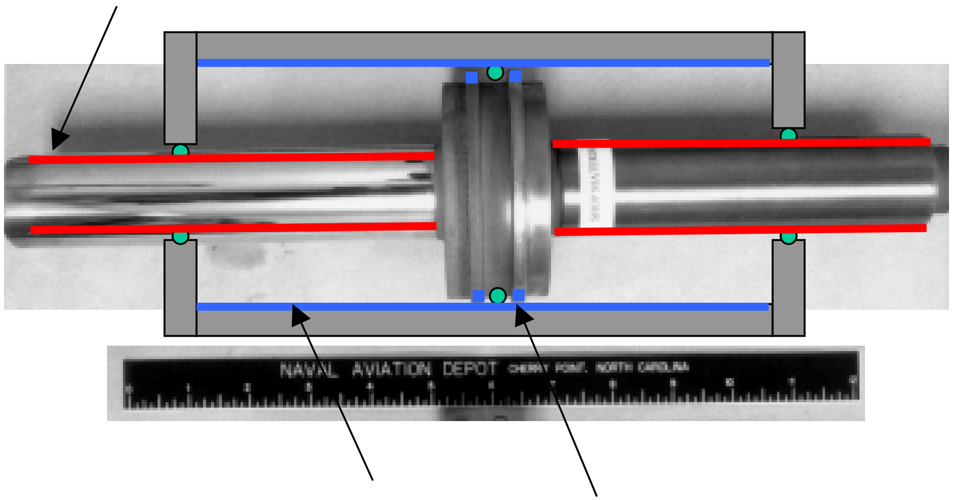
CH-53 helicopter blade damper

- 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)

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Advantages and limitations

Advantages

- Similar to HVOF
- Able to coat inside IDs down to 3" ID for most guns, 1.6" for Sulzer F-300 gun

Limitations

- Adhesion not as good as HVOF
  - 3-7 ksi vs >10 ksi
- Lower porosity than HVOF
  - 10% vs 1 - 2%
  - Can allow leak-by in gas-over-fluid systems
- Requires grind, superfinish
  - More difficult for ID than OD

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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=GRP000000GOW&V=0

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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

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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

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Cadmium replacement options

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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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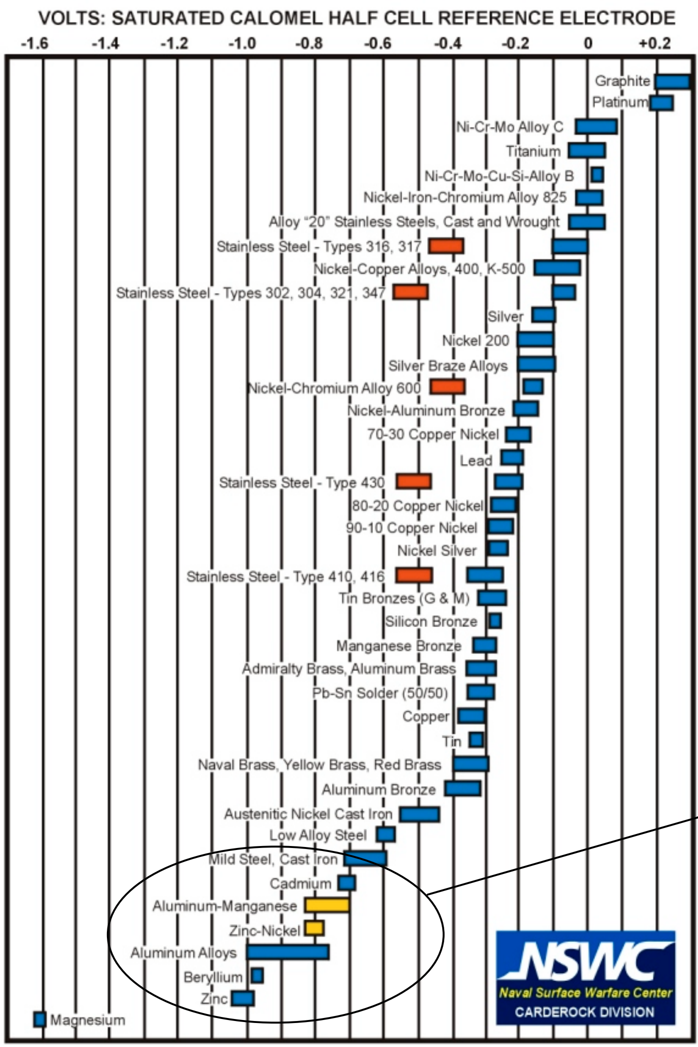
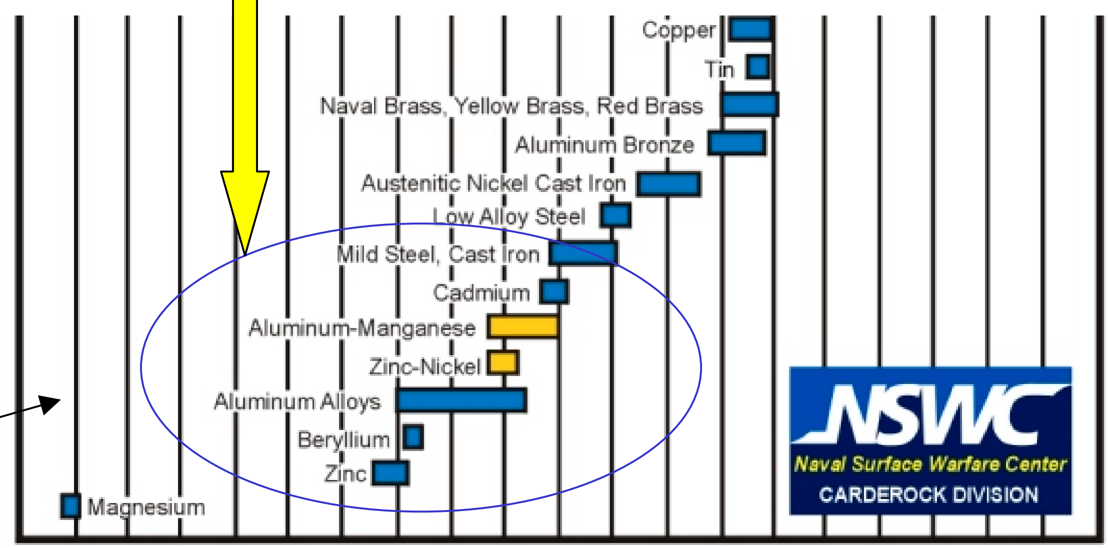
Galvanic series



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

Mother Nature left us short on options!



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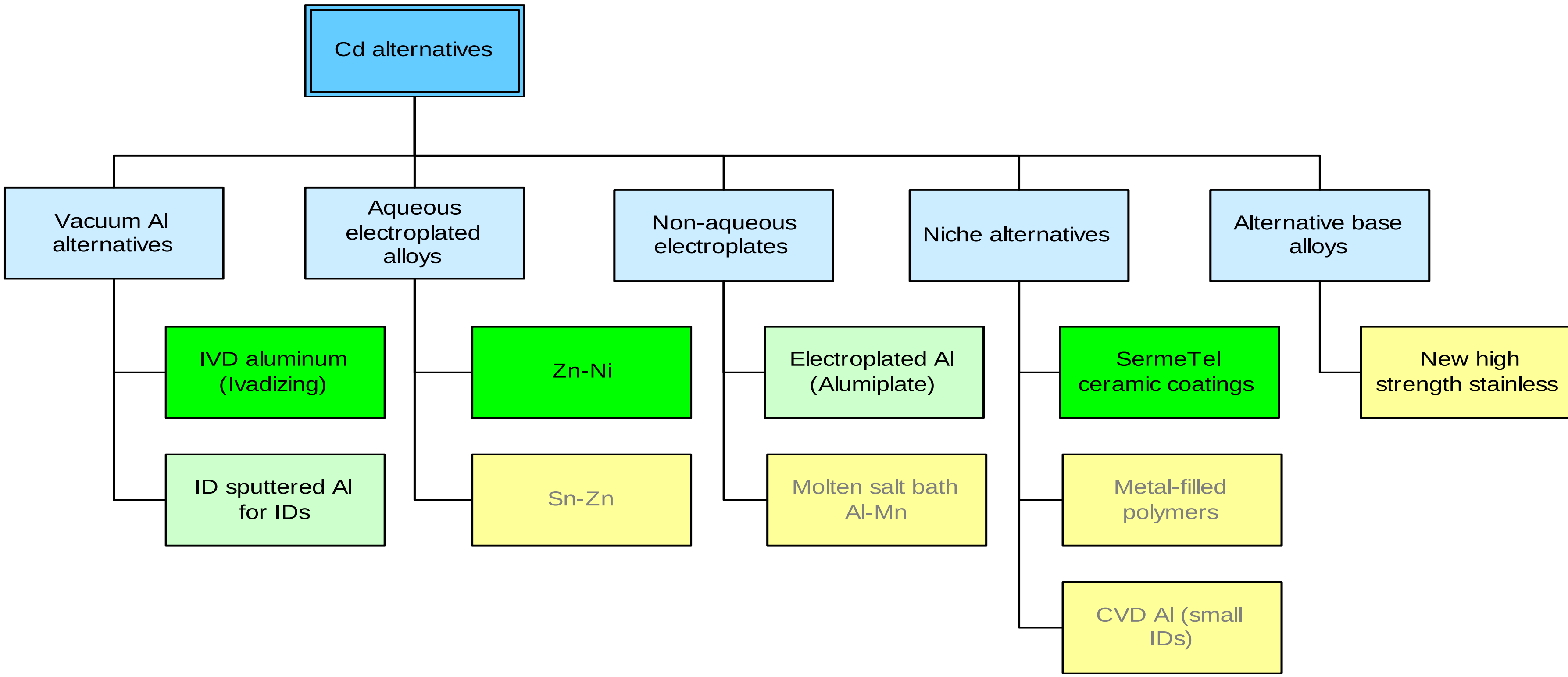
Summary of Cd alternative options



Al is the only "global" replacement
Almost everything needs chromate conversion

In use **In test** **In development**

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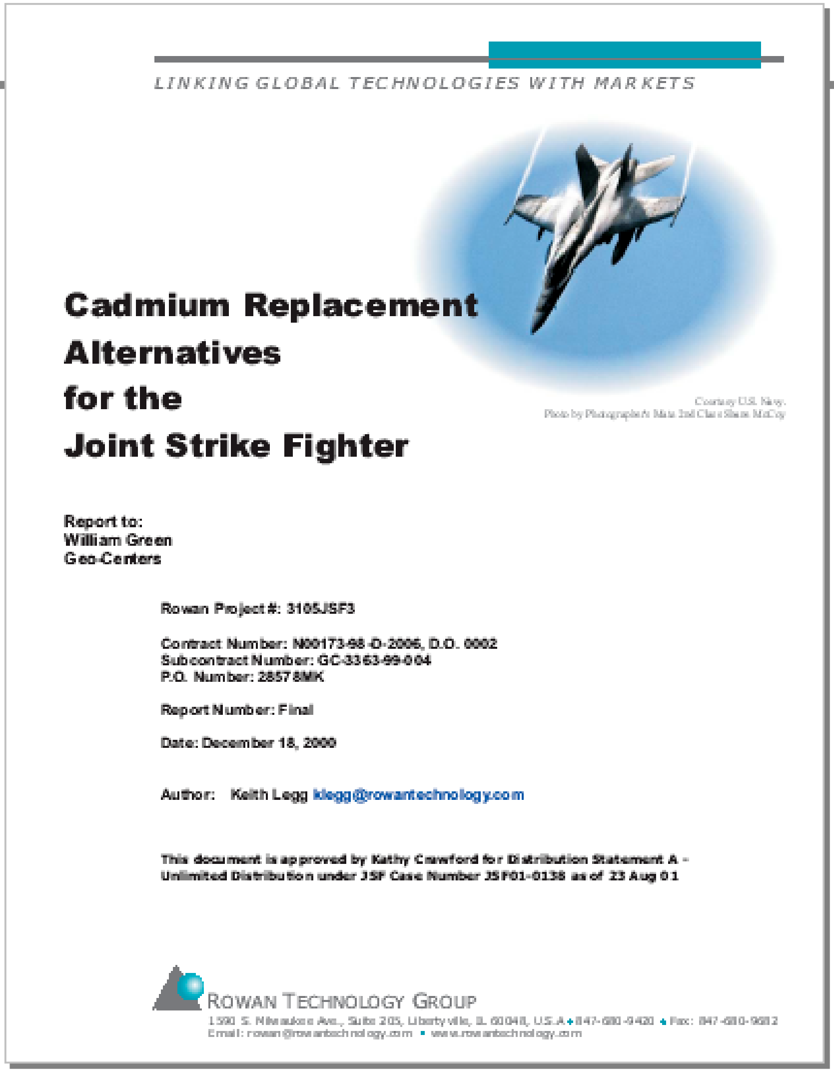
JSF Cd Alternatives Report

- 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/kmcgi.exe?O=DIR0000000GK9&V=0



LINKING GLOBAL TECHNOLOGIES WITH MARKETS

Cadmium Replacement Alternatives for the Joint Strike Fighter

Report to:
William Green
Geo-Centers

Rowan Project #: 3105JSF3

Contract Number: N00173-98-D-2006, D.O. 0002
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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.jgpp.com/projects/cadmium/jtr.html
http://www.materialoptions.com/w2g/cgi/kmcgi.exe?O=DIR000000I6D&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

Distribution Statement "A" applies.
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Contract No. DAAE30-98-C-1050
Task No. N.272
CDRL A006

Prepared by:
National Defense Center for Environmental Excellence (NDCEE)

Submitted by:
Concurrent Technologies Corporation (*CTC*)
100 *CTC* Drive
Johnstown, PA 15904

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

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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

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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

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Data available

Data available from Boeing, JGPP report

http://www.jgpp.com/projects/cadmium/jtr.html

http://www.materialoptions.com/w2g/cgi/kmcgi.exe?O=DIR000000I6D&V=0

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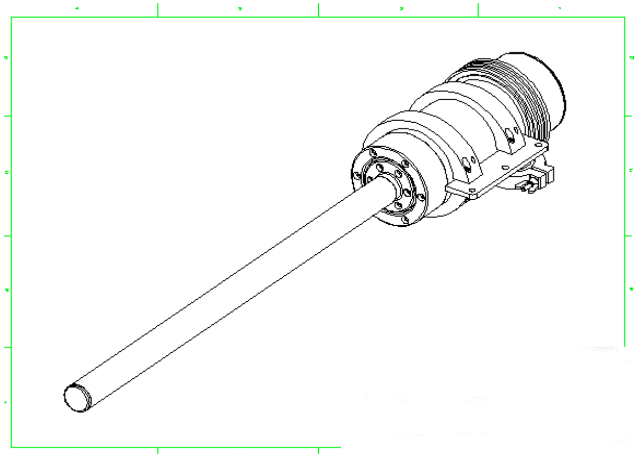
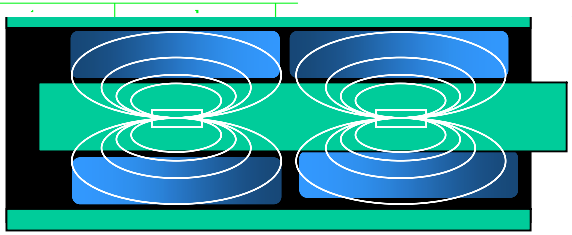
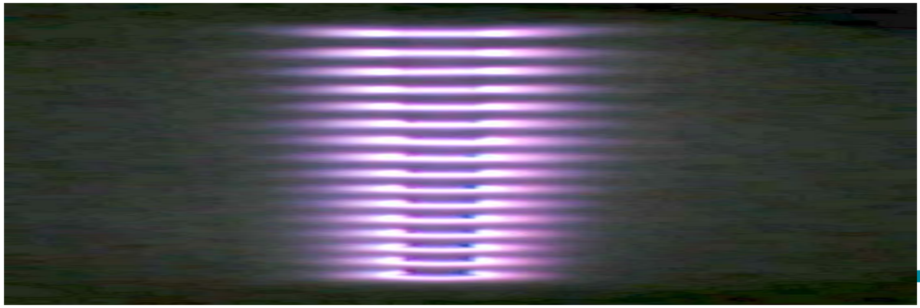
PVD Al for IDs – sputtered Al

- **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)**







ROWAN TECHNOLOGY GROUP
Linking Global Technologies with Markets

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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

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Electroplated Al (Alumiplate™)

Alumiplate, Minneapolis
Deposited from organic solution

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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)

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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

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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

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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

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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

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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

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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)

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SermeTel®

Metal-filled ceramics from SermaTech

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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

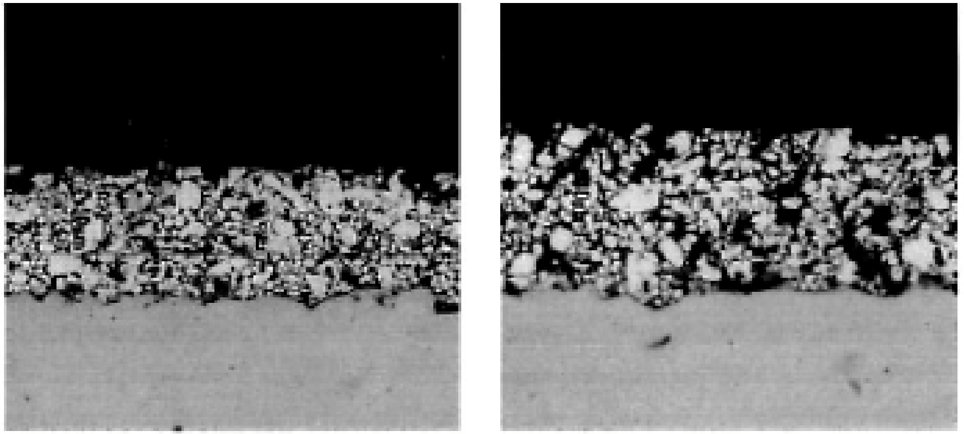

Figure 17. SermeTel aluminum-ceramic coating cross sections 500x. Left chromate-containing coating; right chromium-free coating.

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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)

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Advantages and limitations

Advantages

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

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

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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Data available

Little publicly available data

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Zn-Ni electroplate

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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

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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

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Data available

Data available from Boeing, JGPP report

http://www.jgpp.com/projects/cadmium/jtr.html

http://www.materialoptions.com/w2g/cgi/kmcgi.exe?O=DIR000000I6D&V=0

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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?

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High strength stainless steel

S-53 – new steel developed by QuesTek Innovations LLC

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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

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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

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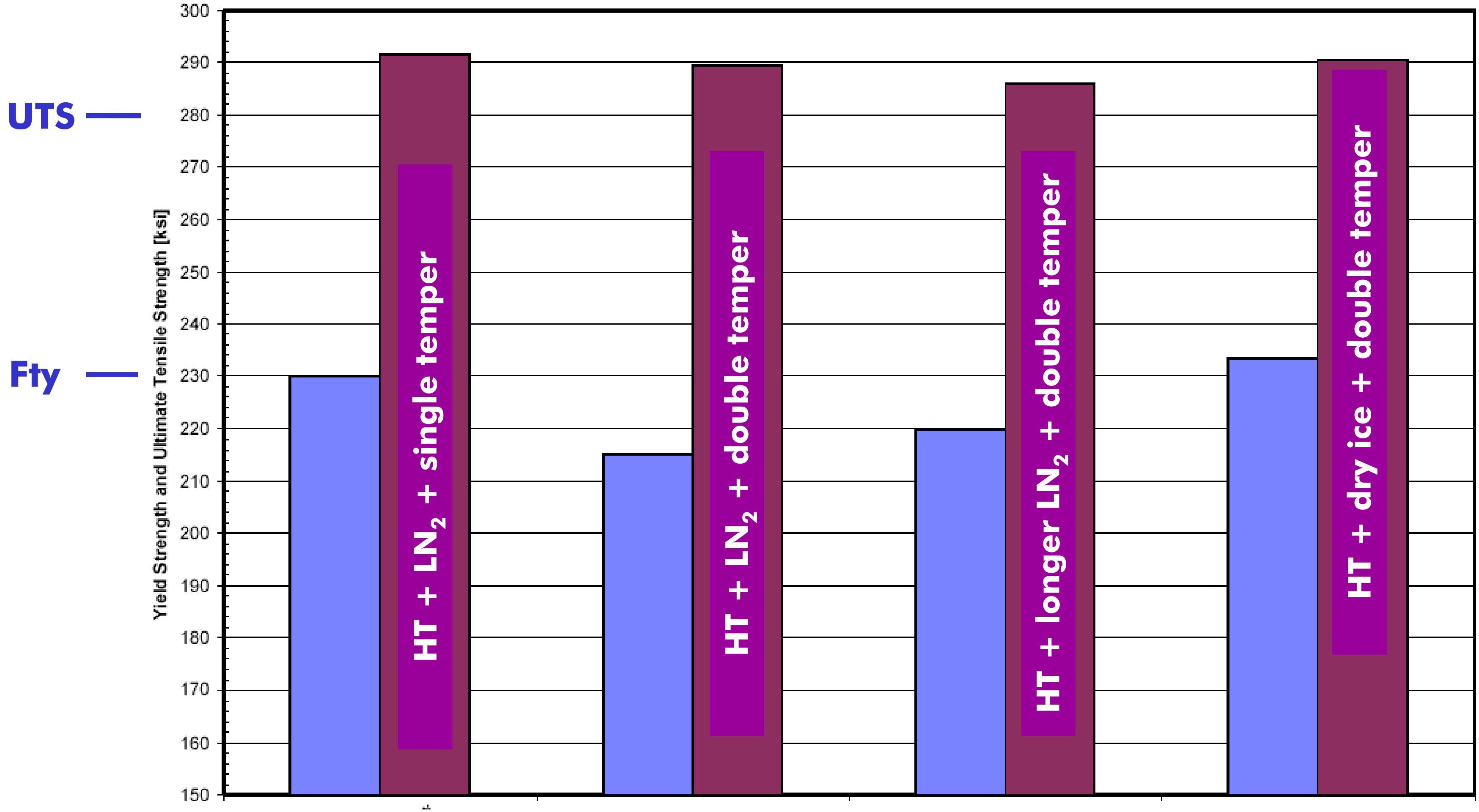
HSSS properties



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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

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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