NANO COBALT COMPOSITES AS ALTERNATIVES FOR Cr AND Ni PLATING IN REPAIR OPERATIONS

Project Number (WP-2609)

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SERDP
DOD ▪ EPA ▪ DOE

Team Members

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NAVAIR FRCSE, DoD Stakeholder, End user, Input for requirements

Technical Background

Electrodeposited Nickel and Chromium are commonly used for repairing worn and damaged components during repair and overhaul operations.

The sequence of operations involves:

1) Preparing the surface for rebuild
2) Bulk Nickel plating for the rebuild (tank or brush plating)
3) Grinding (if necessary)
4) Chrome plating (tank plating) & polishing if necessary

Opportunities exist for significant improvements, particularly with regard to:

1) Use of a single base process (nCoP) instead of Ni+Cr
2) Increased deposition rates
3) Reducing the risk of substrate embrittlement
4) Enhancing ductility, and
5) Improving spalling and corrosion resistance.

Problem Statement

- Electrodeposited nickel and hard chromium coatings are extensively used throughout the DoD for the repair and overhaul of damaged components.
  - Health risks associated with the use of Cr^{6+} baths have been recognized since the early 1930's, wherein skin irritation and inflammation, particularly in the nasal passages, were identified. More recently, such Cr^{6+} baths have been shown to enhance the risk of cancer of the lung and nose.
  - Nickel compounds are known to be human carcinogens based on sufficient evidence of carcinogenicity from studies in humans, including epidemiological and mechanistic studies
  - Metallic nickel is reasonably anticipated to be a human carcinogen* and nickel refinery dust is listed as a known carcinogen by the EPA.
- Due to the increase in operational costs associated with compliance to new rules there is tremendous pressure to find a EPA/OHSA compliant alternative to hard chrome.

**U.S. Department of Health and Human Services 13th Report on Carcinogens on October 2, 2014.*
*International Agency for Research on Cancer (IARC)

General Technical Objective

Replace Cr and Ni Plating in Repair Operations

- Develop and validate an alternative repair technology based on electrodeposited nanostructured cobalt alloy
- Must meet or exceed the properties and performance of:
  - Electroplated nickel coatings
    - Standards: MIL-STD-868A and AMS-QQ-N-290
  - Electrolytic hard chrome coatings
    - Standard: MS-QQ-C-320
  - Selective plating, repair, and rebuilds
    - Standard: MIL-STD-865C

Specific Technical Objectives

Replace Cr and Ni Plating in Repair Operations

Matrix Optimization / Ease-of-use

- Optimize a nanocrystalline cobalt-phosphorus electrodeposition process for repair operations that is based on conventional DC rectifiers in order to reduce infrastructure costs associated with pulse plating;

Property Enhancement

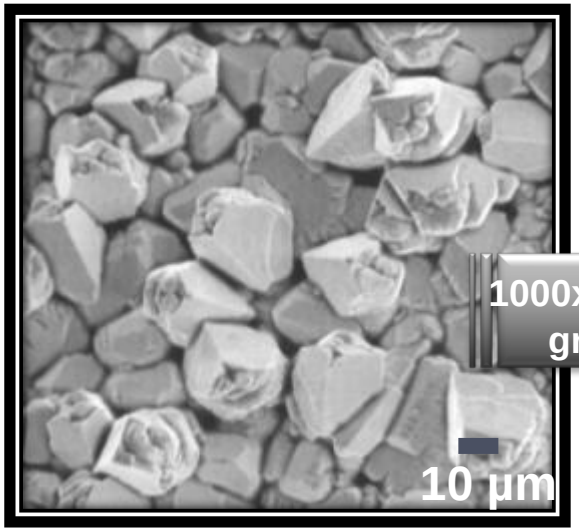
- Develop novel nanocomposite coating systems consisting of a nCoP matrix embedded with second-phase hard particles in order to improve Taber wear performance and Hardness; Composite coatings will be created by
  - Co-deposition of suspended particles, and
  - Novel in-situ particle formation and deposition of nanoparticles (Cirrus Materials Science technology);

Selective/Local Repair Development

- Evaluate suitable equipment to enable brush plating for specialized repair using the optimized material

Nanostructured Materials

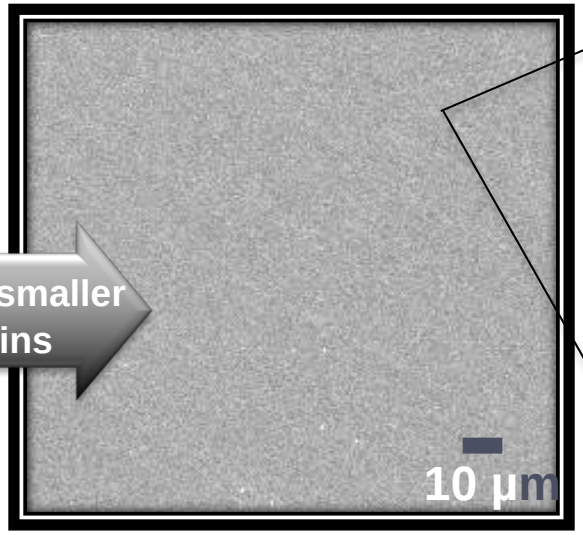
Conventional Metals



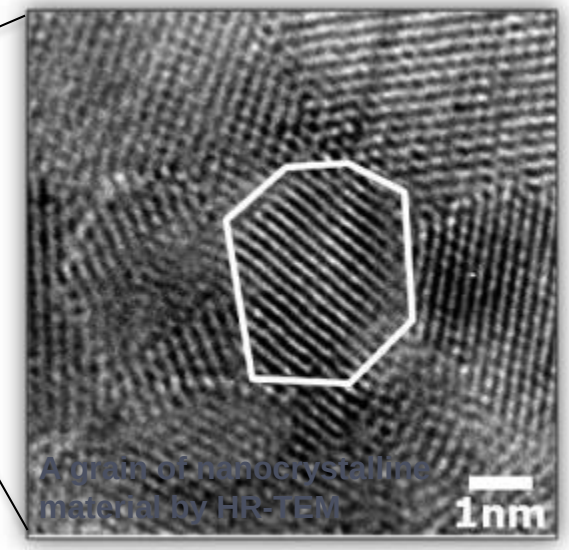
Grain size = 10 – 100 µm

1000x smaller grains

Nanovate™ Metals



Grain size = ≤ 20 nm



A grain of nanocrystalline material by HR-TEM

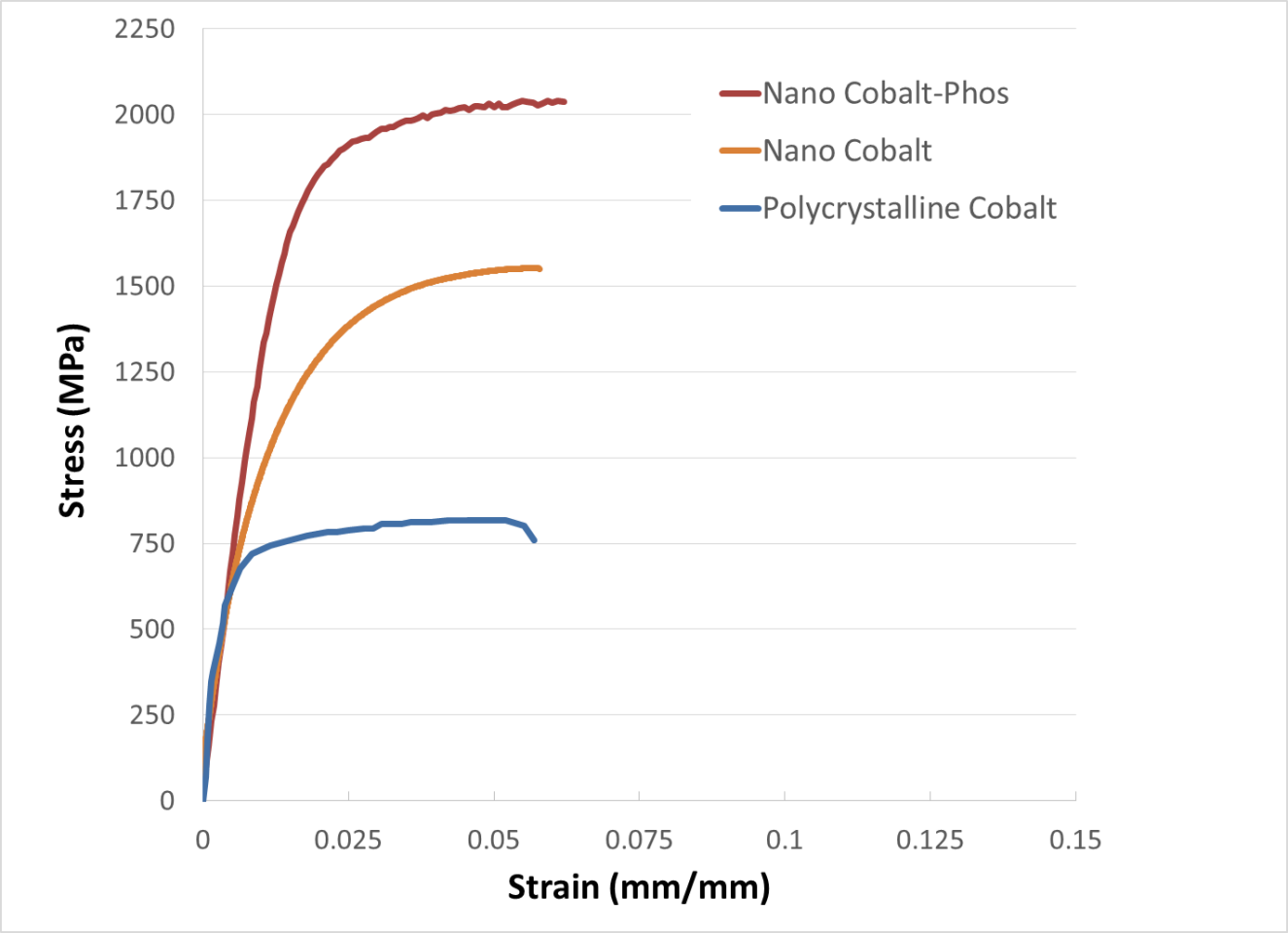
A **nanostructured metal** is simple a metal with an average grain size in the nanometer range (10 - 100 nm) compared to >1 µm for a conventional metal

Decreasing Grain Size Dramatically Improves Hardness and Strength

Property	Units	Conventional Ni (20 µm)	Nanovate Ni (20 nm)
Yield Strength	MPa	100	900
Ult. Tensile Strength	MPa	400	1400
Vickers Hardness	kg/mm^2	140	450

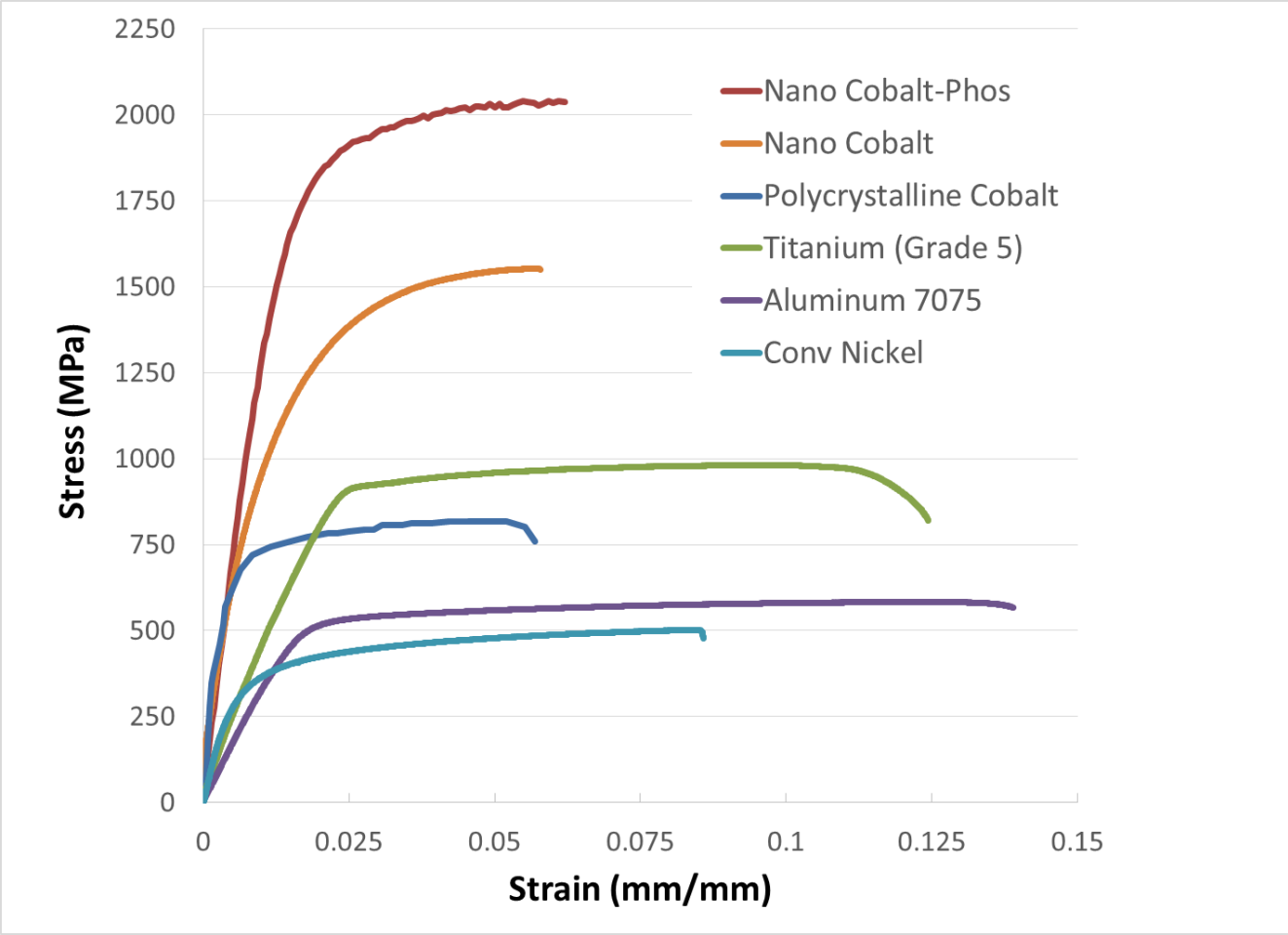
High Strength Structural Materials

Stress-Strain Comparison for nCo and nCoP alloys with conventional structural materials



High Strength Structural Materials

Stress-Strain Comparison for nCo and nCoP alloys with conventional structural materials

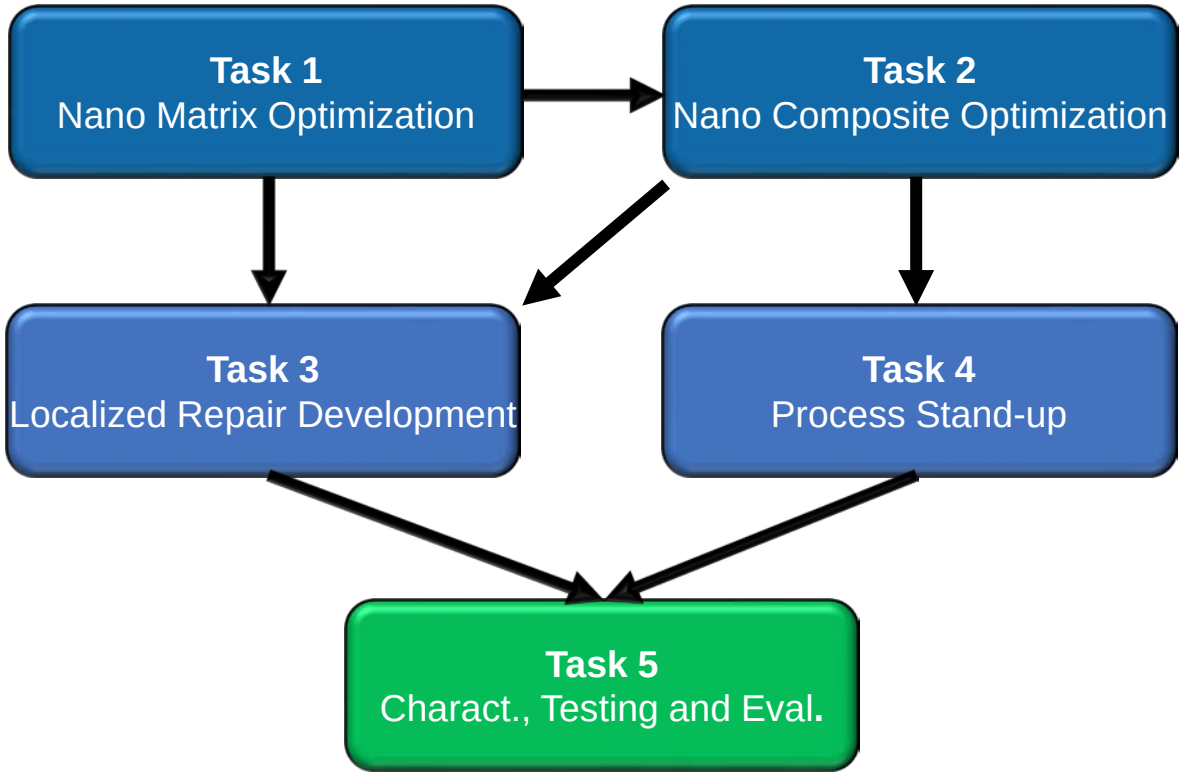


nCoP vs Nickel / Chrome Property Comparison

PROPERTY	TEST METHOD	ELECTROPLATED NI	HARD CHROME	NANOSTRUCTURED COP R3010
Appearance	Microscopy	Pit/Pore/Crack Free	Micro-cracked	Pit/Pore/Crack Free
Microstructure	TEM/XRD	Microcrystalline	-	Nanocrystalline (grain size 5-15nm)
Hardness	Vickers Microhardness	100-150 VHN	Min. 600 VHN	530 – 600 VHN
		-	-	600 – 750 VHN (HT)
Ductility	Bend Test	10%	<1%	2-7%
Wear Volume Loss	Pin-on-disc (against Al_2O_3 pin)	N/A	9 - 11 x 10^{-6} mm^3/Nm	6 – 7 x 10^{-6} mm^3/Nm
Coefficient of Friction	Pin-on-disc (against Al_2O_3 pin)	N/A	0.7	0.4 - 0.5
Taber Wear	CS-17 abrasive wheel	42 mg/1000cycles	3-4 mg/1000cycles	17-18 mg/1000cycles
Corrosion Resistance	Salt Spray	Protection Rating 8 (1000 h salt spray)	Protection Rating 2 (1000 h salt spray)	Protection Rating 8 (1000 h salt spray)
Hydrogen Embrittlement	Mechanical Hydrogen Embrittlement	Pass with bake	Pass with bake	Pass with bake
Fatigue	Rotating Beam Fatigue	N/A	Significant debit	Credit vs. EHC, Similar to vs. bare
	Axial Fatigue	N/A	Significant debit	Credit vs. EHC and bare

Technical Approach

Project Flow Chart



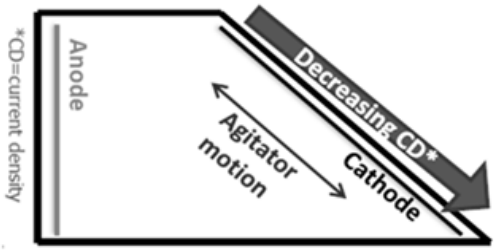
- The workplan for the project consists of five Tasks.
- The optimization of the coating process, material synthesis, and material characterization and testing has been performed on a real time feedback basis for effective process and material optimization.
- All successful systems developed in Tasks 1 to 3 are being evaluated in Task 5.

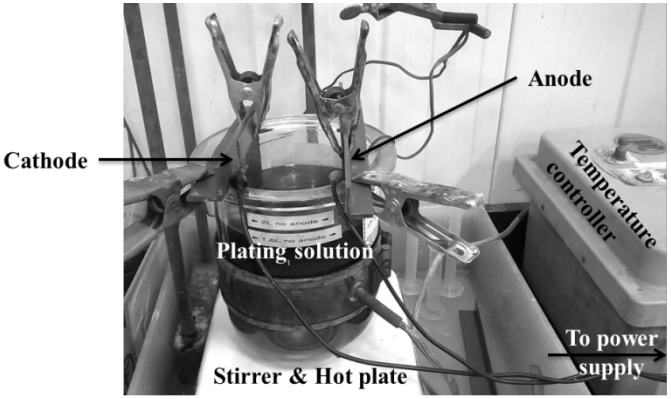
Task 1

Task 1 - Development and Optimization of Matrix Material

Nanostructured Cobalt "Matrix" Optimization

- Laboratory-scale DOEs were conducted. Parameters investigated included:
  - Temp, pH, Current density, pulse conditions, additive concentration, phosphorous concentration
- Sample analysis/characterization included:
  - integrity/uniformity of the deposit, microstructure, microhardness, and composition
- Optimization of the Nano Cobalt coating process for Steel and Aluminum Substrates





Task 1: CoP Process Optimization

- **Objective**: Develop DC plating capability at reduced operating temperature
- DOE resulted in successfully identifying operating conditions & bath chemistry that works with conventional DC rectifiers & reduced operating temperatures with no significant change to key deposit properties.

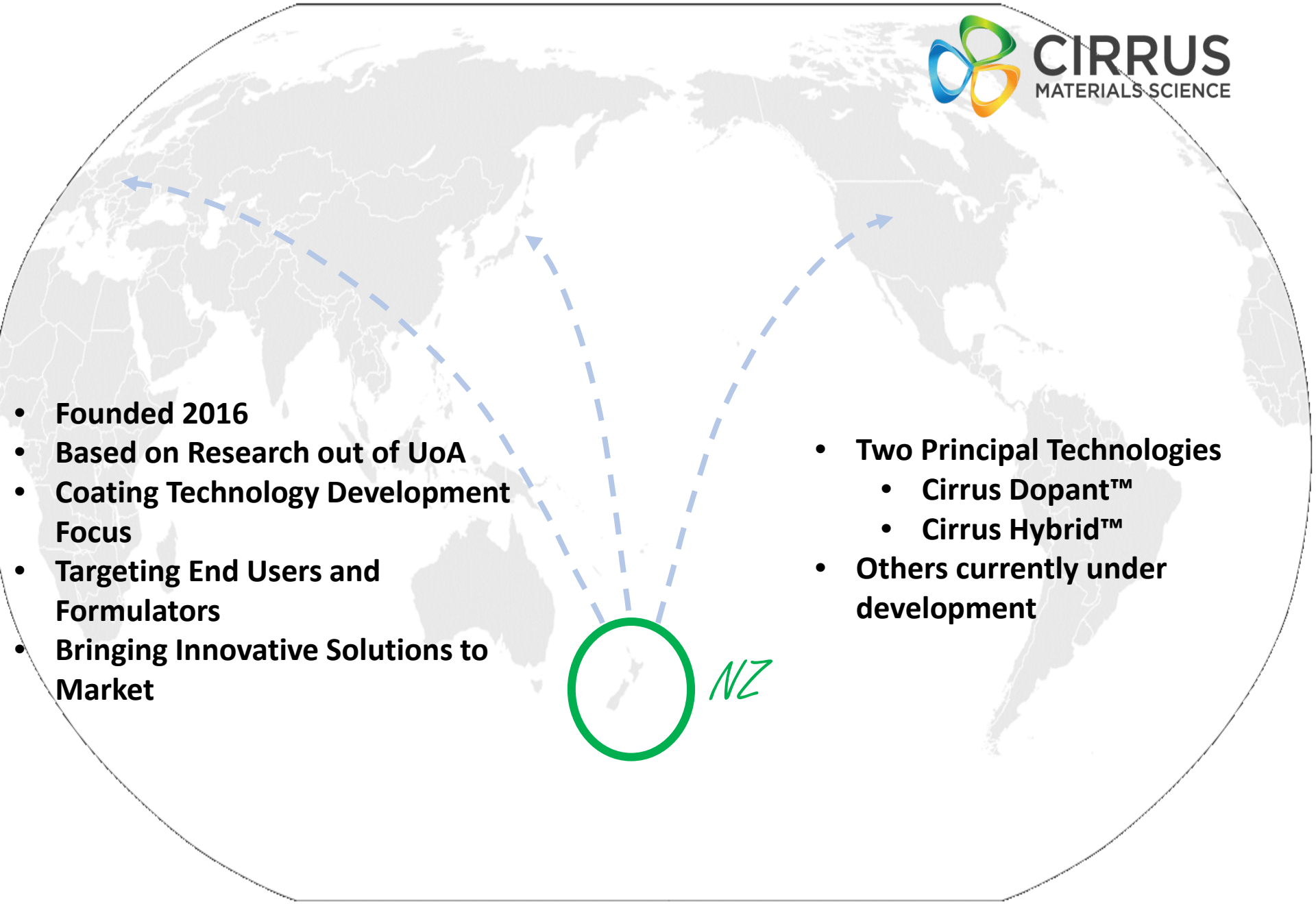
Plating conditions	Hardness (VHN)	Taber Wear Index (mg/1000 cycles, CS-17 wheels)	Pin on Disk (Al_2O_3 pin)	
			Average Coefficient of friction (μ)	Sliding wear rate* (10^{-6} mm^3/Nm)
Standard Operating Conditions: 85°C, 135 mA/cm^2, PP	530 - 600	18	0.58	12.4
Re-optimized Conditions: 70 - 75°C, 80 - 150 mA/cm^2, DC	530 - 550	15 - 18	0.49 - 0.63	12.8 - 13.7

Benefits of results:

- DC-compatibility: Reduced infrastructure costs associated with pulse plating
- Lower operating temperature: improved operator handleability, compatibility with various masking waxes, reduced processing cost
- Larger current density window: enhanced ability to plate on more complex geometries, reduced processing cost

CIRRUS
MATERIALS SCIENCE

- Founded 2016
- Based on Research out of UoA
- Coating Technology Development Focus
- Targeting End Users and Formulators
- Bringing Innovative Solutions to Market



- Two Principal Technologies
  - Cirrus Dopant™
  - Cirrus Hybrid™
- Others currently under development

Technical Approach - Task 2

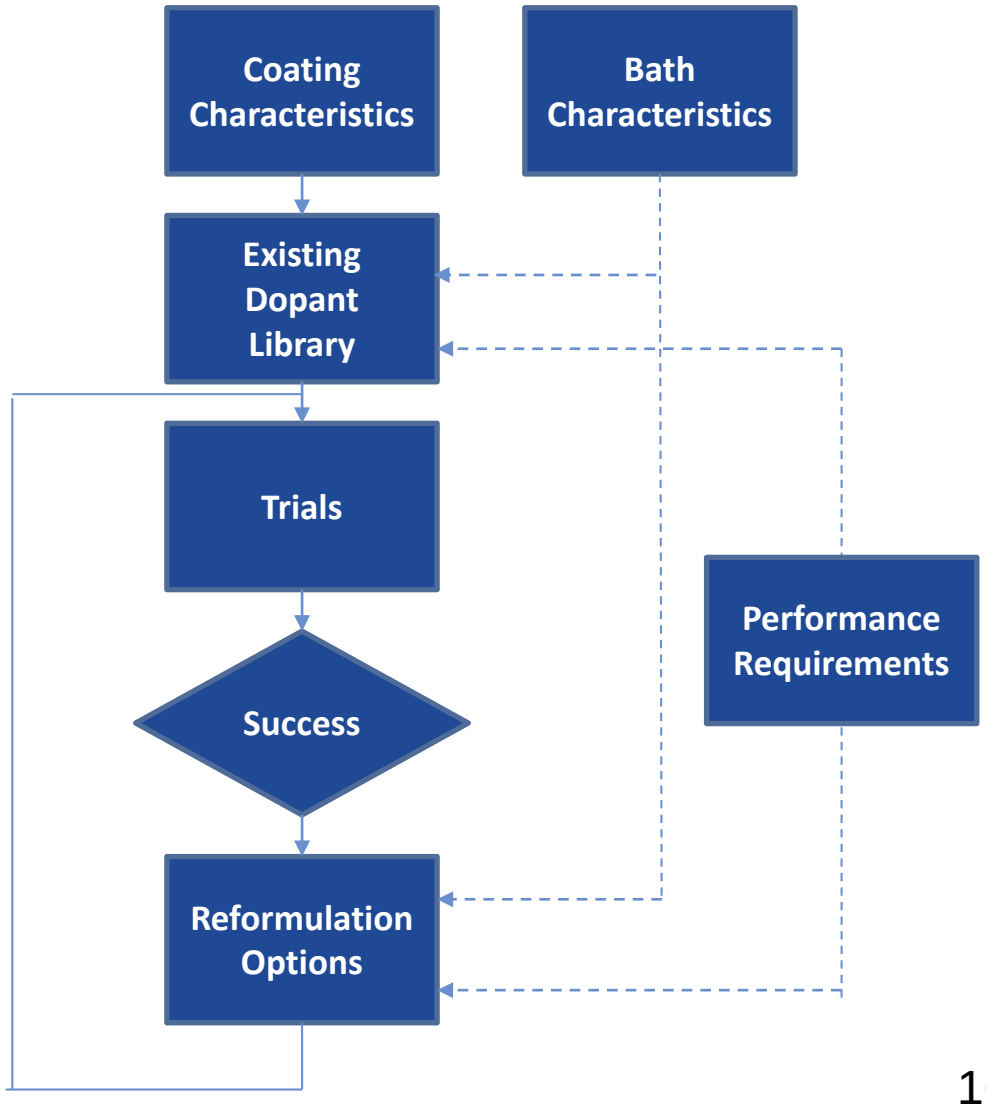
TASK 2 – DEVELOPMENT OF PROCESS TO CO-DEPOSIT HARD CERAMIC SECOND PHASE PARTICLES INTO THE NANOMETAL MATRIX

Task 2A – Cirrus Dopant™ In-situ Nanoparticle Formation

- Objective: to achieve the formation of nano-particles of a characteristic (size, charge, structure) that allows them to be co-deposited uniformly throughout the coating matrix.
- This included the following subtasks:
  1. nCoP process stand-up
  2. Evaluation of dopant compatibility with nCoP chemistry: Zr-, Al-, Ti- based dopants were investigated.
  3. Determination of doping levels: 5 mL/L to 20mL/L
  4. Confirm coating performance: Composition, micro-hardness, reciprocating wear tests
  5. Development of Al- and Ti- dopants with improved bath stability
  6. Determination of bath management parameters
  7. Technology transfer to Integran

Dopant Selection

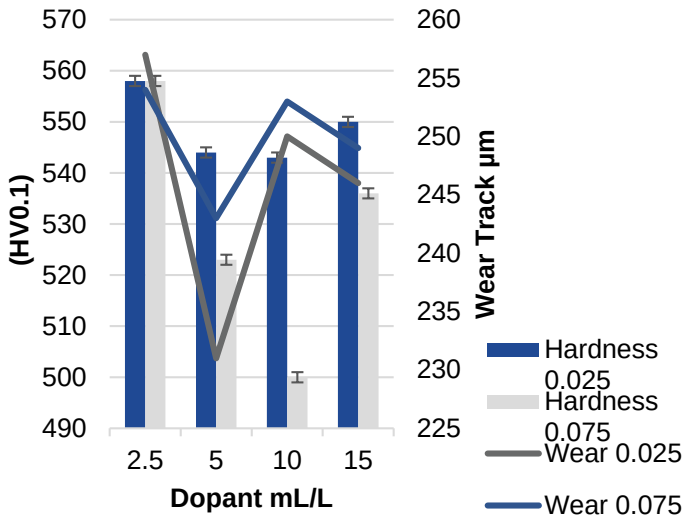
- Dopant Selection is a process
- Primarily dopants are optimised for particle type
- Secondary optimisation for bath pH and chemistry
- Tertiary optimisation for particle concentration
- All factors can affect a dopants operation within a specific bath

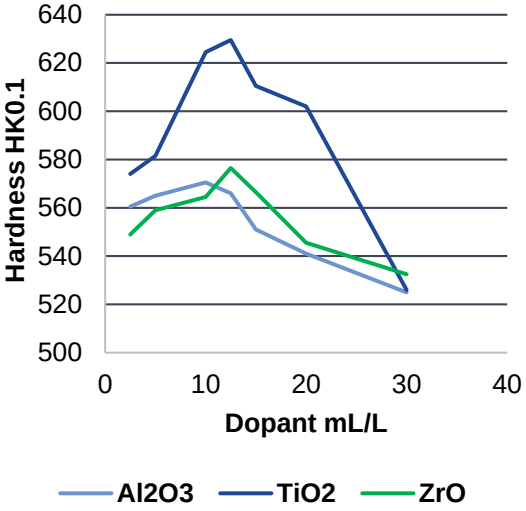


Task 2: Property Enhancement via Nanocomposite Generation – Cirrus dopants

First Trails:

- Existing dopants
  - Aqueous Al_2O_3
  - Organic TiO_2 and ZrO_2
- Looking for trends



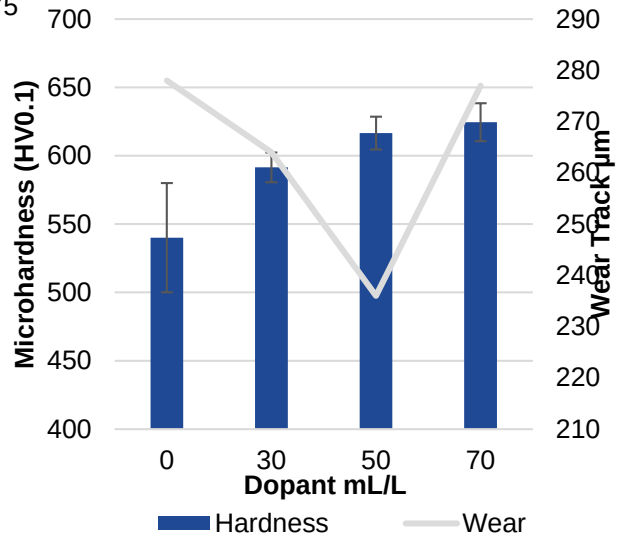


Second Trials:

- Focus on alumina dopant
- Higher particle density
- More compatible dopant formulation

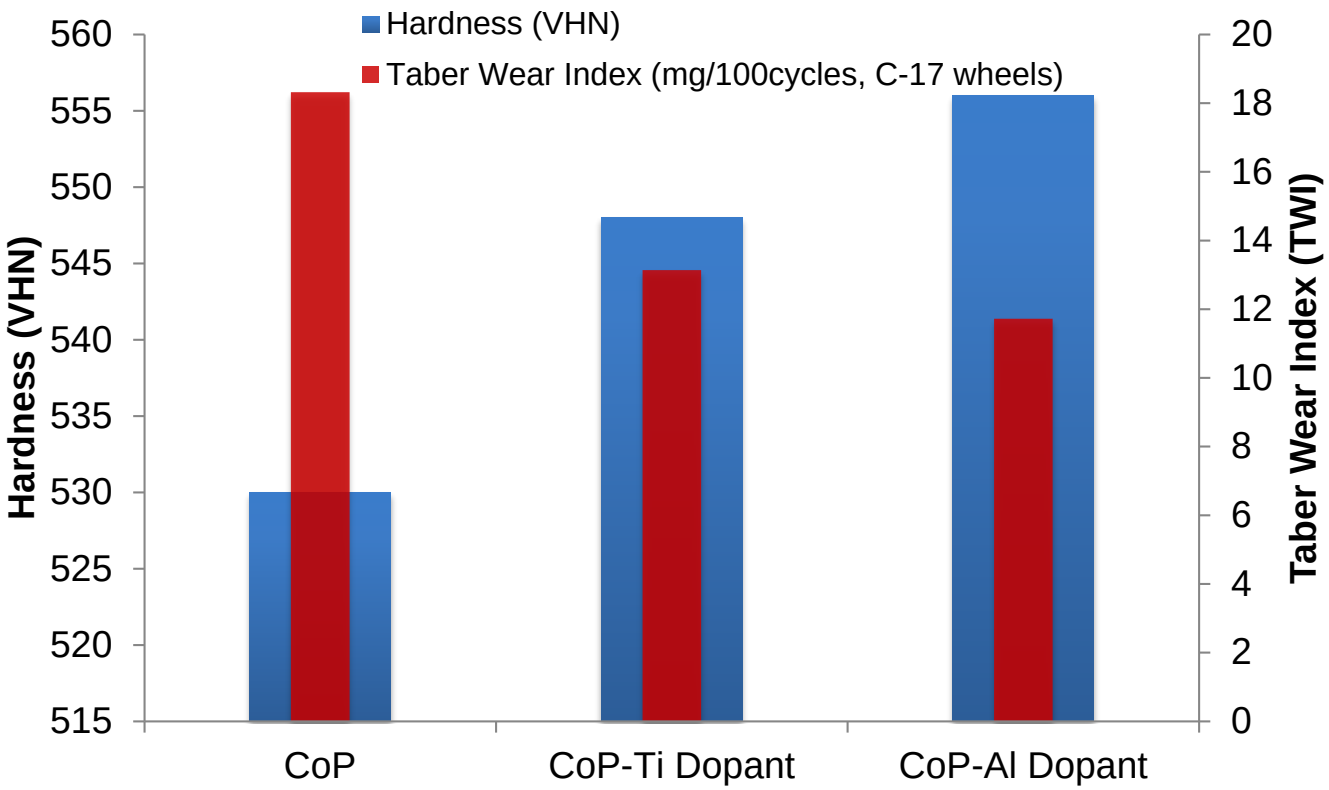
Third Trials:

- Looking for smaller particle
- Improved Aqueous TiO_2
- Promising hardness > 600HV
- No stable high particle concentration formulation
- Bath lifetime insufficient



Task 2: Property Enhancement via Nanocomposite Generation – Cirrus dopants

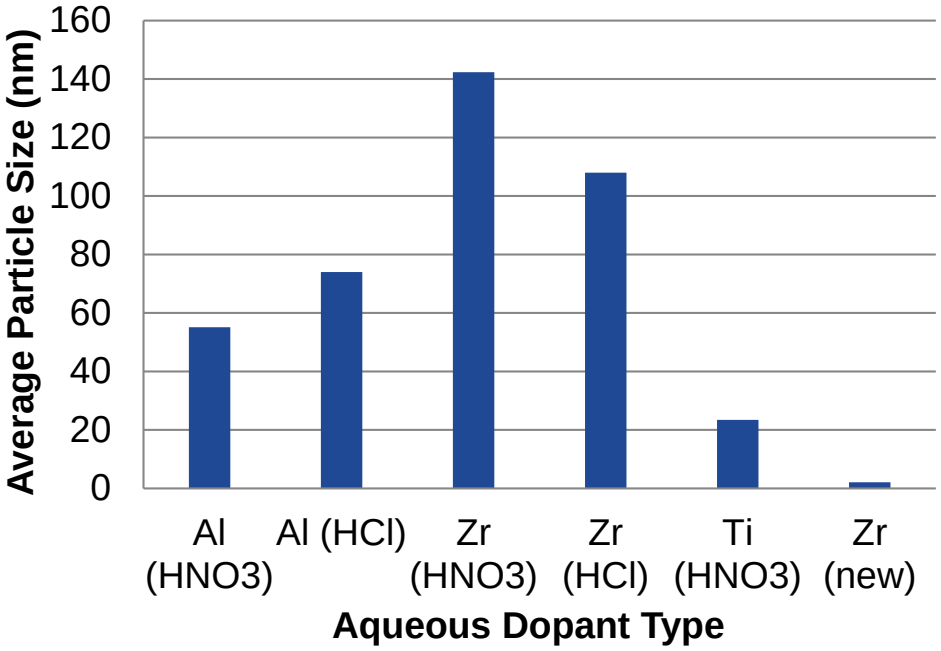
- Second generation CoP-compatible dopant chemistries successfully developed.
- Improved wear and hardness achieved with dopant additions.



- TiO_2 and Al_2O_3 dopant technology was transferred to Integran for scale-up.

Cirrus dopants – Current Research Directions

- High concentration Zirconia dopant
  - Reliable 'clear dopant' developed
  - Optimum range < 20 nm particle size
  - High and controllable particle density
  - Designed for low pH baths



- Operation of dual dopants
  - Requires high particle density, <<1% dilution
- Other particle types
  - Researching formulations for carbide and other particles types

Technical Approach - Task 2 (Cont.)

Task 2B – Co-deposition of Second Phase Particulate

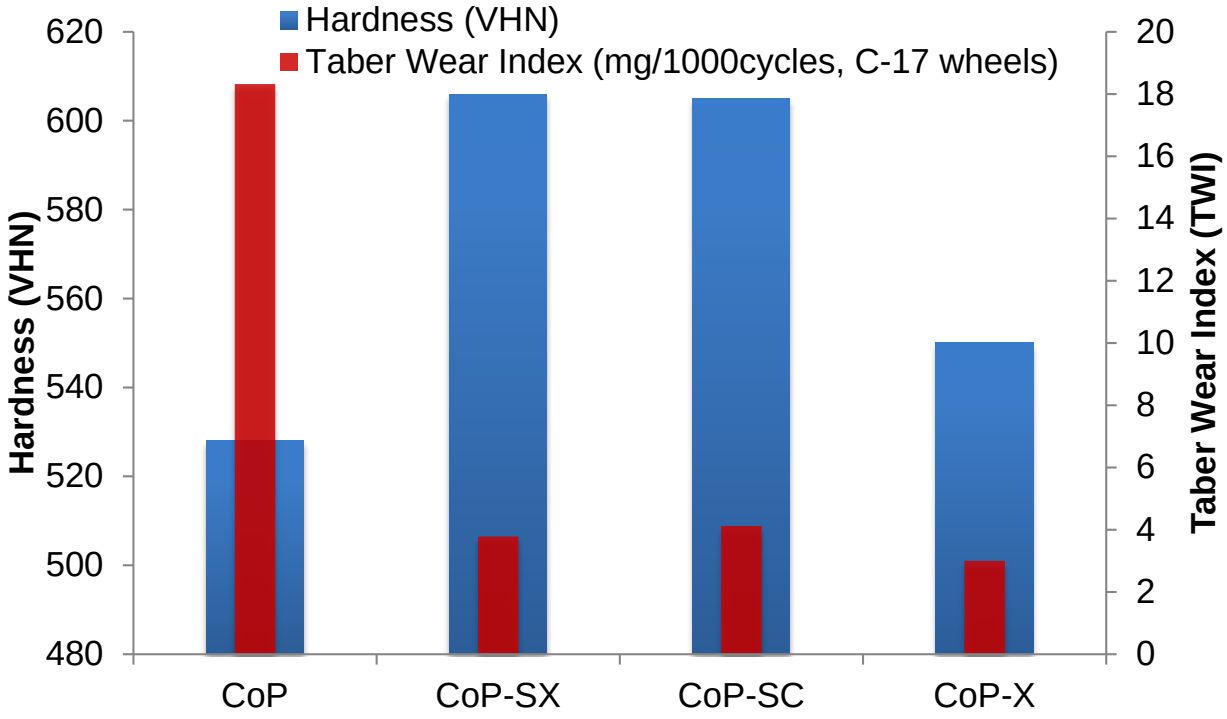
- Objective was to obtain a particulate content sufficient to achieve good Taber wear performance.
- Particle systems investigated included:

Particle type	Particle Size (nm)	Particle loading concentration (g/L)
Chrome carbide, Cr_3C_2	800 - 1300	10 to 120
Silicon carbide, SiC	40, 500, 1000	10 to 120
Alumina, Al_2O_3	800	10 to 120
Diamond	700	2.5 to 10

- DOEs investigated:
  - concentration of particles in solution, particle size, solution flow, various surfactant and surfactant concentration, temperature and electrical parameters.
- Focus was to determine which particle system /size /geometry provides the best increase in hardness and wear resistance

Task 2: Property Enhancement via Nanocomposite Generation – Suspended particles

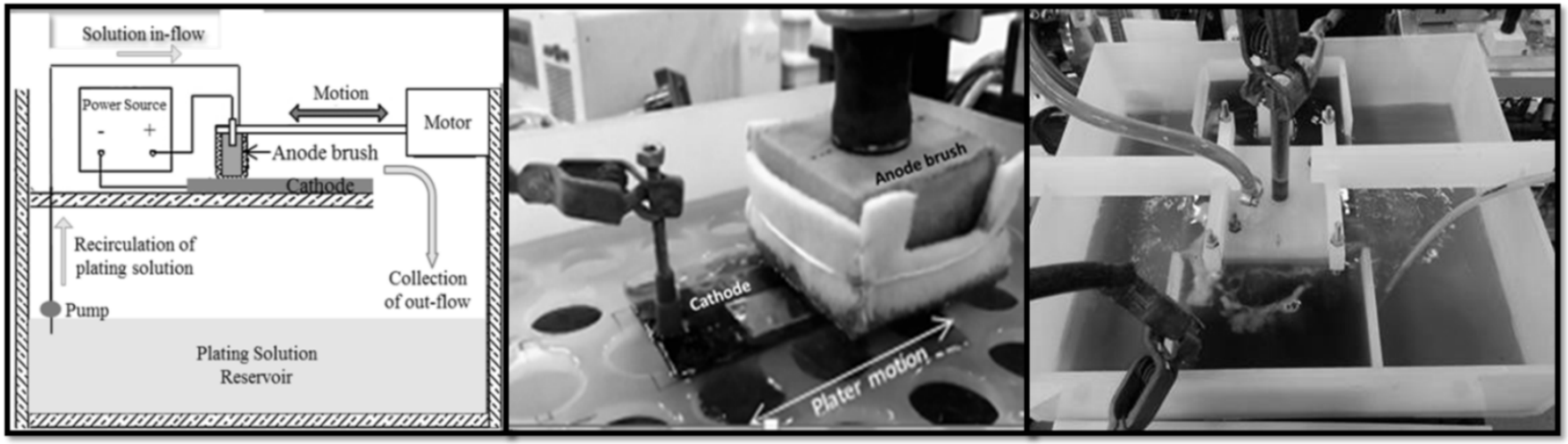
- *Objective:* Property enhancement via nanocomposite generation
- Successfully developed novel nanocomposite coating systems via co-deposition of suspended particles.
- Improved deposit property: hardness and abrasive (Taber) wear performance.
- Feasibly translate to improved in-field performance and extended service life of component.



Technical Approach - Task 3

Task 3 – Development of Specialized Repair Methods via Brush Plating

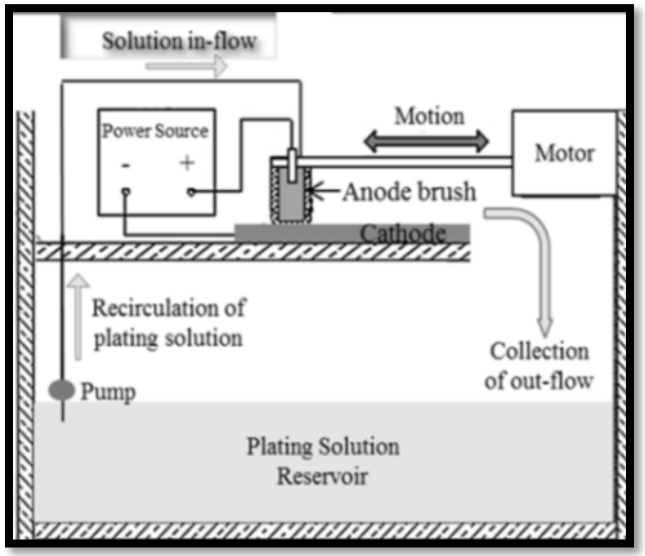
- Developed specialized repair methods using brush plating with the optimized Nano Co-alloy coating, first from from Task 1 (Nano Matrix), then from Task 2 (Nano Composite).
- Design of experiments (DOE) studying:
  - Particulate concentration, solution replenishment i.e. flow rate, brush motion (speed, distance), absorbent material, operating parameters (temperature / current density)
  - Evaluation of microstructure, composition particle conc., micro-hardness and taber wear

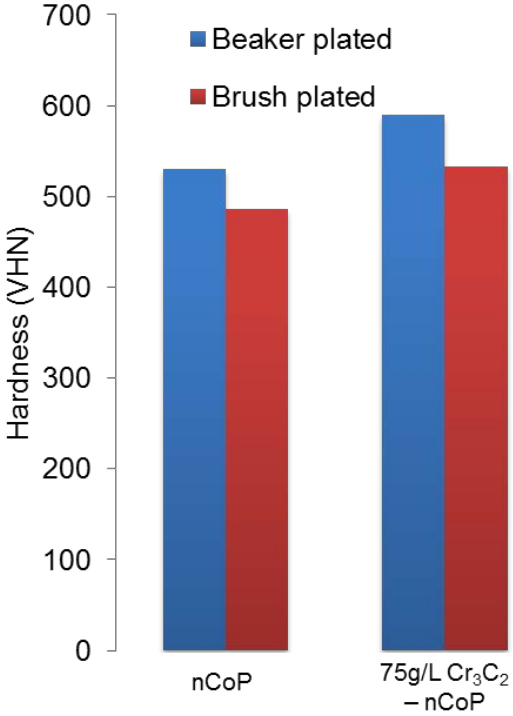


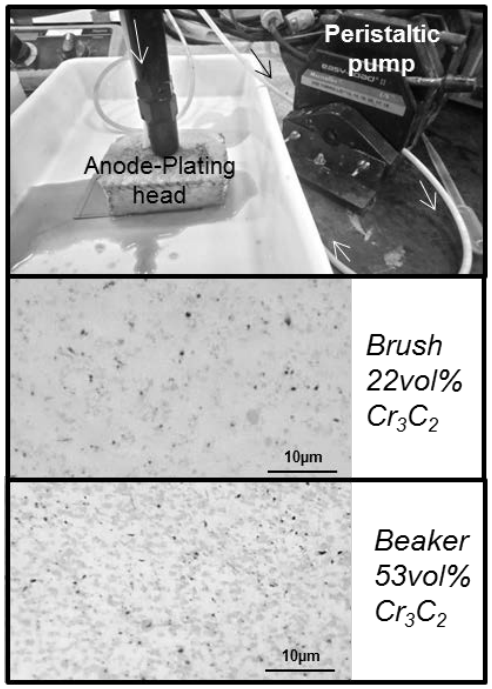
Standard Brush Plating Set-up

Task 3: Brush Plating Systems for Repair Operations

- ***Objective**:* Evaluate brush plating systems for repair operations using optimized materials
- Successfully co-deposited particles using brush plating setup.

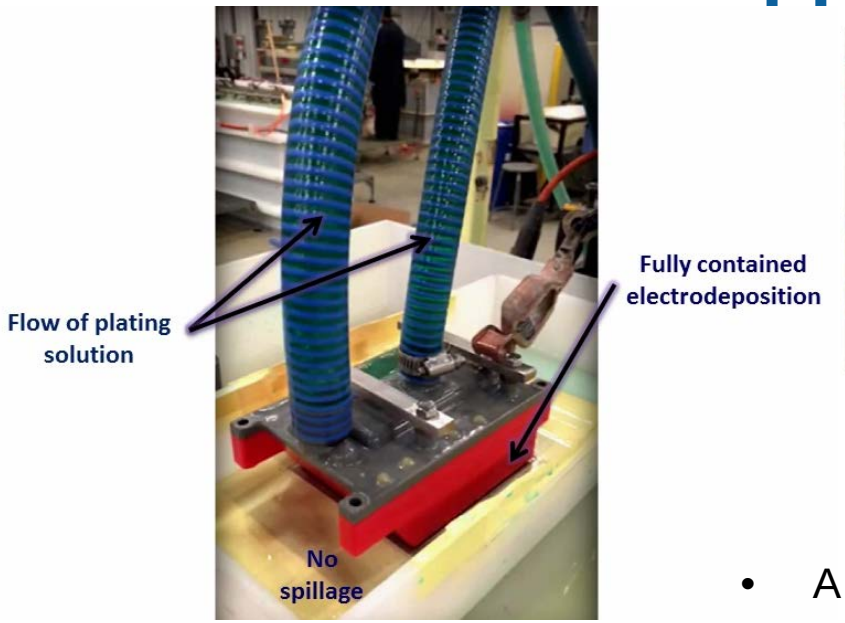


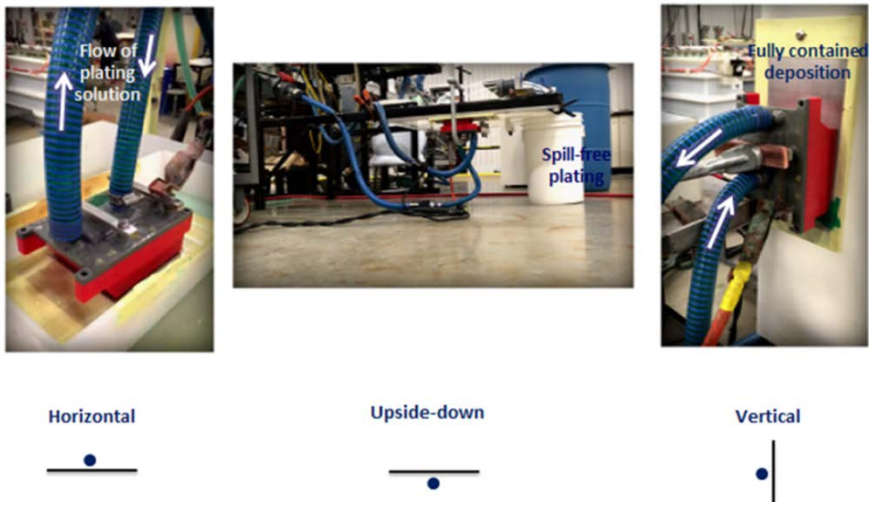




- Standard brush plating set-up worked well for the CoP but not CoP-particle systems
- Issue: entrapment of particles in anode brush
- Solution: Integran's Encased Contact Free Plating Apparatus

Task 3: Encased Contact Free (ECF) Plating Apparatus





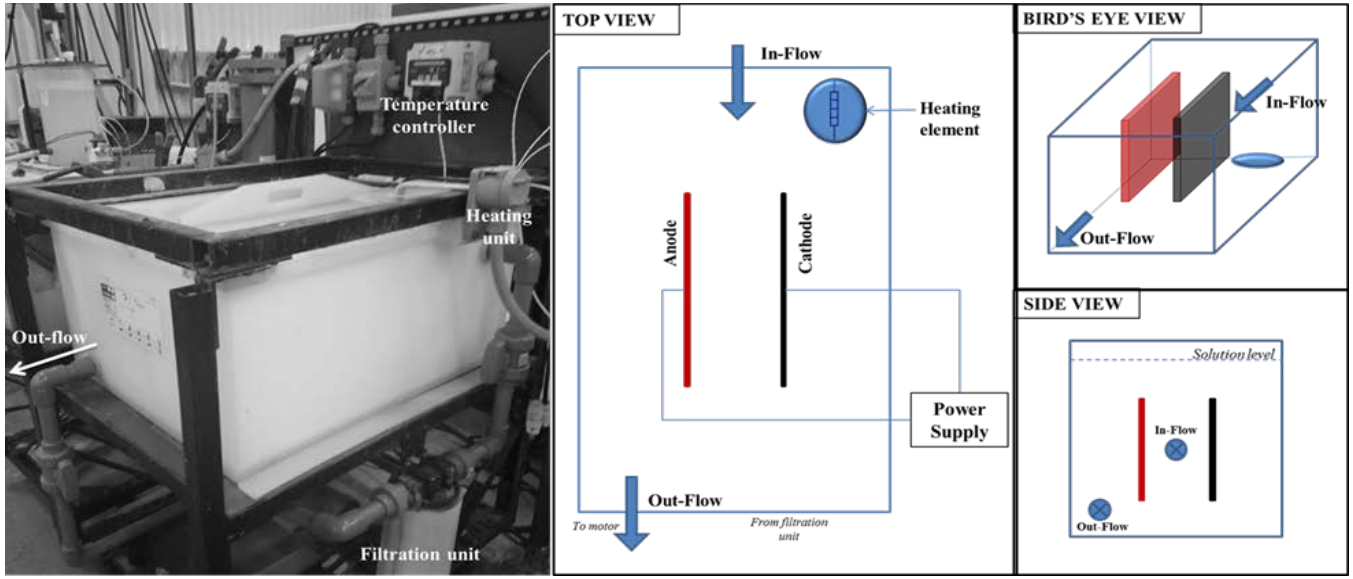
- A ECF-friendly nCoP chemistry was developed and is currently being validated.

Property →	Hardness (VHN)		Taber Wear (mg/1000cycles, CS-17 wheels)	
Chemistry → System ↓	Conventional Plating	ECF Plating	Conventional Plating	ECF Plating
CoP	530 - 600	620 - 630	17 - 18	18 - 21
CoP- X	530 - 600	620 - 630	4 - 6	3 - 5
CoP- AD	530 - 550	630 - 640	12 - 15	TBD

Technical Approach - Task 4

TASK 4 – FINAL PROCESS STAND-UP

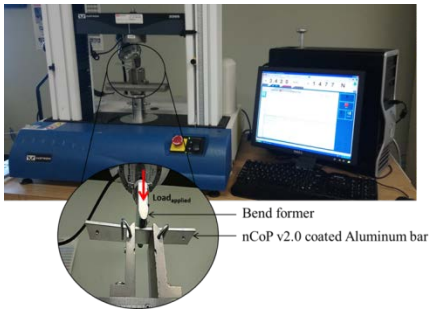
- Stand-up of the down-selected nanostructured cobalt metal matrix and second-phase particulate and/or Cirrus dopant™ at Integran in a 40-60L plating tank.
- A short DOE is being conducted to determine the optimal windows of operation for the scaled-up process. Optimization has been completed for baseline CoP.
- Test coupons are being fabricated for further property and performance testing in Task 5.



Technical Approach - Task 5

TASK 5 – COATING CHARACTERIZATION, TESTING AND EVALUATION

- Test/evaluation program was designed and is being followed
- Testing to be performed alongside the development and optimization of the coating include:
  - Characterization: composition, microstructure, surface finish (Integran/Cirrus)
  - Adhesion testing: Bend adhesion (Integran)
  - Mechanical testing: micro-hardness, coating ductility (Integran)
  - Wear testing: pin-on-disk (Integran), Taber wear (Integran)
  - Corrosion testing: 1000h salt spray (Integran), galvanic compatibility (Corrdesa)
  - Embrittlement testing: Sustained load testing on notched bars
- Baseline comparisons made against nickel and hard chrome repair
- Goal is to meet and/or exceed the properties of the benchmark material.



nCoP vs Nickel / Chrome Property Comparison

PROPERTY	TEST METHOD	ELECTRO-PLATED NI	HARD CHROME	NANO-STRUCTURED CoP R3010	NANO-STRUCTURED CoP R3010 (TASK 1) *	NANO-STRUCTURED CoP-X *	NANO-STRUCTURED CoP-AD*
Appearance	Microscopy	Pit/Pore/ Crack Free	Micro-cracked	Pit/Pore/Crack Free	Pit/Pore/ Crack Free	Pit/Pore/ Crack Free	Pit/Pore/ Crack Free
Micro-structure	TEM/XRD	Microcrystalline	-	Nano-crystalline (grain size 5-15nm)	Nano-crystalline (grain size 5-15nm)	Nano-crystalline (grain size 5-15nm	Nano-crystalline (grain size 5-15nm
Hardness	Vickers Micro-hardness	100-150 VHN	Min. 600 VHN	530 – 600 VHN	530 – 600 VHN	530 – 600 VHN	530 – 600 VHN
		-	-	600 – 750 VHN (HT)	*In progress*	*In progress*	*In progress*
Ductility	Bend Test	10%	<1%	2-7%	2-7%	*In progress*	*In progress*
Wear Volume Loss	Pin-on-disc (against Al_2O_3 pin)	N/A	9 - 11 x 10^{-6} mm^3/Nm	6 – 7 x 10^{-6} mm^3/Nm	5 – 7 x 10^{-6} mm^3/Nm	11 – 13 x 10^{-6} mm^3/Nm	5 – 7 x 10^{-6} mm^3/Nm
Coefficient of Friction	Pin-on-disc (against Al_2O_3 pin)	N/A	0.7	0.4 - 0.5	0.4 - 0.6	0.5 – 0.7	0.4 – 0.6

** Results are currently being verified*

nCoP vs Nickel / Chrome Property Comparison

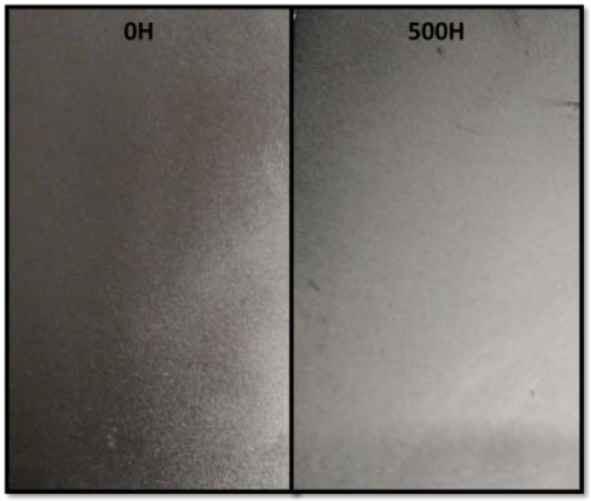
PROPERTY	TEST METHOD	ELECTRO-PLATED NI	HARD CHROME	NANO-STRUCTURED CoP R3010	NANO-STRUCTURED CoP R3010 (TASK 1) *	NANO-STRUCTURED CoP-X *	NANO-STRUCTURED CoP-AD*
Taber Wear	CS-17 abrasive wheel	42 mg/1000 cycles	3-4 mg/1000 cycles	17-18 mg/1000 cycles	15 - 18 mg/1000 cycles	4 - 6 mg/1000 cycles	12 - 15 mg/1000 cycles
Corrosion Resistance	Salt Spray	Protection Rating 8 (1000 h salt spray)	Protection Rating 2 (1000 h salt spray)	Protection Rating 8 (1000 h salt spray)	>1000 h salt spray	>1000 h salt spray	>1000 h salt spray
Hydrogen Embrittle-ment	Mechanical Hydrogen Embrittlement	Pass with bake	Pass with bake	Pass with bake	*In progress*	*In progress*	*In progress*
Fatigue	Rotating Beam Fatigue	N/A	Significant debit	Credit vs. EHC, Similar to vs. bare	-	-	-
	Axial Fatigue	N/A	Significant debit	Credit vs. EHC and bare	-	-	-

** Results are currently being verified*

Structural Anti - Tarnish Coating

- In collaborative effort with VaporTech, CO, a thin-film PVD (physical vapor deposition) topcoat was applied to nCoP base layer and tested for hardness, corrosion and abrasive (Taber) wear performance.
- Top coat is <2um with a hardness >1800 VHN.
- Excellent Taber wear performance and >500h of protection in Salt Spray with no evident sign of tarnishing.

Surface Hardness of Hybrid (VHN)	Taber Wear Index (CS-17 wheels, mg/1000 cycles)
>800	3.7

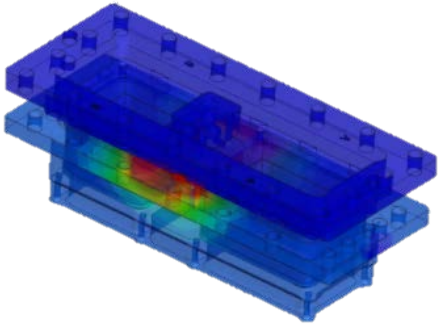


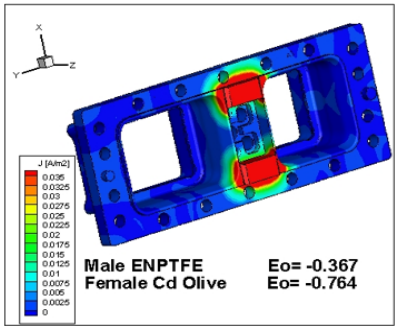
Sample before and after 500h ASTM B117 Salt Spray

- Testing is continuing and results are currently being verified and validated.

Work in Progress

- Continue characterization, evaluation and validation of three developed systems (Integran):
  - Baseline nCoP
  - nCoP-X (ceramic hard particle system)
  - nCoP-AD (Cirrus dopant system)
  - nCoP-Zr based top coat (VaporTech system)
- Performing electrochemical characterization/analysis of the optimization nCoP plating solutions required for FEA modeling (Corrdesa & Integran)
- Investigating a high concentration Zirconia dopant (Cirrus & Integran)





Summary

Nanovate CoP process and performance enhancement via:

Task 1: CoP process optimization

- DC rectifier compatible ✓
- Lower operating temperature ✓
- Plating on steels and aluminum ✓

Task 2: Investigate CoP metal matrix composites for enhanced wear properties

- Co-deposition of suspended particles ✓
- Novel in-situ particle formation and deposition of nanoparticles ✓

Task 3: Brush plating for repair operations

- Evaluation and optimization of equipment to enable brush plating for specialized repair for CoP and CoP-composite systems ✓

Task 4: Process stand-up

- Scale-up of successful chemistries at Integran for production of validation samples ✓

Task 5: Characterization, Evaluation and Validation

- Active task → validation and demonstration of developed technologies to completed by October 2018.

Thank you for your attention

Questions?

BACK-UP SLIDES

nCoP vs Chrome Process Comparison

Nanovate CoP advantages

- **High deposition rate**: 5× faster than chrome, shorter cycle/increased throughput
- **High current efficiency**: Reduced power consumption (up to 20 times less process power)
- **Drop-in technology**: Aqueous bath electroplating, reuse of equipment and minor training
- **Bath stability**: Bath maintenance basic and impurities can be removed

PROCESS COMPARISON		
	Nanovate CoP	**Hard Chrome**
Efficiency	85-95%	15-25%
Deposition Rate	Up to 200 µm/h (0.008”/hour)	Up to 40 µm/h (0.0016”/hour)
Power Consumption	Low – Highly efficient process	High due to inefficient process
Anode	Co Anode	Lead Anode

Drop In Processing Time Significantly Improves Productivity

Toxicity Information

- Current status with respect to cobalt toxicity is that there is "*inadequate evidence for the carcinogenicity of cobalt and cobalt compounds in humans*", International Agency for Research on Cancer (IARC)
- Cobalt, or any of the chemicals used in the nano Cobalt deposition process, are not listed as a known carcinogen in any organization (EPA, IARC, U.S. Department of Health and Human Services 13th Report on Carcinogens (13th ROC)).
  - Only Cobalt sulfate is listed in 13th ROC and IARC as a substance that is *possibly carcinogenic to humans* based on animal studies; cobalt sulfate is not used or produced in the nCoP process

Whereas:

- Hexavalent Chromium – Known Carcinogen (EPA, IARC, 13th ROC)
- Nickel compounds – Known Carcinogens (EPA, IARC, 13th ROC)
- Nickel metal –A substance reasonably anticipated to be a human carcinogen (13th ROC)
- The EPA has determined that nickel refinery dust and nickel sub-sulfide are human carcinogens (http://www.atsdr.cdc.gov)

Cobalt Environment & Worker Safety

Key facts (from EPA):

- Cobalt is a natural element found throughout environment
- Cobalt is an essential element in humans, as a constituent of vitamin B_{12}. Cobalt carbonate is added to animal feed (cows, sheep) to increase B12 content in meat
- Used in lithium-ion batteries, aerospace superalloys, pigment manufacturing, surface finishing, Vitamin B12 (hydroxocyanocobalamin)
- Acute (short-term) exposure to <u>high levels</u> of cobalt by inhalation in humans and animals results in respiratory effects, such as a significant decrease in ventilatory function, congestion, edema, and hemorrhage of the lung.
- Respiratory issues are also the major effects noted from chronic (long-term) exposure to cobalt by inhalation, with respiratory irritation, wheezing, asthma, pneumonia, and fibrosis noted. Cardiac effects, congestion of the liver, kidneys, and conjunctiva, and immunological effects have also been noted in <u>chronically-exposed humans</u>.
- Human studies are <u>inconclusive</u> regarding inhalation exposure to cobalt and cancer, and the one available oral study did not report a correlation between cobalt in the drinking water and cancer deaths.
- EPA, IARC and 13th ROC have <u>**not**</u> classified cobalt for carcinogenicity.

Cobalt Environment & Worker Safety

Highest risk of exposure is through inhalation risks

- Due to high efficiency of process, almost no airborne emissions occur during processing
- Compared to Chrome plating were 80% of electricity used generates hydrogen gas which create Cr(VI) mists during the coating process.
- Nano CoP Process complies with all current cobalt emission limits

Cobalt Occupational Health & Safety Limits:

- NIOSH IDLH (as Co) – 20 mg/m^3

Agency		Limit
ACGIH	TLV-TWA	0.02 mg/m^3
NIOSH	REL (TWA)	0.05 mg/m^3
OSHA	PEL (8-hr TWA)	0.1 mg/m^3

- Inhalation risk also present during grinding or finishing operations, however, standard precautions must be taken as *all particulate* is dangerous if inhaled (e.g.,wood dust is a known carcinogen); no studies to suggest cobalt is more dangerous.
- Cobalt exposure already exists in grinding operations (CoWC tools, HVOF coatings); standard precautions are already being applied.

IH Assessment at NAVAIR JAX

- NAVAIR-JAX industrial hygiene assessment on CoP emission on the Dem/Val tank.

DATE:	PERSONAL SAMPLING RESULTS (8-HR TWAS)	AREA SAMPLING RESULTS (8-HR TWAS)	VENTILATION MEASUREMENTS (TAKEN ON THE PULL SIDE)	DRY BULB READINGS (2)	RELATIVE HUMIDITY (3)
8 Aug 2007	Below the LOD	0.0023 mg/m^3	3519 FPM	Initial: 79.1^{o}F Final: 97.3^{o}F	Initial: 100% Final: 58%
9 Aug 2007	Below the LOD	0.0074 mg/m^3	3545 FPM	Initial: 81.2^{o}F Final: 97.6^{o}F	Initial: 100% Final: 58%
16 Aug 2007	Below the LOD	0.0017 mg/m^3	4001 FPM	Initial: 79.0^{o}F Final: 94.4^{o}F	Initial: 91% Final: 51%
22 Aug 2007	Below the LOD	Below the LOD	4366 FPM	Initial: 78.5^{o}F Final: 95.0^{o}F	Initial: 94% Final: 50%
24 Aug 2007	Below the LOD	Below the LOD	4088 FPM	Initial: 77.5^{o}F Final: 94.2^{o}F	Initial: 100% Final: 58%

Co PEL is 0.0200 mg/m^3

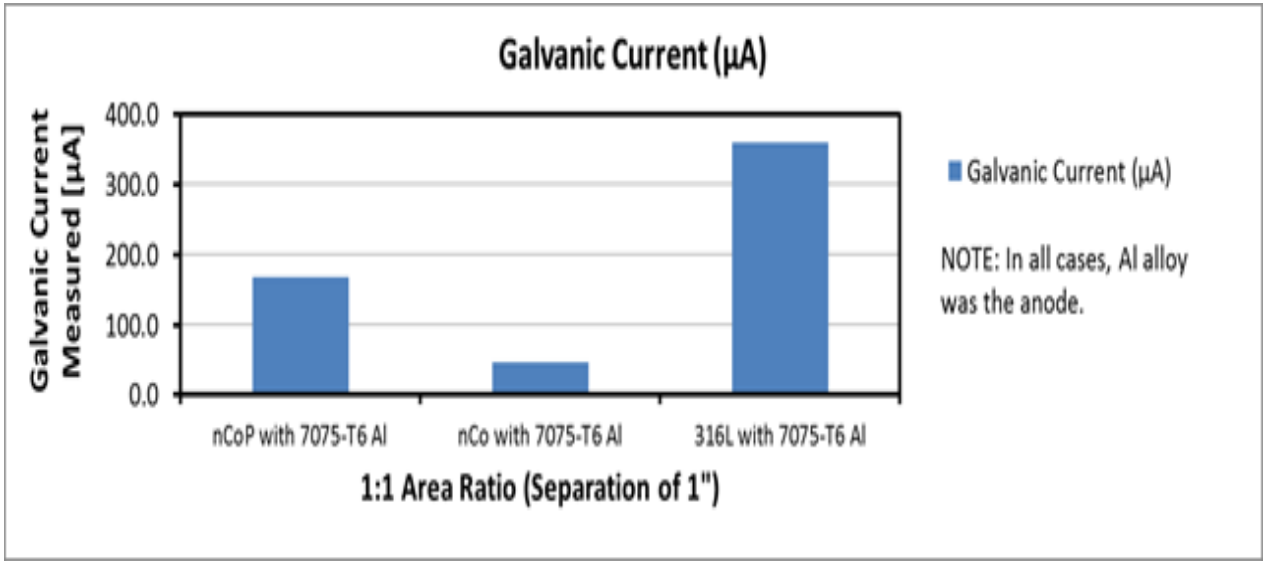
Transition Plan

- The nanoscale technology is expected to possess extremely high economic feasibility and transition potential to existing manufacturing facilities and/or DoD suppliers.
- Pending the successful conclusion of the SERDP project, further demonstration validation will be conducted at the depot level and can likely leverage the current Nano CoP plating infrastructure at FRC-SE (JAX), and transfer to DoD primes and suppliers will be considered via an ESTCP program that would be bid in fiscal year 2017 for implementation in 2018-2019.
- Continued participation in ASETS Defense and various DoD and SERDP sponsored conferences will keep the user community advised on the progress of the development activities.
- In addition, peer reviewed journal articles will be prepared and presented in appropriate journals and/or conferences.

Task 1: Plating on Aluminum

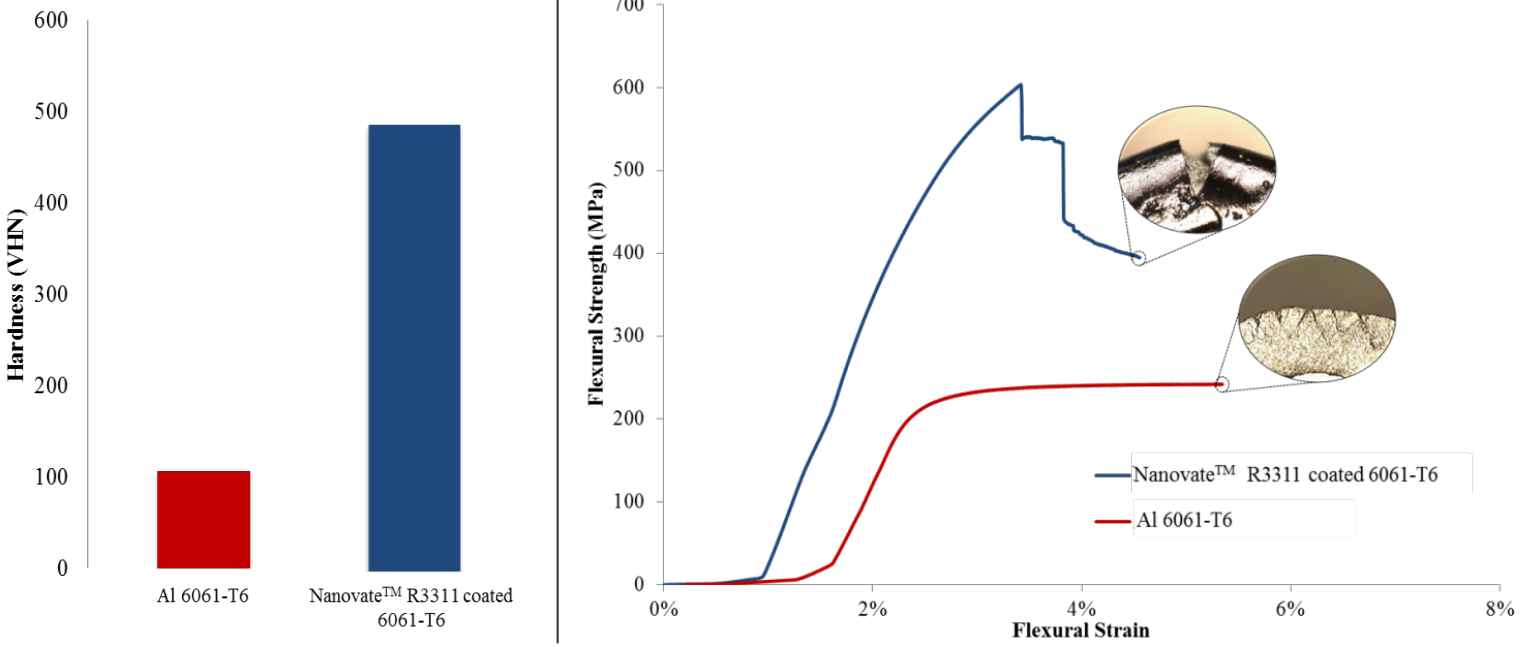
- *Objective:* nCoP plating on Aluminum - enhance strength, maintain weight advantages.
- Nano-Co alloys have good galvanic compatibility with typical aluminum aircraft alloy.
- Specifically corrosion potential (OCP) close to steel and aluminum → reduced driving force for galvanic corrosion:

Material/Coating	Open Circuit Potential
Aluminum Alloys	-800mV to -1000mV
4130 Steel	-680mV to -780mV
Nano CoP	-450mV to -550mV
Nickel 200	-100mV to -200mV



Task 1: Plating on Aluminum

- *Objective:* nCoP plating on Aluminum - enhance strength, maintain weight advantages.
- New CoP chemistry (R3311) developed to improve plating chemistry compatibility with Aluminum substrates.



Flexural stress-strain curve and corresponding hardness graph demonstrating the added advantage of 50µm Nanovate™ coating on Al 6061-T6 (cross-sectional dimensions: 5cm x 0.75cm)

- Enhanced strength of Aluminum with minimal weight addition
- The R3010 and R3311 plating processes suitable for plating various substrates - steel, aluminum, most polymers and polymer composites.