Advancements in Brush Plated Metal Matrix Composites

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Who is SIFCO?

- SIFCO Applied Surface Concepts
  - Founded in 1959
  - Acquired as part of the Surface Coatings Division of Norman Hay in 2012.
  - Headquartered in Cleveland, Ohio, USA
- Norman Hay Group
  - Headquartered in Coventry, UK
  - Other divisions specialize in impregnation sealants, surface coatings, design, manufacture, and installation of process plant equipment. `
    - Ultraseal International, Surface Technology, and NHE
  - Company founded in 1940s doing chromium plating and hard anodizing.

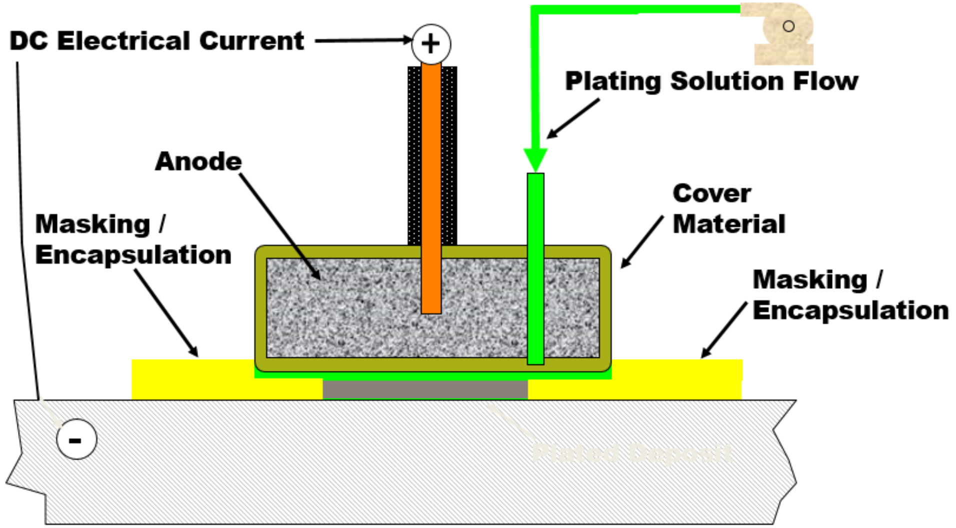
NORMANHAY PLC

Metal Matrix Composite (MMC) Agenda

- What is Selective Plating (aka Brush Plating)?
- MMC What, Why, How, & Where?
- Equipment Set-Up and Design Evolution
- General Plating Conditions
- Ni/WC Processing Parameters and Evaluation
- Ni/Cr_3C_2 Processing Parameter and Evaluation
- Co/Cr_3C_2 Processing Parameters and Evaluation

What do WE do? …. Selective Plating…Brush Plating…

- The SIFCO Process is a portable method of electroplating localized areas without the use of an immersion tank.
  - An electrolyte containing metal ions is introduced between a positively charged anode and a negatively charged part / component.



- Selective Plating Features
  - Brushing action disturbs the hydrodynamic boundary layer at the surface resulting in faster solution movement.
  - High solution velocity also replenishes metal ions at the surface more quickly.
  - Hydrogen gas bubbles are removed by the brushing action and high solution velocity.
  - Brush action levels the deposit as it builds.
  - Selective plating allows for easily controllable application of the coating just where it is needed on the part / component.

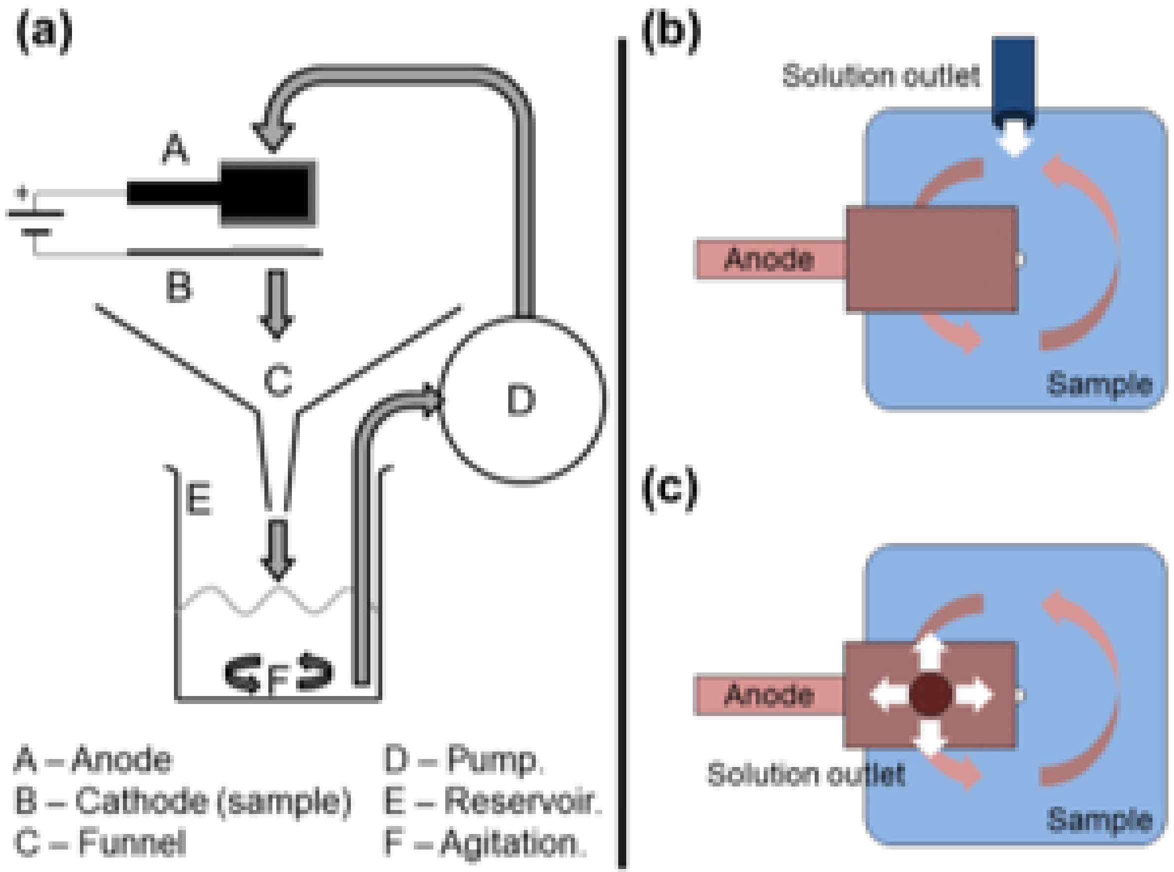
Metal Matrix Composite Coating (MMC)

- What is MMC?
  - ➢Composite material with at least two constituent parts
  - ➢Two phases formed
- How?
  - ➢Particles are suspended in the solution
  - ➢Mixed metal matrix formed during co-deposition
- Why use an MMC?
  - ➢Structural reinforcement
  - ➢Wear resistance
  - ➢Friction coefficient
  - ➢Oxidation protection at high temperatures
  - ➢Main Driver → Safer eco-friendly alternative to chrome
- Where?
  - ➢Bearing Surfaces
  - ➢Tubes and nozzles carrying abrasive particles
  - ➢Rotor Blades and stator vanes

Brush Plating Set-Up

3 Main Pieces of Equipment

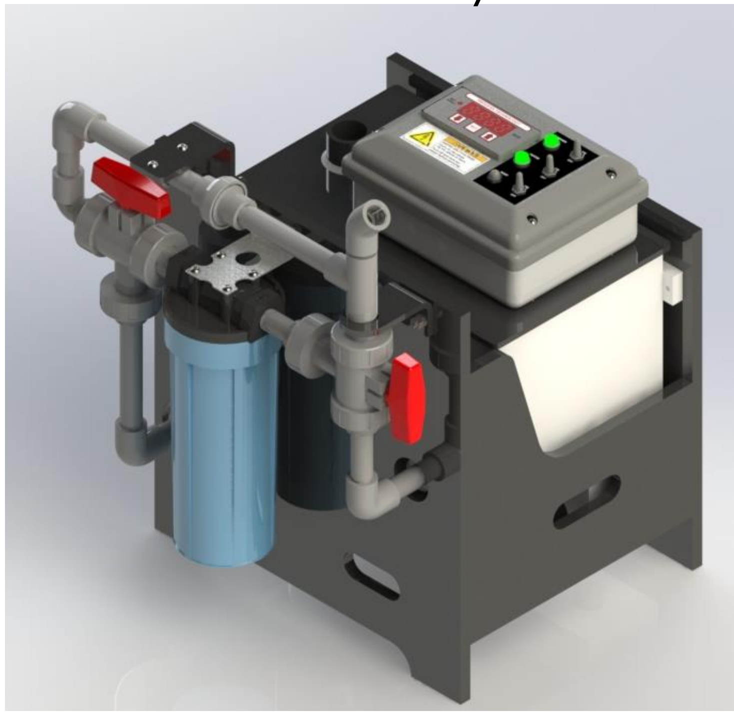
1. Solution collection and circulating system
2. Rectifier
3. Anode and wrap
   - Non-abrasive vs abrasive



Tank Design – Fluid Transport

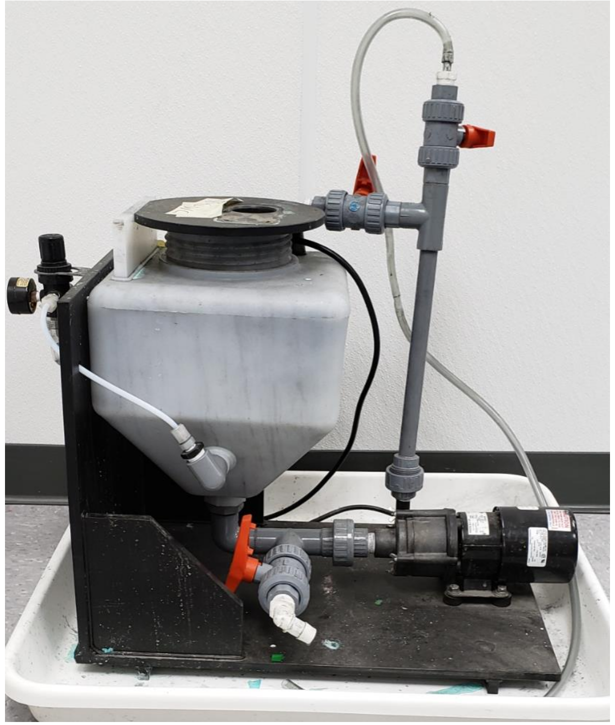
Generation 1

Traditional Flow System



~10 – 20% particle suspension

Generation 2



Generation 3

~90% particle suspension

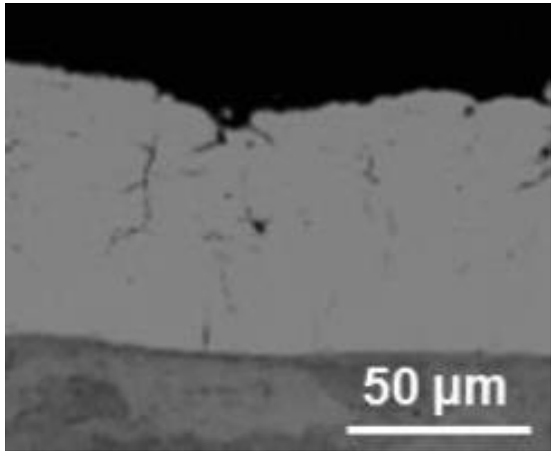
General Plating Conditions

Step	Description	Plating Parameters
Preparatory Steps	Electroclean	10 – 15Volts (Fwd)
	Etch	9 – 10 Volts (Rev)
	Desmut	12 – 15 Volts (Rev)
Preplate	Ni Sulfate	9 – 10 Volts (Fwd) 2 µm
Plate	I) Co-Cr_3C_2 pH 1.6 80 gr/lt Co 40 – 500 gr/lt Cr_3C_2 Particle Size: 6 µm	Temperature: 20 - 40°C Current Density: 0.3 – 1.24 A/cm^2 (2 – 8 ASI)
	II) Ni-Cr_3C_2 pH 7.6 52 gr/lt Ni 50 gr/lt Cr_3C_2 Particle Size: 1.7 & 6 µm	Temperature: Room Temperature Current Density: 0.75 A/cm^2 (5 ASI)
	III) Ni-WC pH 7.6 52 gr/lt Ni 20 & 50 gr/lt WC Particle Size: 6 µm	Temperature: Room Temperature Current Density: 0.75 A/cm^2 – 1.24 A/cm^2 (5 – 8 ASI)

Ni-WC Evaluation

1) Demonstrate feasibility of depositing a Ni-WC matrix
2) Evaluate various process parameters
   - Brush materials
     - Abrasive red and purple scotch brite materials
     - Non-Abrasive white scotch brite material
   - Current Density 0.75 – 1.24 Amps/cm^2
   - Bath Loading at 20 gr/lt and 50 gr/lt of WC powder
   - Particle size → 6 µm Cr_3C_2

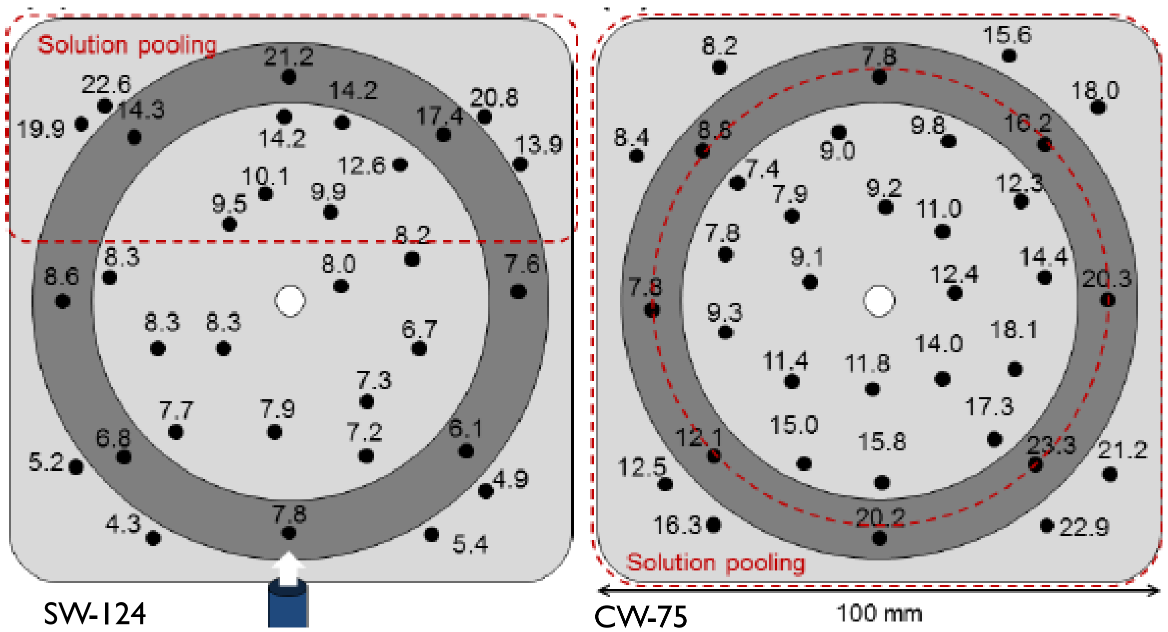
... Overall impact on composition, morphology, and wear



Pure Nickel
Abrasive Red @ 0.37 A/cm^2

Pure Nickel
Non-Abrasvie White @ 1.24 A/cm^2

Effect of Flow & Wrap material on Composition



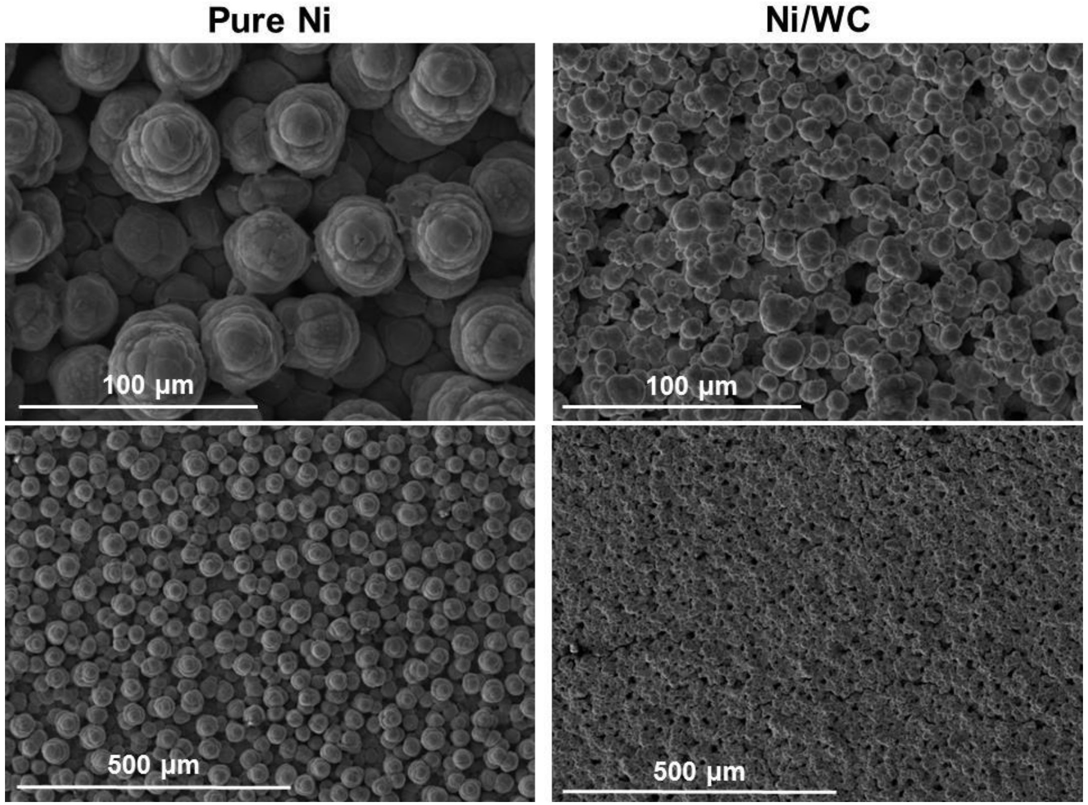
	Sample	Composition Population 1 Average (at.% of W)	Composition Population 1 Coefficient of variation	Composition Population 2 Average (at.% of W)	Composition Population 2 Coefficient of variation
Batch 1	SW-75	4.0±0.7	19%	8.6±2.9	33%
50 gr/lt WC	SW-124	7.3±1.5	20%	14.5±5.3	36%
	CW-75	9.4±1.6	17%	17.3±3.4	20%
Batch 2	AW-75	4.9±1.6	19%	13.3±4.2	31%
20 gr/lt WC	AR-75_1	3.0±0.8	27%	6.6±3.3	49%
	AR-75_2	3.3±0.3	9%	5.6±2.2	40%
	AP-75_1	1.7±0.2	10%	3.6±0.6	18%
	AP-75_2	2.2±0.2	11%	3.6±0.5	14%

- XY-n_m
  - X = magnetically stirred set-up, solution flowing from side (S) or center (C), or air stir setup, solution flow from center (A)
  - Y = Brush material, white (W), red (R), purple (P)
  - n = Current density (0.75 or 1.24 A/cm^2)
  - m = Sample Number

Abrasive materials provide a more uniform W composition

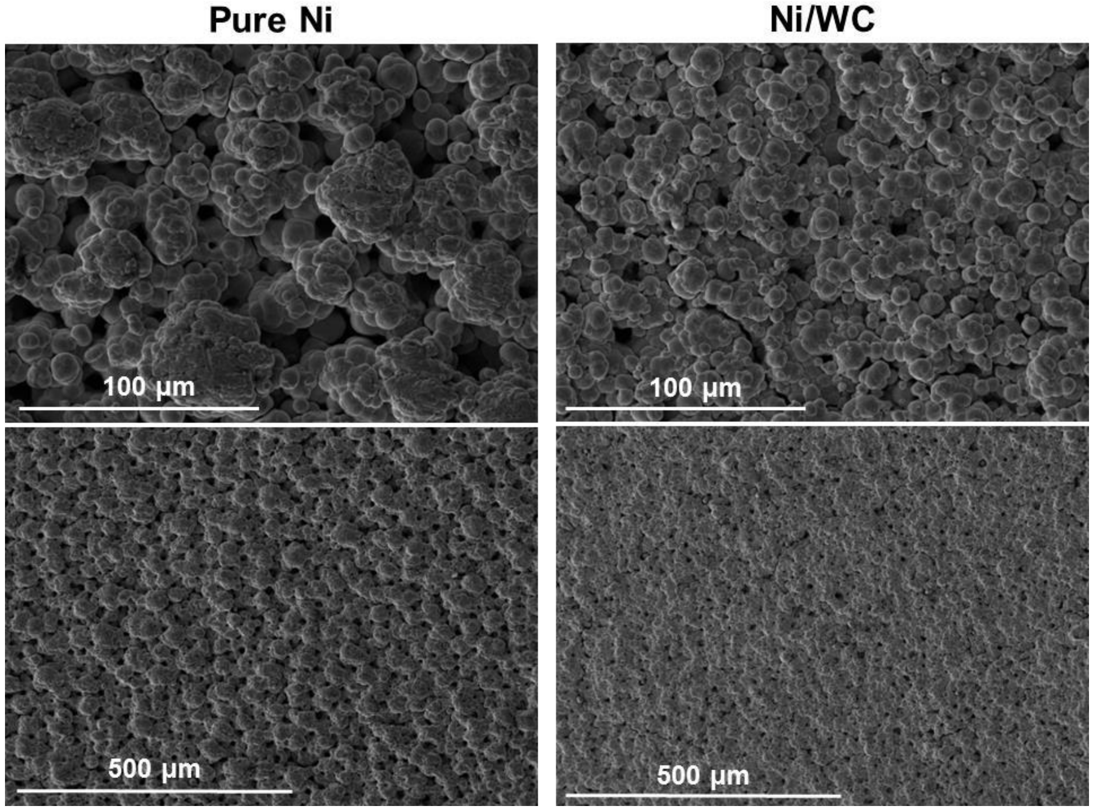
- Two particle distribution zones
  - Population 1 → Continuous Flow
    - Lower composition, less variation
  - Population 2 → Solution pooling and sedimentation
    - Higher composition average, higher variation

Ni-WC deposits produced with Abrasive vs Non-Abrasive Materials



AW-75

White Non Abrasive @ 0.75 A/cm^2

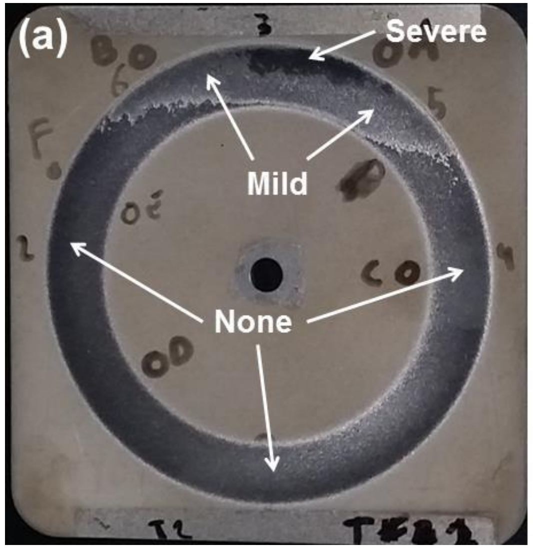


AR-75

Red Abrasive @ 0.75 A/cm^2

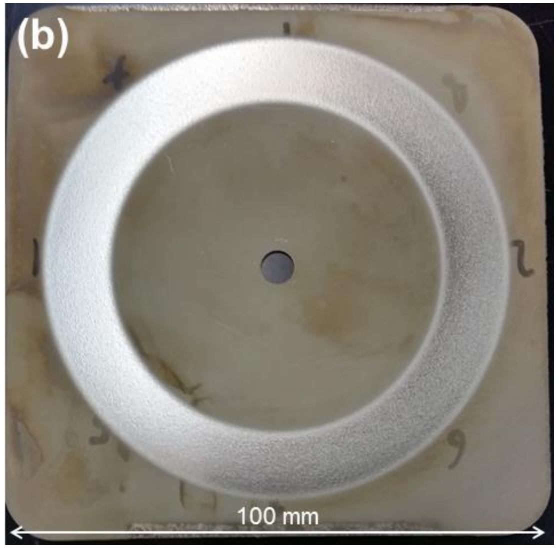
Ni-WC Abrasive Wear: Taber Wear Testing

❖Taber Wear
15,000 cycles
Resurface every 1000 cycles
CS-17 wheels



SW-124

Localized coating failures for all samples from Batch 1 with 50 gr/lt WC



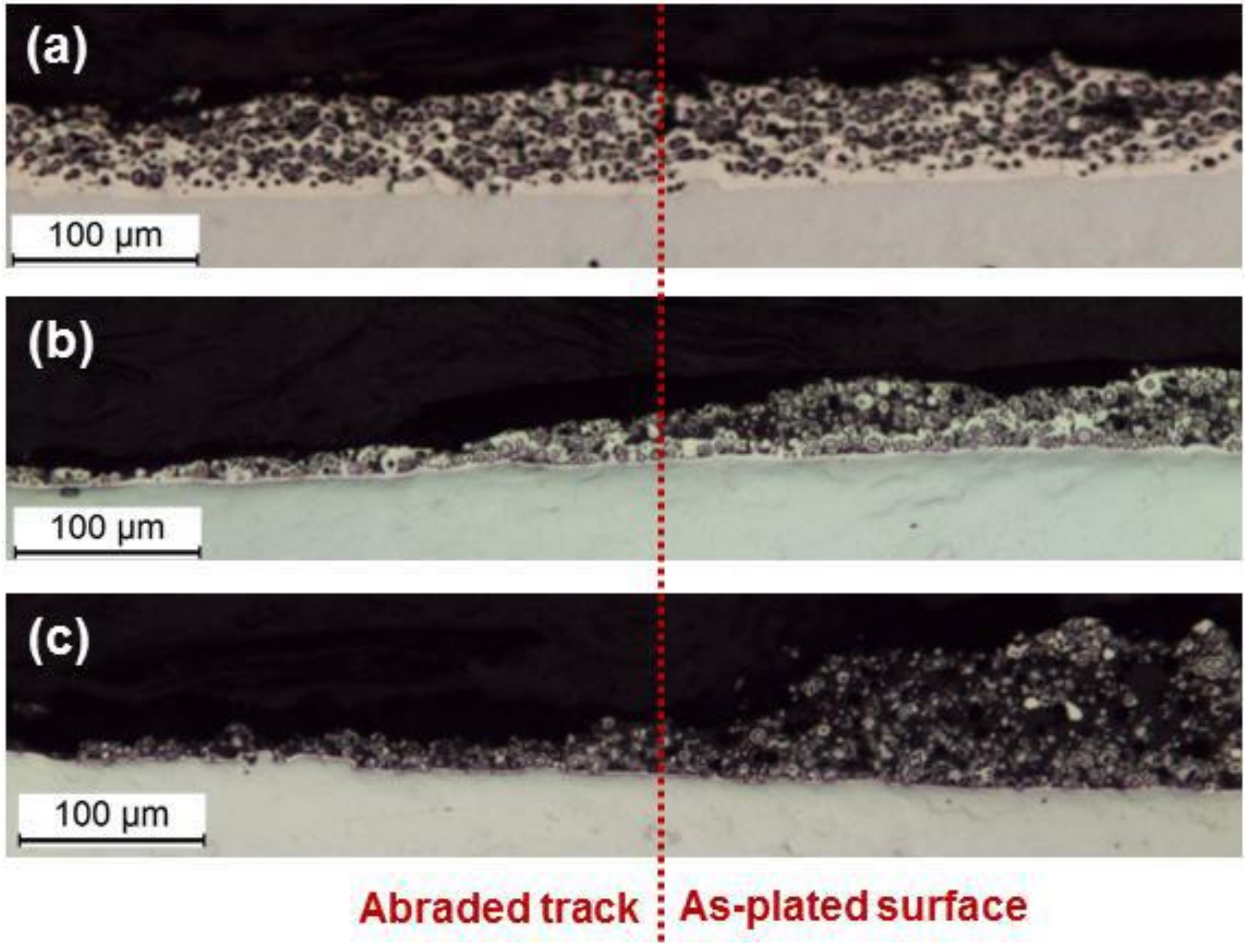
AR-75_2

No coating failures with 20 gr/lt WC loading

Comparison

- Pure Nickel TWI = 14 -20
- Ni-WC TWI = 6
- Hard Chrome TWI = 3.2

Ni-WC Abrasive Wear: Taber Wear Testing



No failure

2.6 – 10.2 at% W

Mild failure

Severe failure

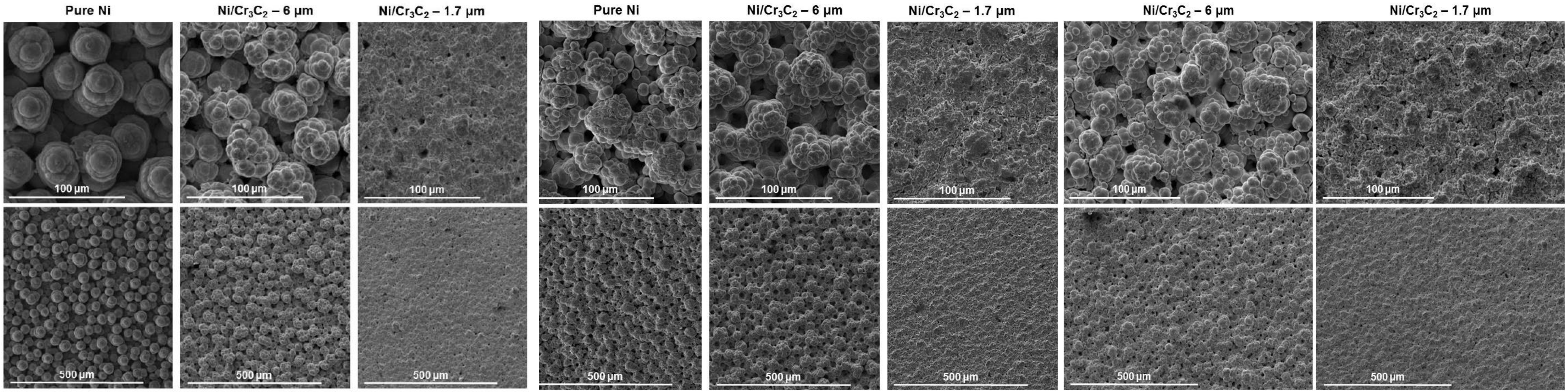
> 21.3 at% W

Ni-Cr_3C_2 Evaluation

1) Demonstrate feasibility of depositing a Ni- Cr_3C_2 matrix
2) Evaluate various process parameters different brush materials
    - Brush Materials
        - Abrasive red and purple scotch brite material
        - Non-Abrasive white scotch brite material
    - particle sizes
        - 1.7 and 6 µm Cr_3C_2

... Overall impact on composition, morphology, and wear

Ni-Cr_3C_2 deposits produced with Abrasive vs Non-Abrasive Materials

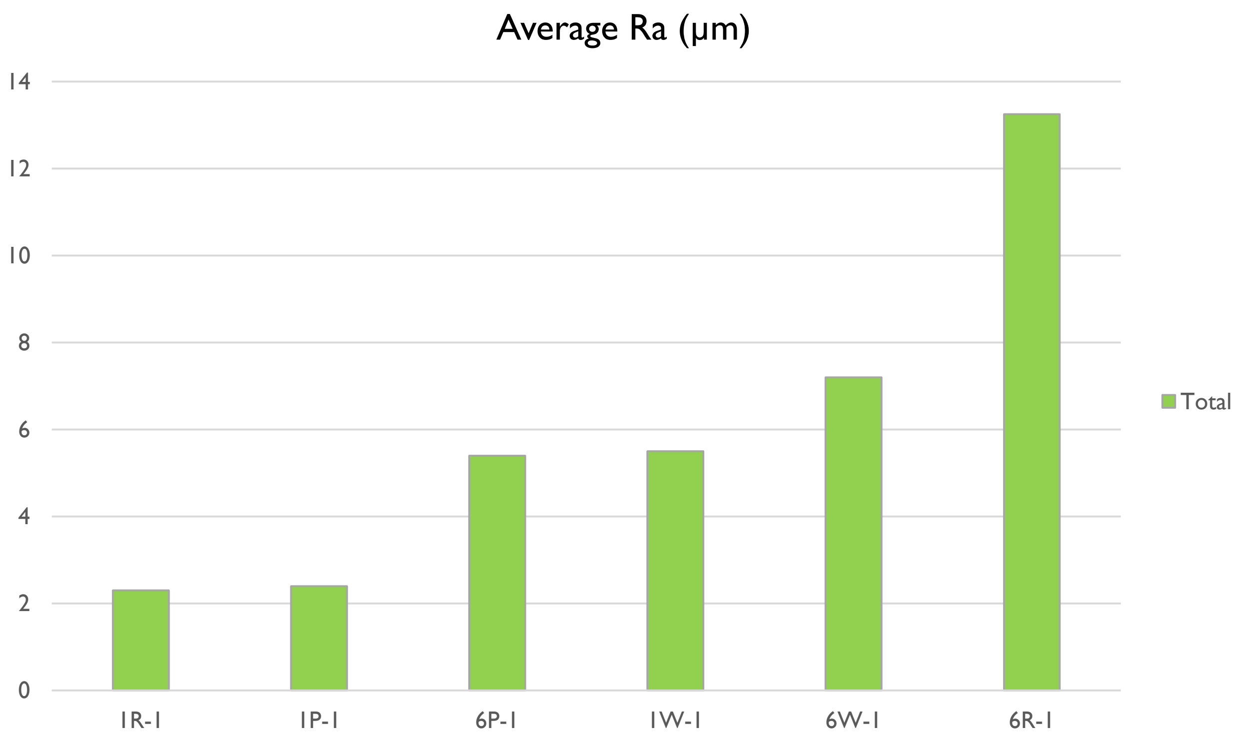


White Non- Abrasive | Red Abrasive | Purple Abrasive

All samples plated at 0.75 A/cm^2

Particle size has the largest impact on the overall composite deposit morphology.
Deposit morphology containing 1.7 micron particles are the same for all brush materials.
Abrasive materials (red and purple) produced a smoother finish with smaller nodules.

Ni-Cr_3C_2 Surface Roughness

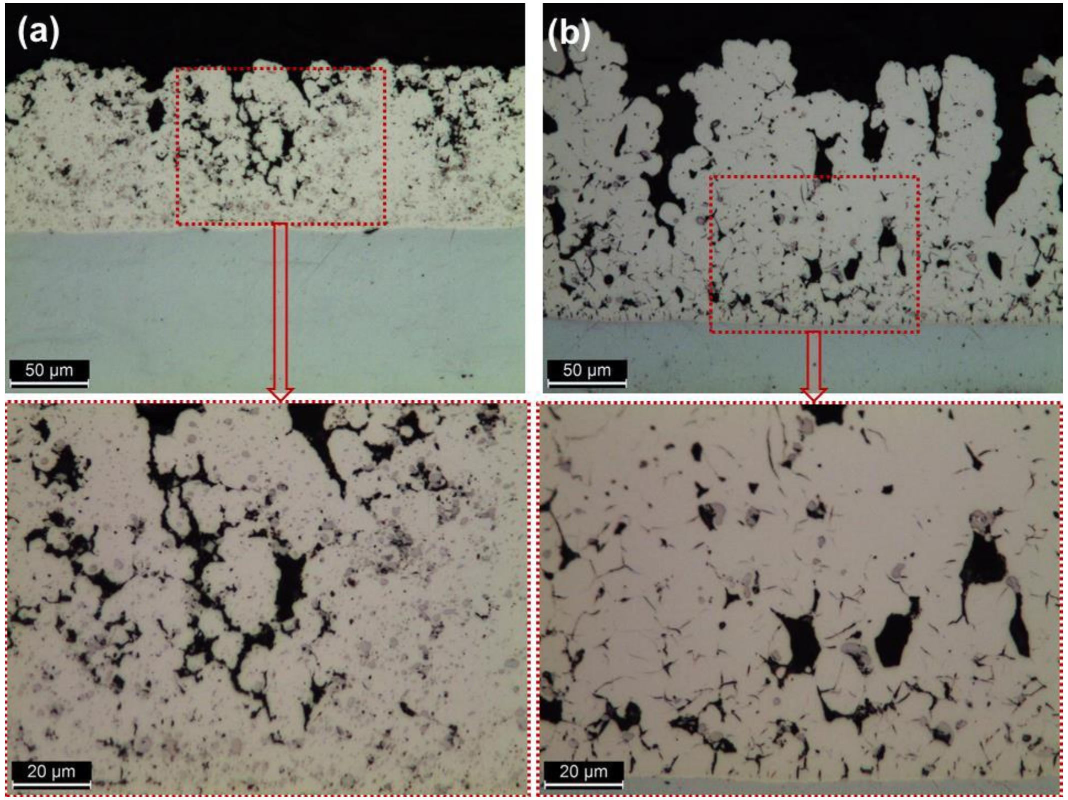


Sample	R_a (µm)	Mr_1 (% of profile)	Mr_1 (% of profile)	A1 (µm x % profile)	A2 (µm x % profile)	R_{pk} (µm)	R_{vk} (µm)
1P-1	2.5±0.3	11±3	86±4	15± 8	29±14	2.6±0.8	4.2±1.2
1P-2	2.3±0.2	12±5	88±2	17±10	20±10	2.7±0.6	3.2±1.3
6P-1	6.7±0.7	16±5	91±3	200±12	50±30	22.7±9.3	10.6±3.5
6P-2	4.1±0.4	10±4	90±3	19±11	24±10	3.6±1.2	4.6±0.8
1R-1	2.3±0.3	14±4	90±3	40±20	21±10	5.4±1.9	4.3±1.8
1R-2	2.3±0.3	12±3	89±3	19± 6	19± 6	3.2±0.7	3.3±0.7
6R-1	10.6±1.6	12±5	90±4	80±60	60±50	12.1±5.6	11.5±4.6
6R-2	15.9±1.8	12±3	91±2	110±90	70±40	17.2±8.9	15.0±4.3
1W-1	6.9±1.1	15±6	87±4	120±60	70±30	14.4±5.6	10.3±3.0
1W-2	4.1±0.5	9±2	84±2	20±12	61±14	4.3±1.8	7.5±1.2
6W-1	10.3±1.5	10±7	91±4	70±80	40±30	8.9±6.4	7.9±3.5
6W-2	4.1±0.2	8±2	86±3	12± 5	40±40	3.0±1.0	5.9±1.2

- pB-n
  - p = Particle size 1 or 6 µm
  - B = Brush material, white (W), red (R), purple (P)
  - n = Sample Number

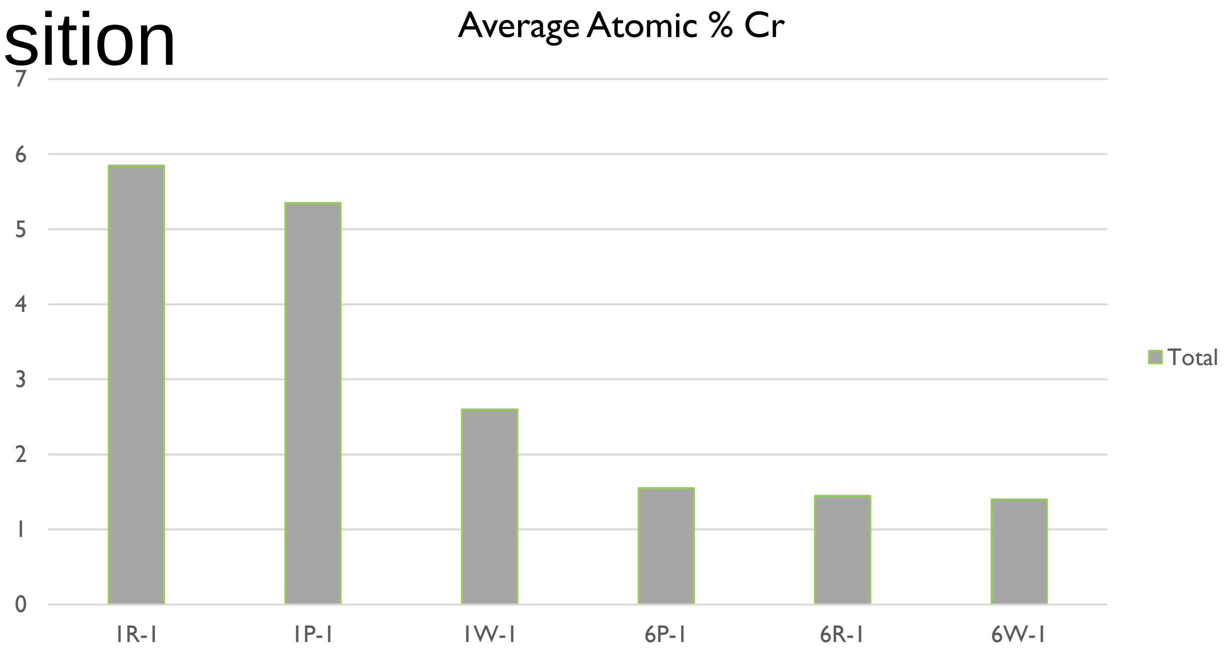
- Abbott Firestone Curves show roughness values
- Surface roughness in good agreement with SEM images

Ni-Cr_3C_2 Cross Section & Composition



1.7 μm Cr3C2 particles | 6 μm Cr3C2 particles

Abrasive Purple Brush

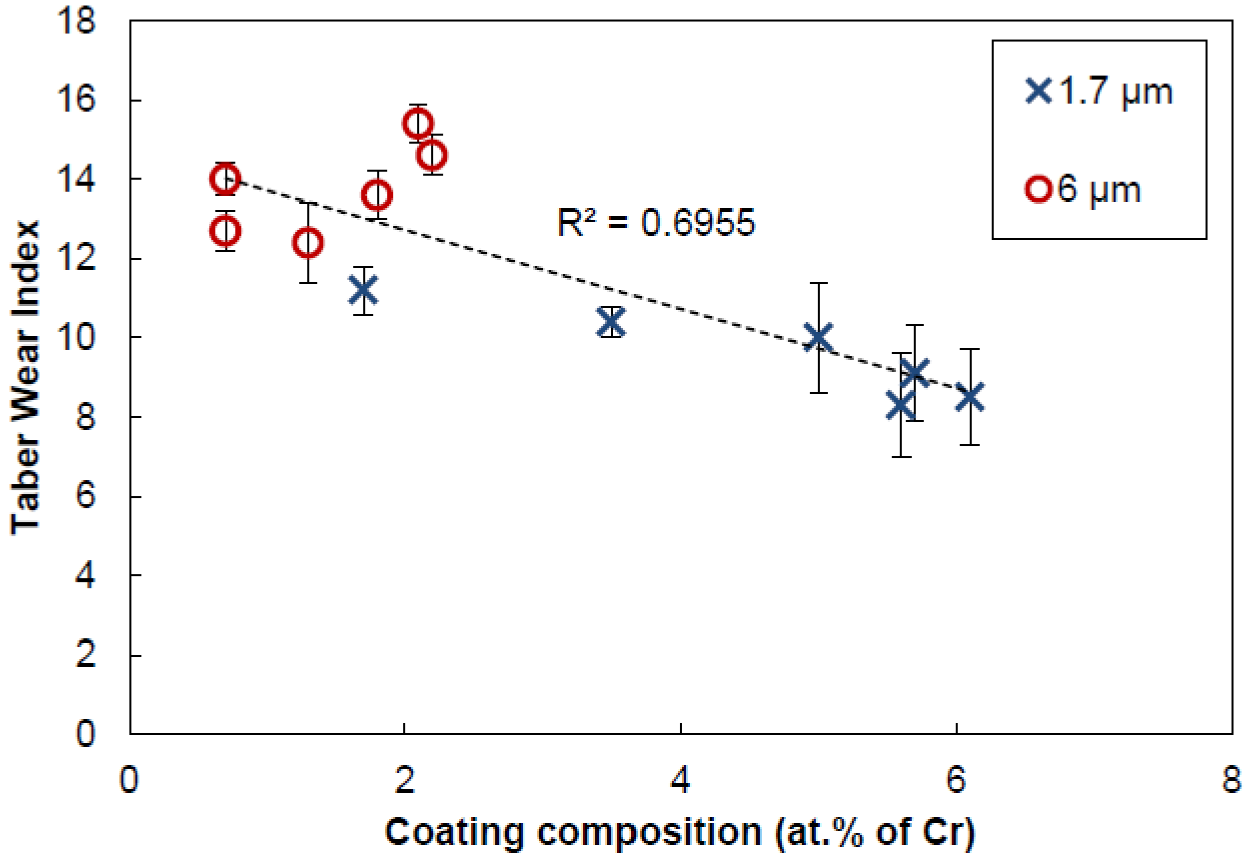


	General		Composition Population 1			Composition Population 2		
Sample	R^2	Average (at.% of Cr)	Points	Average (at.% of Cr)	CoV	Points	Average (at.% of Cr)	CoV
1P-1	0.84	5.7±1.2	6	7.4±1.5	20%	26	5.3±0.6	12%
1P-2	0.81	5.0±1.4	11	6.3±1.7	27%	21	4.4±0.5	12%
6P-1	0.89	1.8±0.6	12	2.5±0.6	24%	20	1.6±0.3	18%
6P-2	0.73	1.3±1.0	12	2.2±1.1	52%	20	0.7±0.2	24%
1R-1	0.91	6.1±1.2	32	6.1±1.2	15%	0	---	---
1R-2	0.89	5.6±1.3	3	8.6±0.1	1%	29	5.3±1.0	18%
6R-1	0.87	0.7±0.4	16	1.0±0.5	48%	16	0.4±0.1	32%
6R-2	0.91	2.2±0.5	32	2.2±0.5	24%	0	---	---
1W-1	0.91	3.5±0.4	32	3.5±0.4	12%	0	---	---
1W-2	0.83	1.7±0.6	5	2.7±0.7	23%	27	1.5±0.3	18%
6W-1	0.97	2.1±0.5	32	2.1±0.5	23%	0	---	---
6W-2	0.71	0.7±0.5	2	2.4±0.1	3%	30	0.6±0.3	47%

Ni-Cr_3C_2 Abrasive Wear: Taber Wear Testing

- Taber Wear
  - 15,000 cycles
  - Resurface every 1000 cycles
  - CS-17 wheels
- Compared to…
  - Pure Nickel TWI 14 -20
  - Hard Chrome TWI 3.2
- TWI decreases with particle size
- 8- 10 TWI with 1 micron particle size

Ni-Cr_3C_2 TWI vs. Cr Composition & Particle Size



Wear Performance Correlation

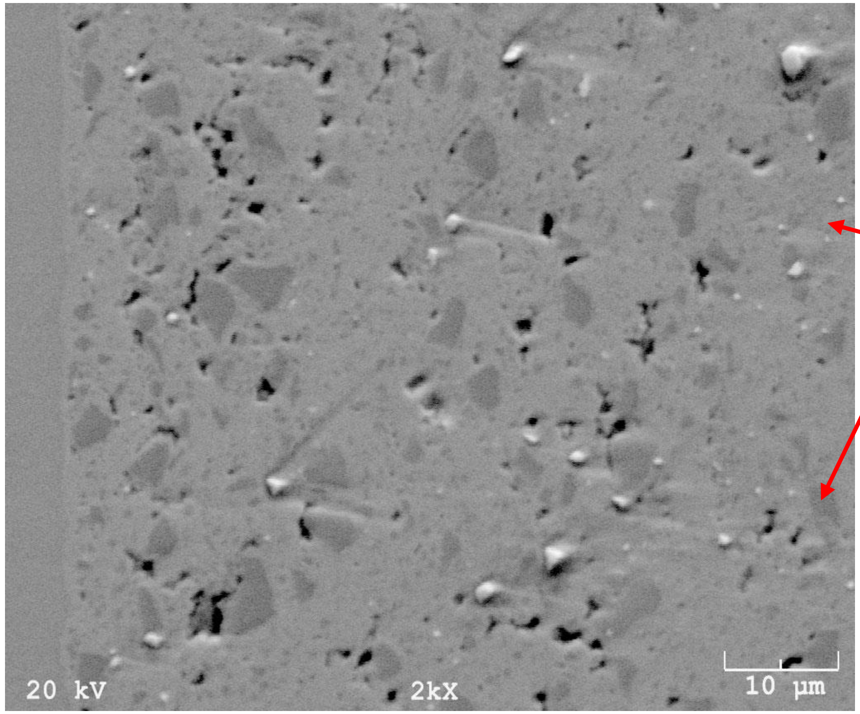
- Increasing chromium content
- Particle size →1.7 µm
- Abrasive wrap

Co-Cr_3C_2 Evaluation

1) Evaluate tank and mixing parameter design
2) Establish processing parameters
   a. Bath Loading Cr_3C_2 40 – 500 gr/lt
   b. Current Density 0.3 – 1.20 A/cm2
   c. Particle size → 6 µm Cr_3C_2
3) Quantify Surface Performance Benefits

…Overall impact on composition, morphology, and wear

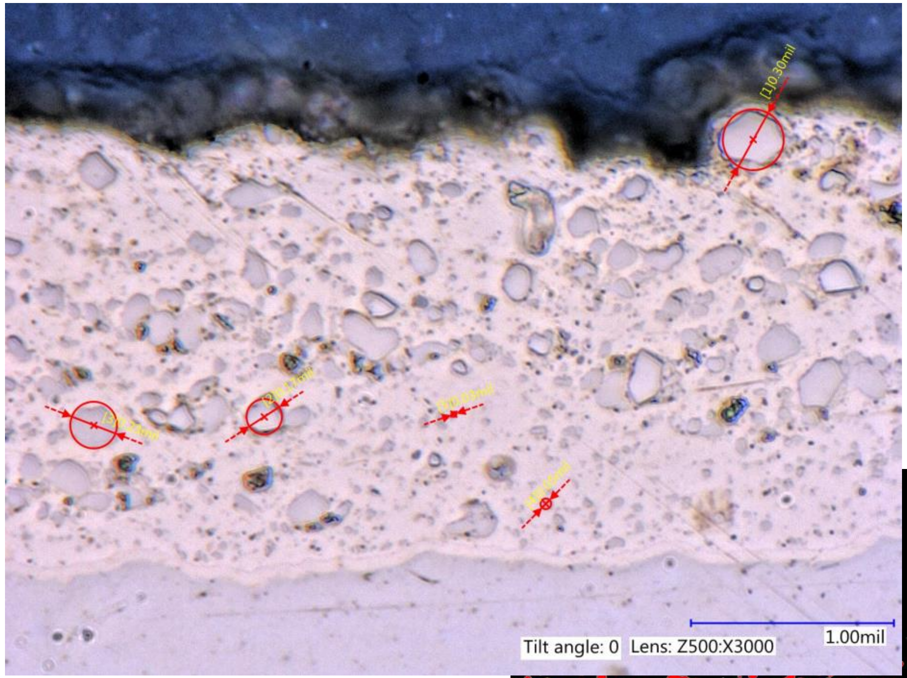
Co-Cr_3C_2 Cross Section & Particle Count



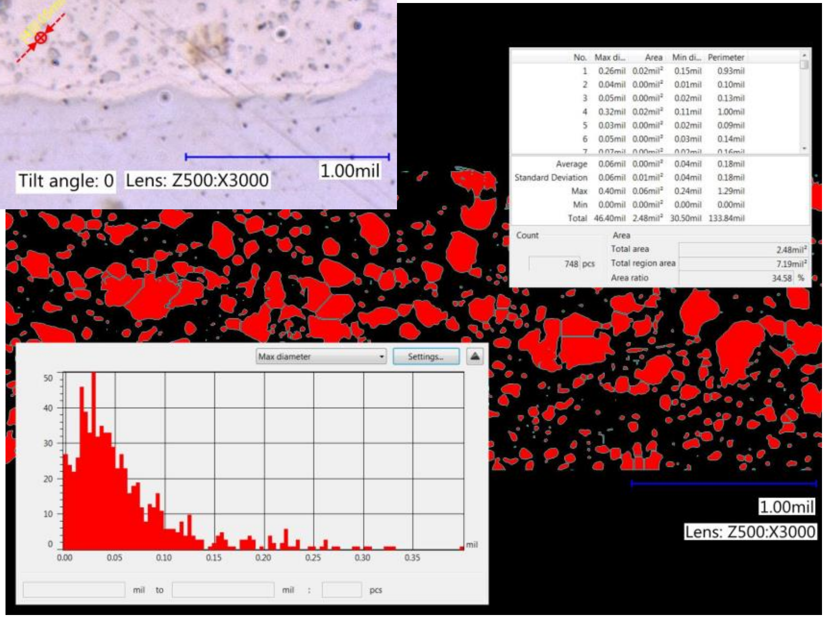
Cobalt metal

Carbide particle

14 wt.% Cr_3C_2



35 wt.% Cr_3C_2



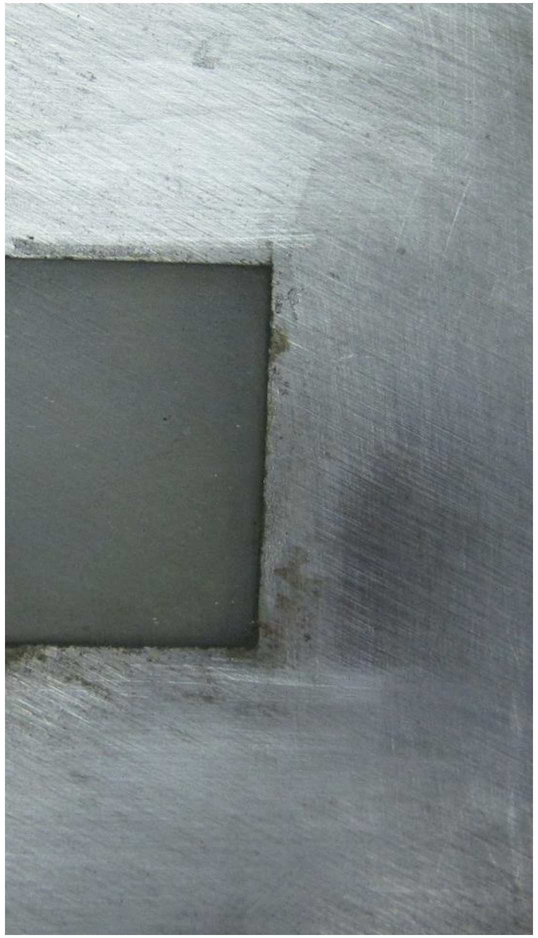
Co-Cr_3C_2 Hardness & Temperature

Cr_3C_2 wt.%	As deposited	400°C	750°C	815°C
12 – 15	442	505	498	485
25 – 30	418	485	476	482

Hardness (VHN) of Co-Cr_3C_2 as deposited and after 1 hour heat treatment

Carbon steel	Ti-6Al-4V	Co-plated
150	330	360

Co-Cr_3C_2 Oxidation Resistance

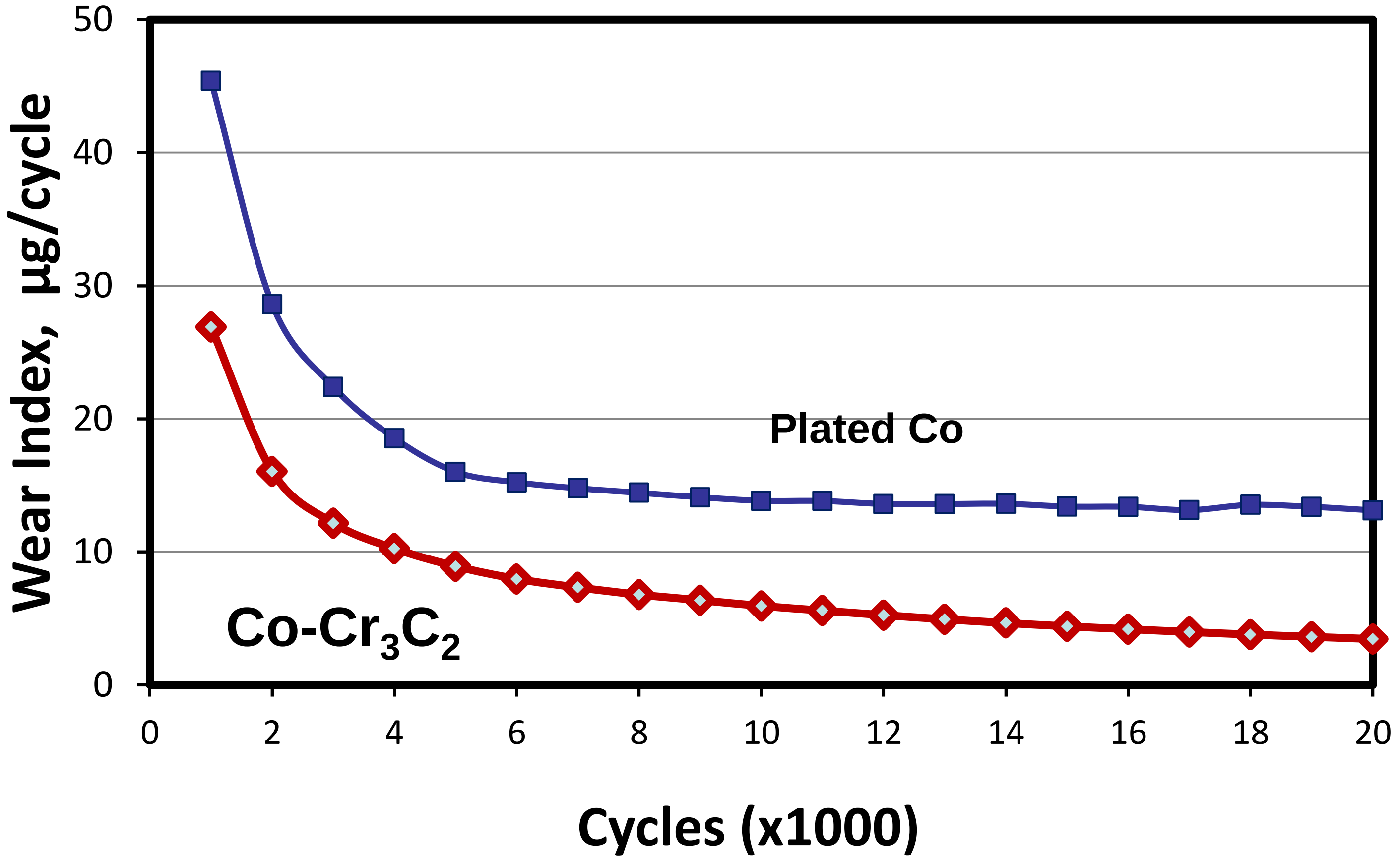


Before Heating

- Heated to 800° C for 30 hours
- Substrate: Steel
- Deposit Co-Cr3C2 15% wt% Cr3C2

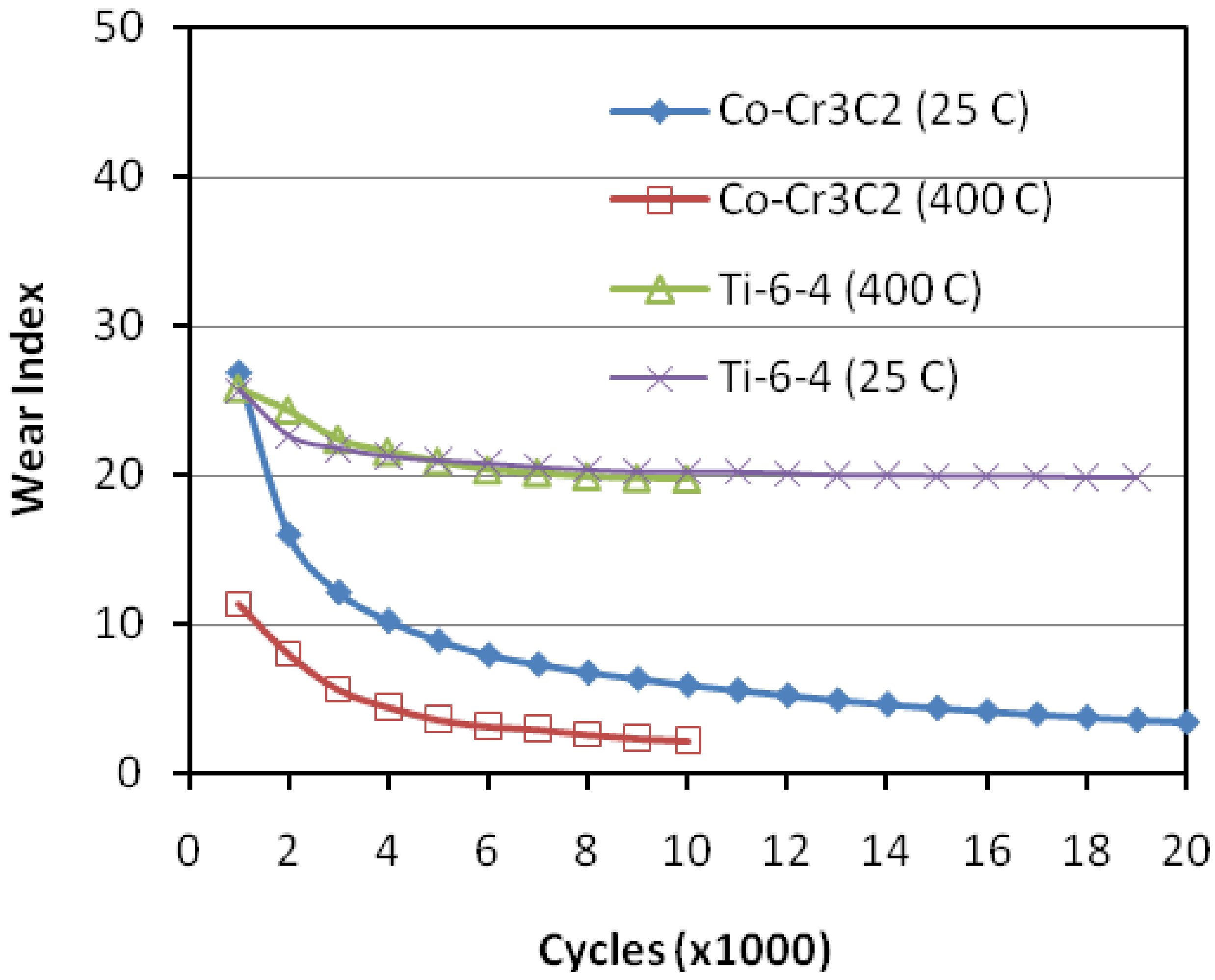
After Heating

Co-Cr_3C_2 Taber Wear Testing



- Co-Cr_3C_2 exhibits > 50% decrease in TWI

Co-Cr_3C_2 Taber Wear @ Elevated Temperature



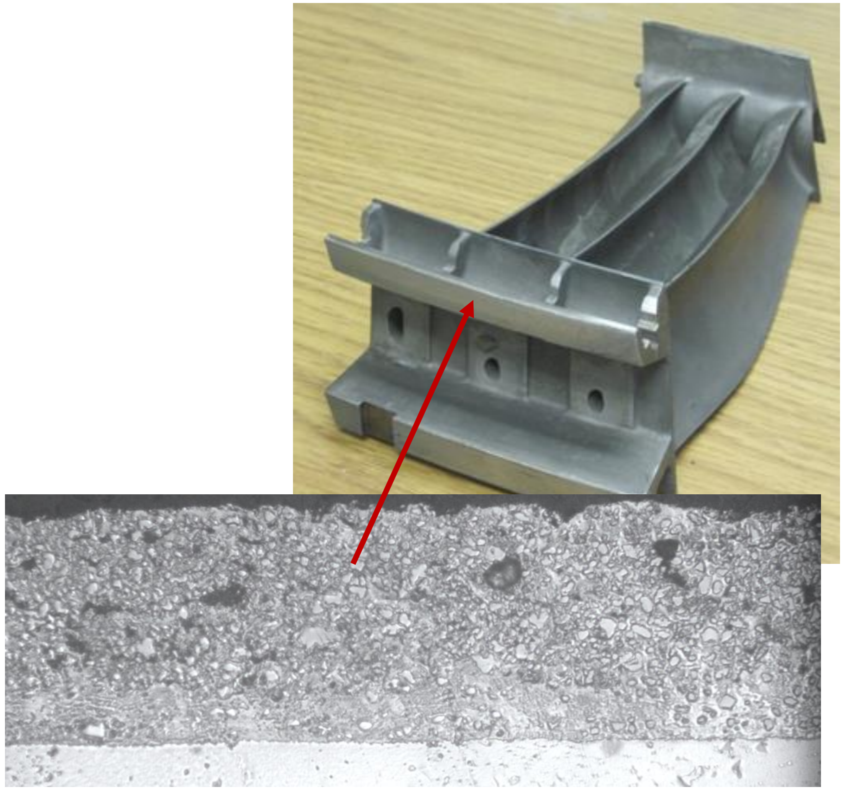
- CoCr3C2 and Ti-6-4 samples heated to 400° C

<u>RESULTS</u>

- Ti-6-4→ No change in TWI
- Co-Cr3C2 → 50% decrease in TWI

Co-Cr_3C_2 Key Characteristics

Property	Unit	Brush Plated Co-Cr_3C_2	Brush Plated Co	Ti-6Al-4V	Carbon Steel
Cr_3C_2	wt. %	10 – 50	0	0	0
Uniformity of Cr_3C_2	wt.%	± 3	-	-	-
Microhardness	VHN	360 – 500	360	330	150
Hardness change after 400° C exposure	%	> + 10 %	> - 10%	> - 5%	> - 15 %
Taber wear index	µg/cycle	8.0	17	21	16
Taber wear index after 400° C exposure	µg/cycle	4.0	15	21	17
Surface finish as deposited, Ra	µm	0.5 - 1.5	0.5 - 1.5	-	-



- Co-Cr_3C_2 MMC on Ni alloy Turbine Vane
- 20 wt.% Cr_3C_2

Future Work

- Further define Ni-WC and Ni-Cr_3C_2 key characteristics
  - Hardness, coefficient of friction, heating effects, etc…
- Focus 1 micron particle size and abrasive wrap materials
  - Evaluate bath loading for composition and wear properties
- Explore other nickel based electrolyte carriers

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