Carbodeon NanoDiamond Materials:
"Hard as Hell, but Cooler"

HVM Graphene + Conference, Oxford, UK

www.hvm-uk.com

15.5.2014

Gavin Farmer, Carbodeon

@carbodeon

Carbodeon Ltd. Oy.

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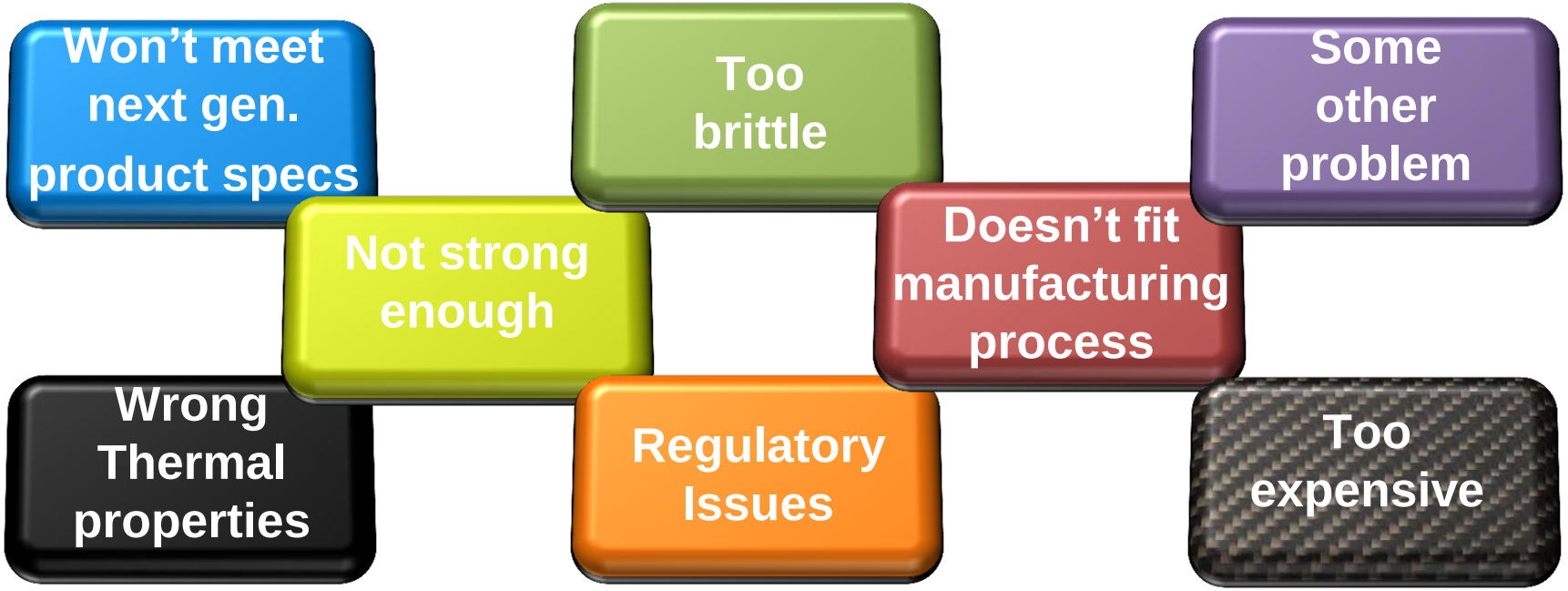
Material selection: Compromise…..



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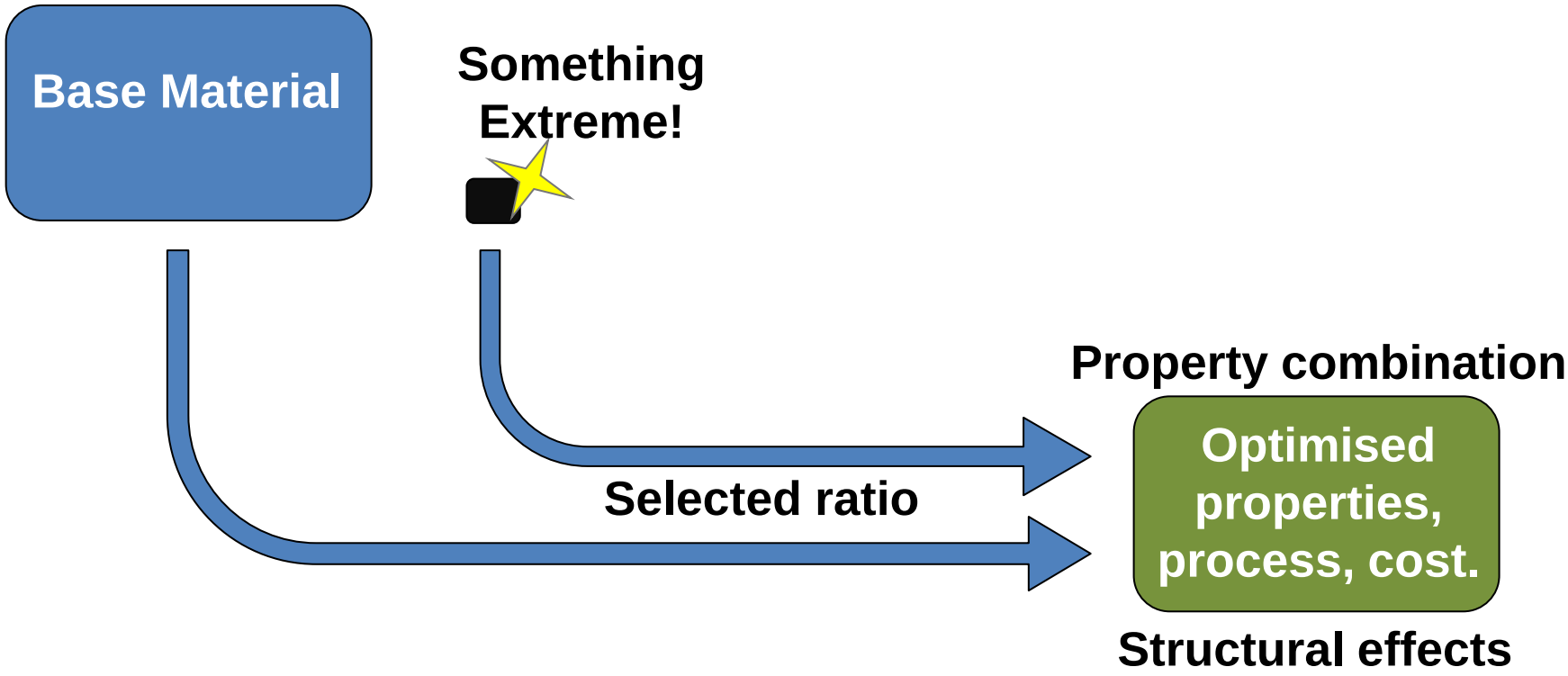
Material design: Combine…..
……. and Optimise



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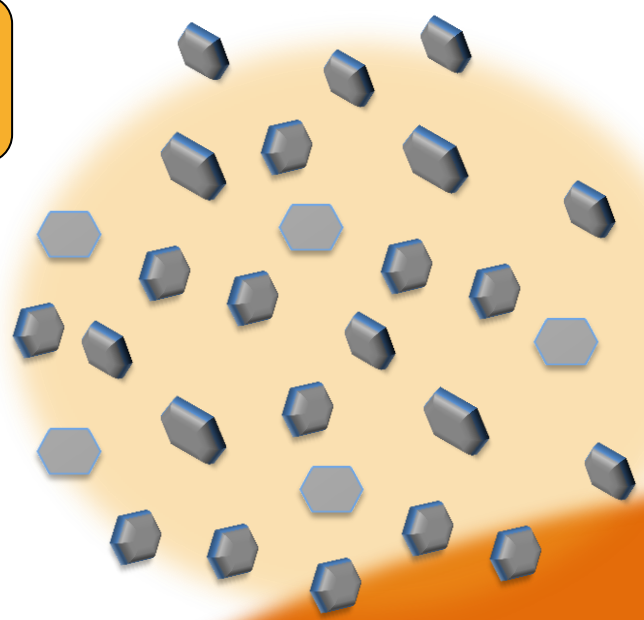
Carbodeon NanoDiamond – Extreme Material.

Strength

Chemically Inert



Hardness

Optical Properties

Surface Friction

Dielectric

Thermal Conductivity

With some unusual combinations

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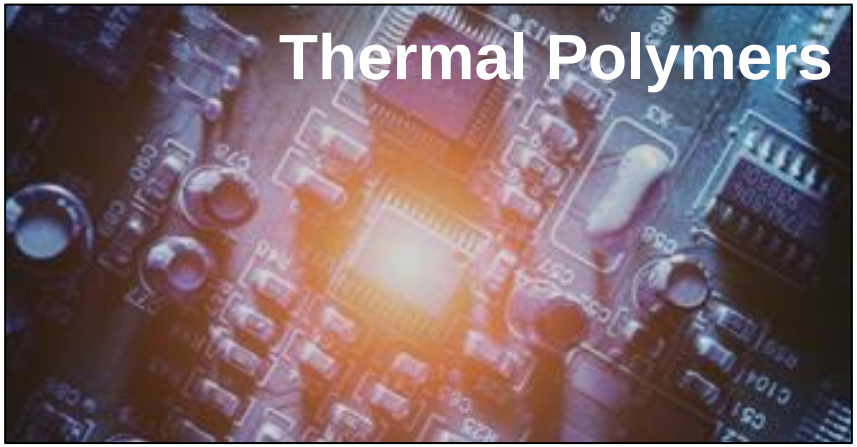
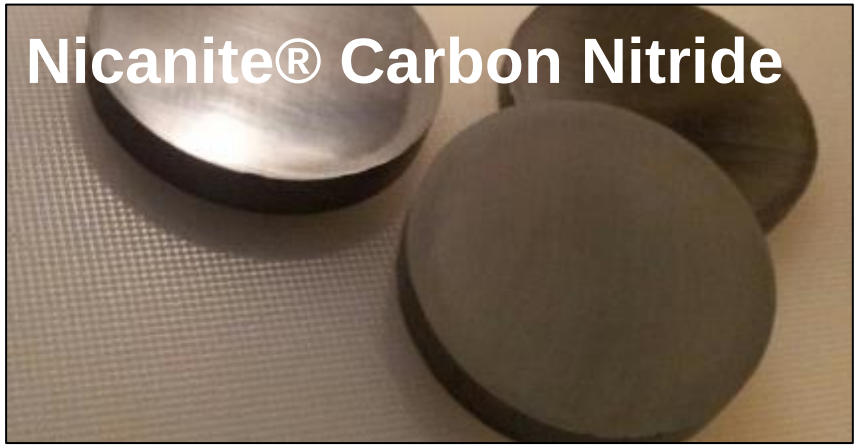
Where, What, & How





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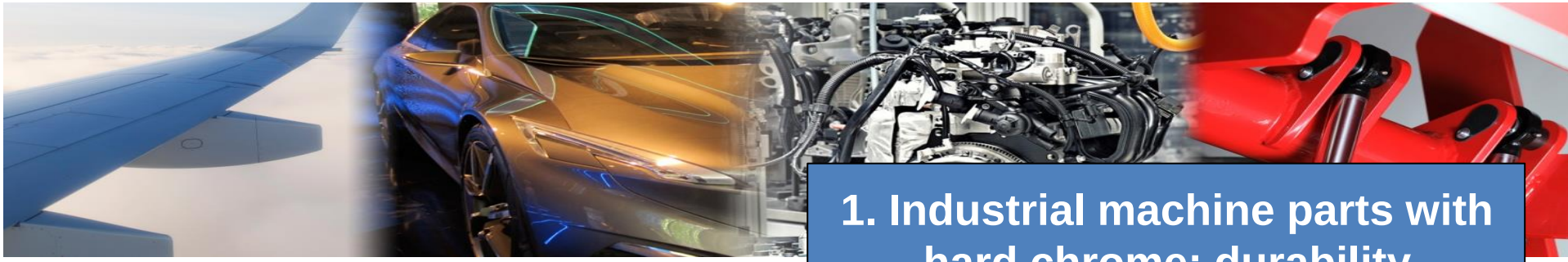
Plating and Anodising

- Nanodiamond suspension or dispersion added to solutions
- Finer grain structure + embedded hard particles



1. Industrial machine parts with hard chrome: durability improved from 3.5 to 5.5 years

2. Gold plated electrical connectors: wear performance improved by 100%

3. Electroless nickel: Abrasion resistance tripled

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Polymer Coatings

- NanoDiamond powder, suspension, or dispersion
- Hard particles bonded to parent material.
- Polymer reinforced/ restructured at molecular scale

1. PTFE and FEP coatings – aqueous and solvent.

Wear improvement up to 50%
Friction reduction up to 66%
Surface finish improved 85%

2. Consumer product: unnamed coating formulations on unnamed products: Wear performance improved by >3X

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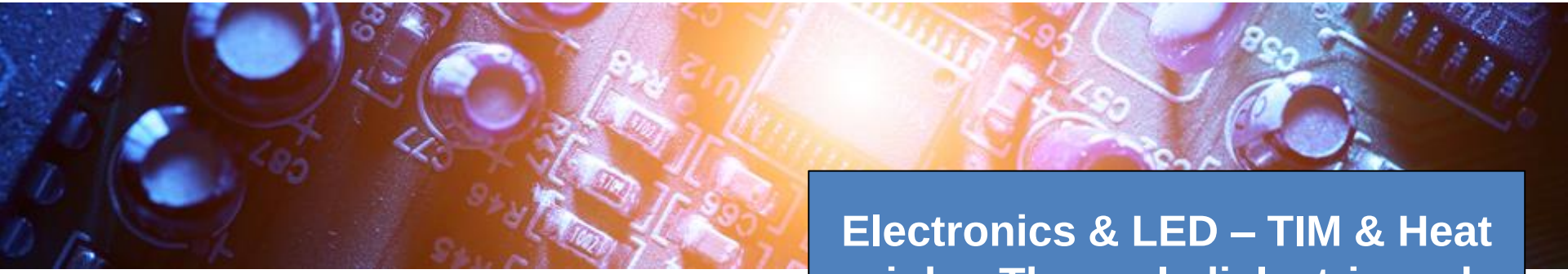
Thermal Management

- Nanodiamond powders added to existing polymers & composites
- Thermal conductivity without compromise to other properties



Electronics & LED – TIM & Heat sinks: Thermal, dielectric and structural properties

Thermoplastic Development: Thermal conductivity increased >25% with 0.1wt% NanoDiamond

Low Carbon Vehicles: Additional Structural, frictional, lightweighting &Tg improvements

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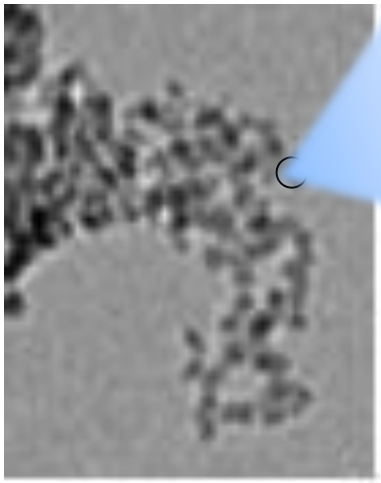
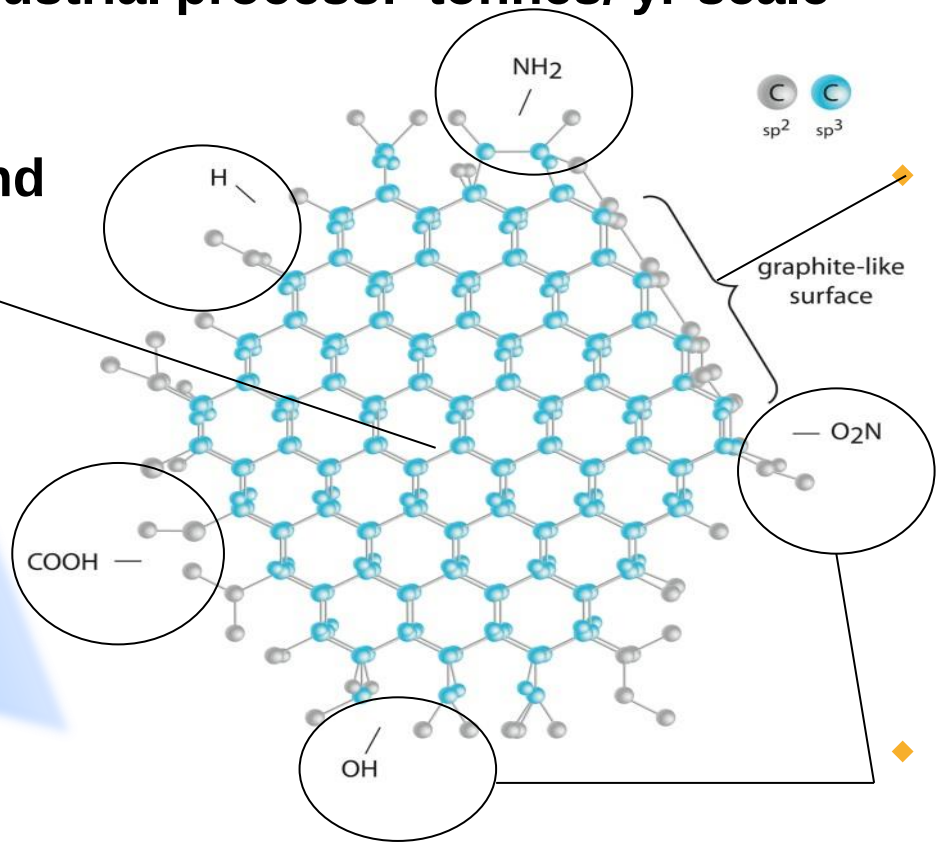
Where, What, & How

- Detonation Produced Nanodiamond – 4-6 nm diamond particles
- Proven industrial process: tonnes/ yr scale

- Sp3 Diamond Core
- Graphitic facets
- With surface functional groups





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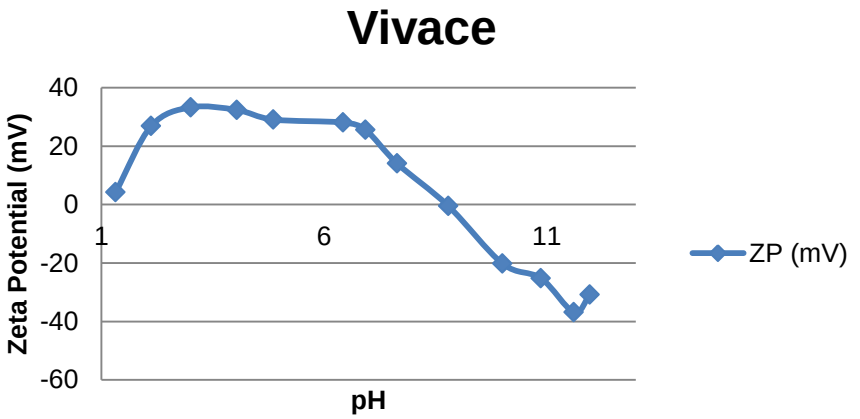
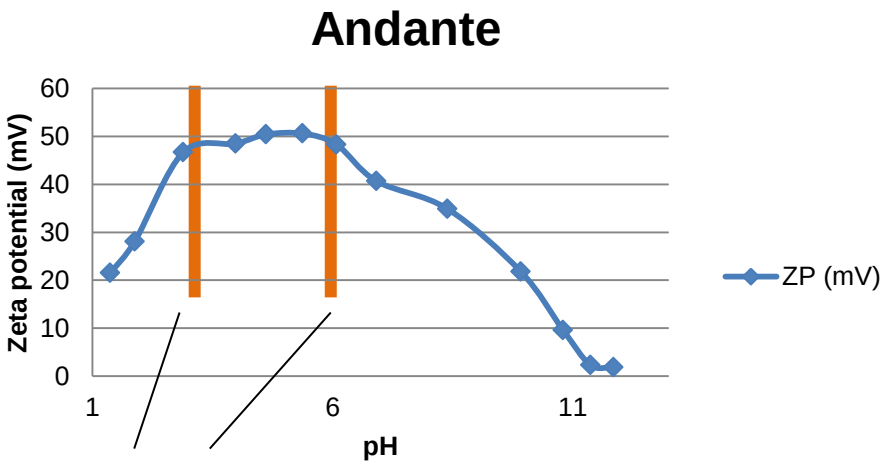
uDiamond® Portfolio - Vivace Suspension and Andante Dispersion

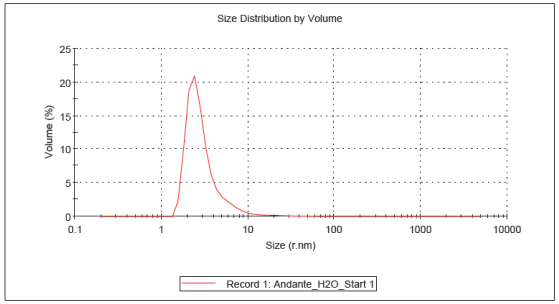
- **uDiamond Vivace**
  - A zeta-positive, 5 wt.% aqueous ND suspension
  - Agglomerated, zeta potential up to + 37 mV
  - Standard grade for plating within acidic region



- **uDiamond Andante**
  - A zeta-positive, 5 wt.% aqueous ND dispersion
  - Dispersion stable within pH range of 3 to 6
  - Zeta potential up to + 52 mV
  - Solvents including Di-Ethylene Glycol



Singe Digit ND Dispersion D90 = 4.6 nm



Dispersion stable within pH 3 to 6

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Vivace, Andante, Andante (Diluted)

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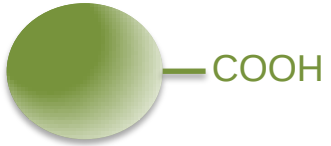
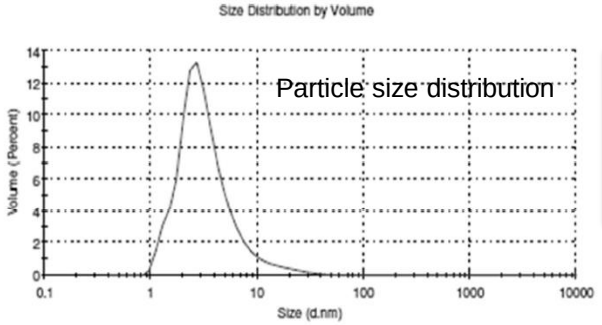
uDiamond® Portfolio - Vox D

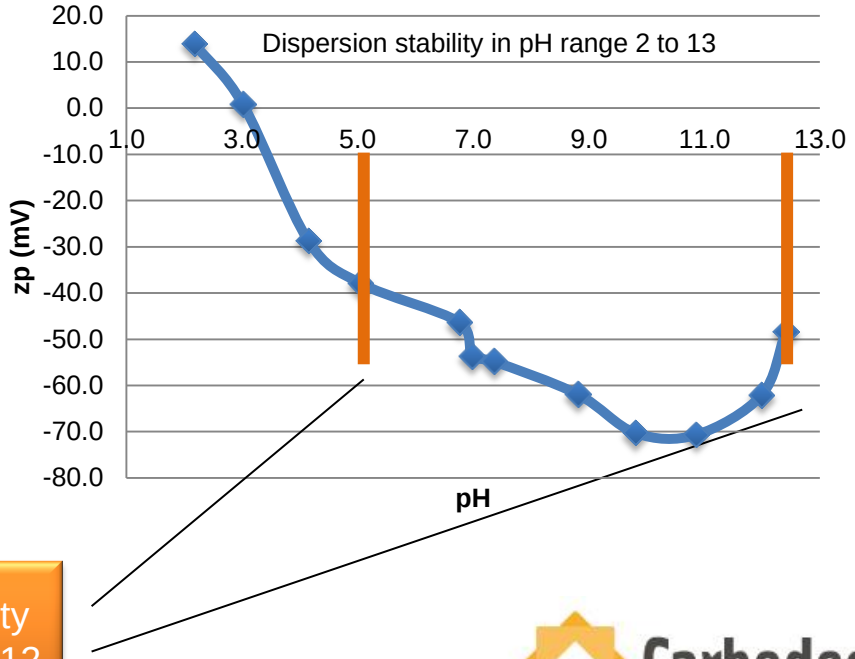


- A new, patented highly zeta negative nanodiamond dispersion
  - Fully carboxylated surface
  - Zeta potentials up to -71 mV
  - Dispersion stable in pH 5 to 12
- Solvents
  - Aqueous, 5 wt.%
  - NMP, 2 wt %
  - NEP, 1 wt%
  - GBL, other solvents on the way
- Applications
  - Paints, resins, fluoropolymer



Singe Digit ND Dispersion

D90 = 6.61 nm



Robust stability within pH 5 to 12

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uDiamond® Portfolio

- **Options for surface chemistry and morphology**
- **Powders -** agglomerated clusters of NanoDiamonds in >100nm scale. Used where no compatible solvent available, e.g. certain thermal polymers.
- **Suspensions –** smaller agglomerates in liquid, easier to incorporate.
- **Dispersions –** single digit 4-6 nm particles in stable dispersion

Very easy dispersion – direct mixing
Increased surface area
Low concentrations 0.05-1.0wt%, <1g/litre (in cases)

Paints, resins with no visual effects
Choice of Solvents
Also for electroplating @ pH>3

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Where, What, & How

NanoDiamond
Material Selection

Material and
Process
Understanding

Dispersion
Methods &
Process
Optimisation

Property
Requirements,
Test Methods,
Economics

Communication

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Where, What, & How

Unfortunately, it isn't as simple as this!

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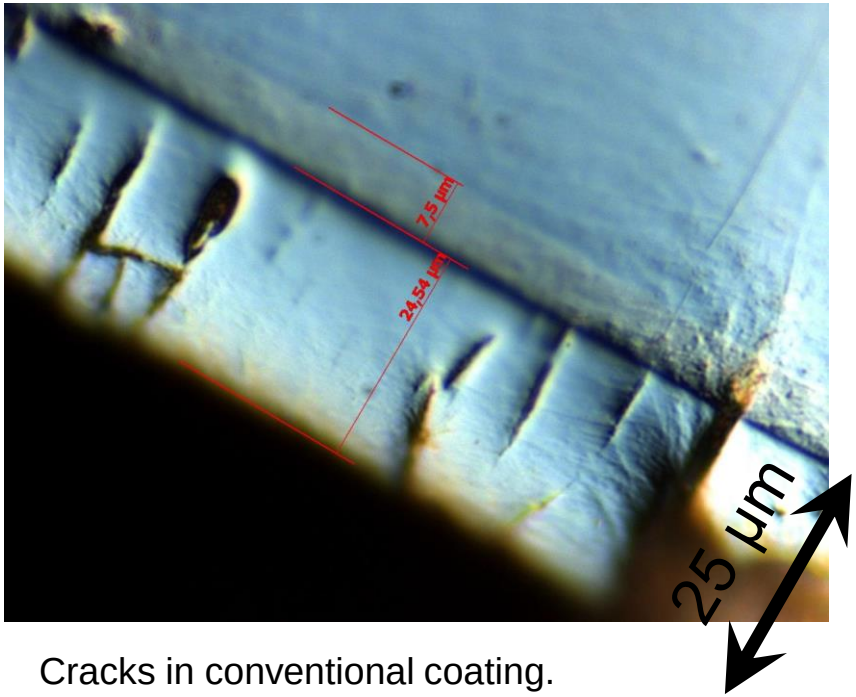
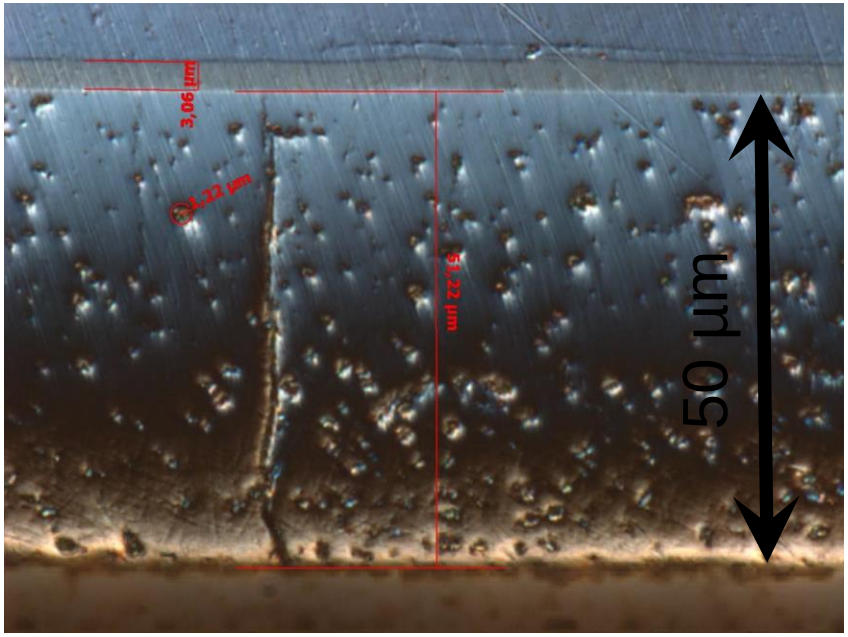
Example Application - Electroplating

- NanoDiamonds result in a denser, less cracked/ porpous stucture leading to improved corrosion resistance.
- Agglomerated NanoDiamond – 100nm plus scale



Cracks in conventional coating.



NanoDiamond reinforced coating with reduced cracking.

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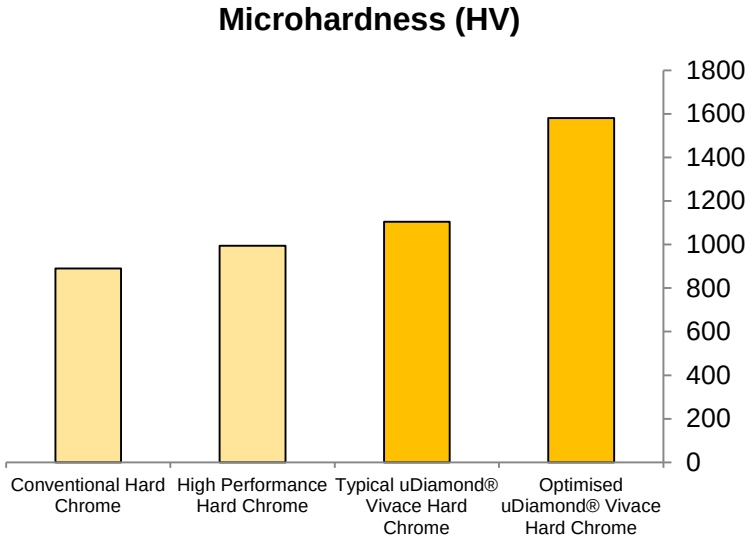
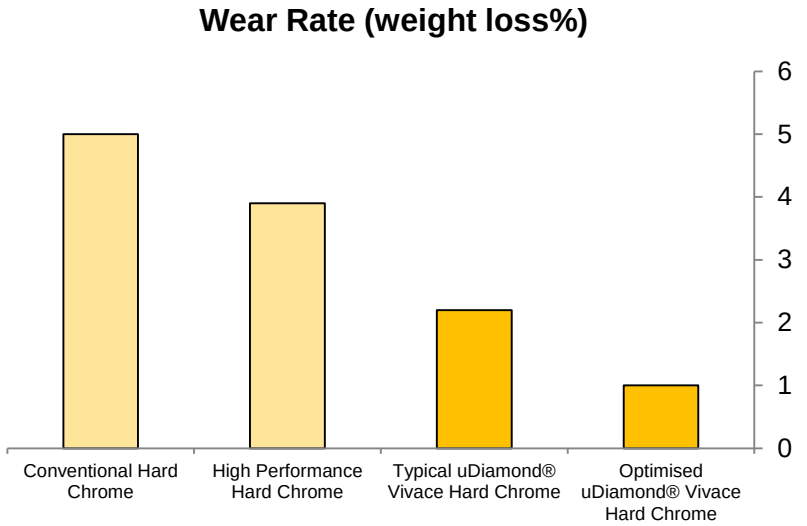
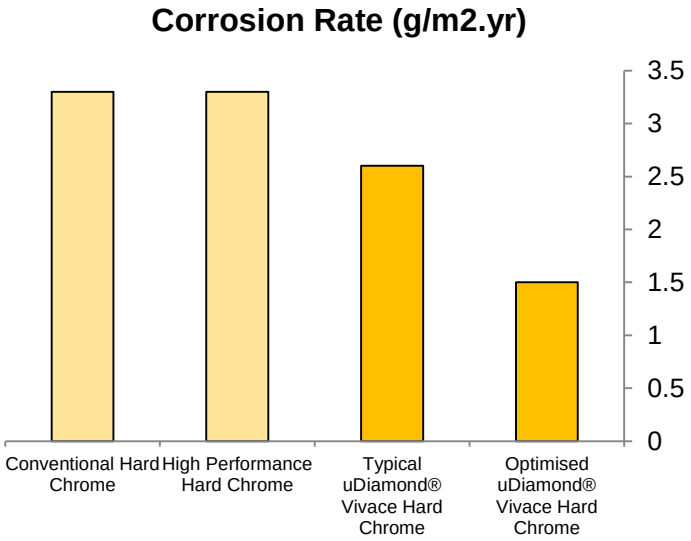
uDiamond® Vivace With Cr^{VI}







- Key improvements:
  - Microhardness: 20-50%
  - Wear resistance: >100%
  - Corrosion resistance: 50-100%
  - Friction coefficient: -30%
- Hurdle:
  - 10g/litre agglomerated NanoDiamond

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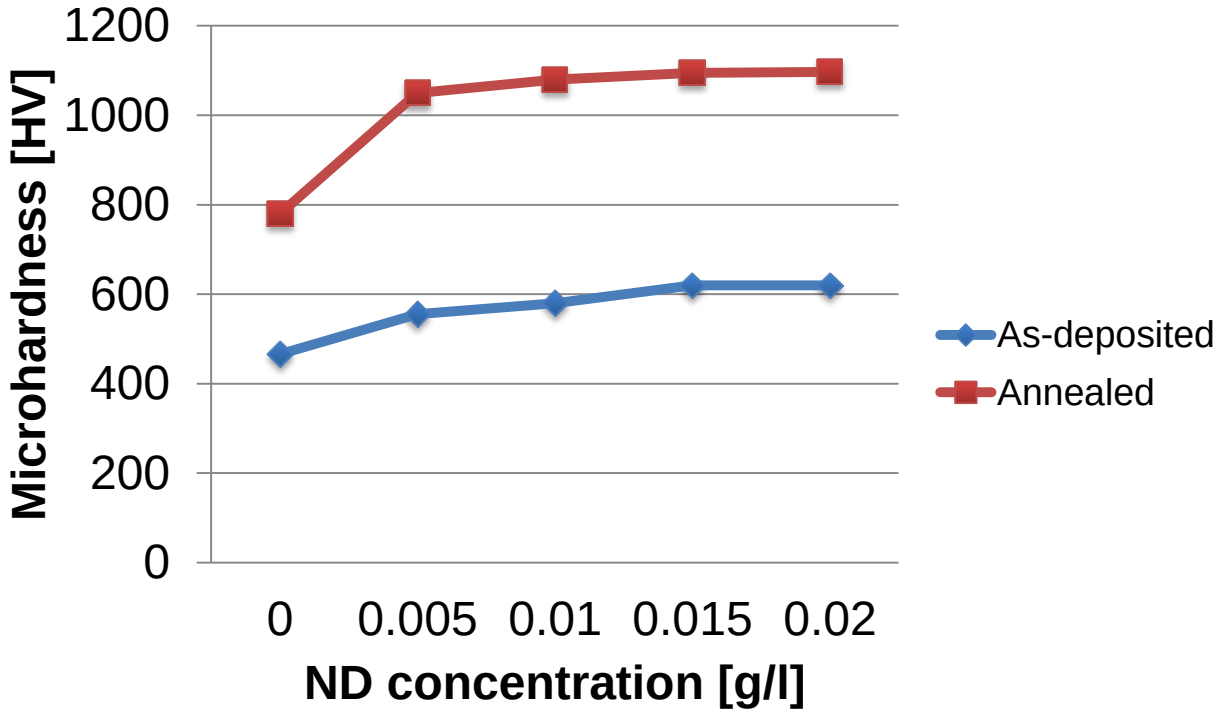
uDiamond® Andante in Electroless Nickel

- Medium phosphorous electroless nickel
- No agglomeration – single digit dispersion
- Annealing at 350 °C

- Nanodiamond surface functionalization has a big impact in electroless processes



Microhardness of electroless nickel with and without ND's. Annealing at 350 °C.

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Introducing Carbodeon's Plating Lab

- Electroless & Electrolytic Nickel
- Trivalent Chromium

- Material analysis – wear testing

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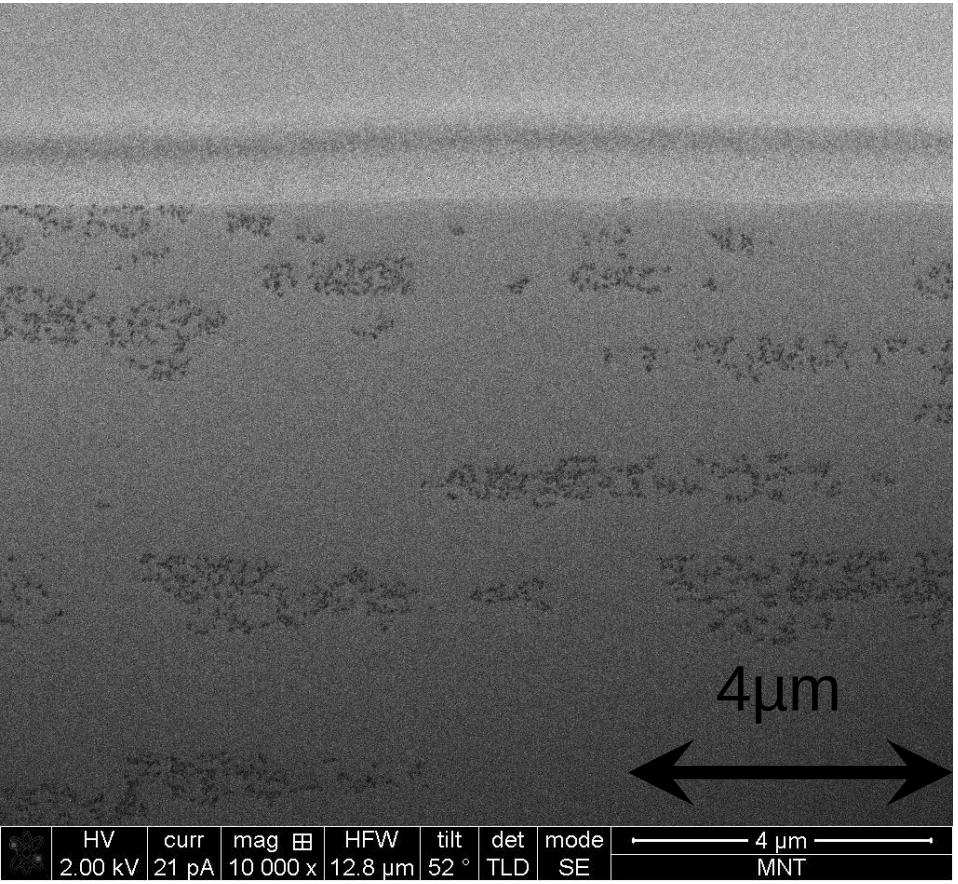
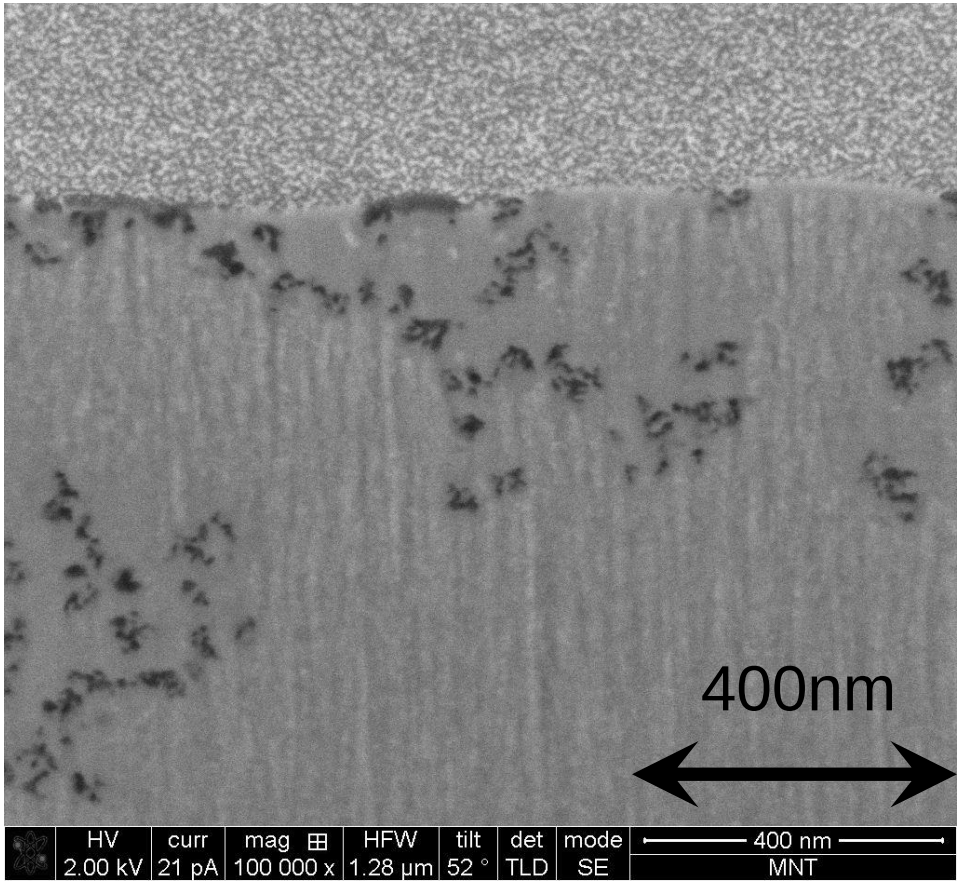
SEM-images of 0,05 g/l ND containing E/N samples





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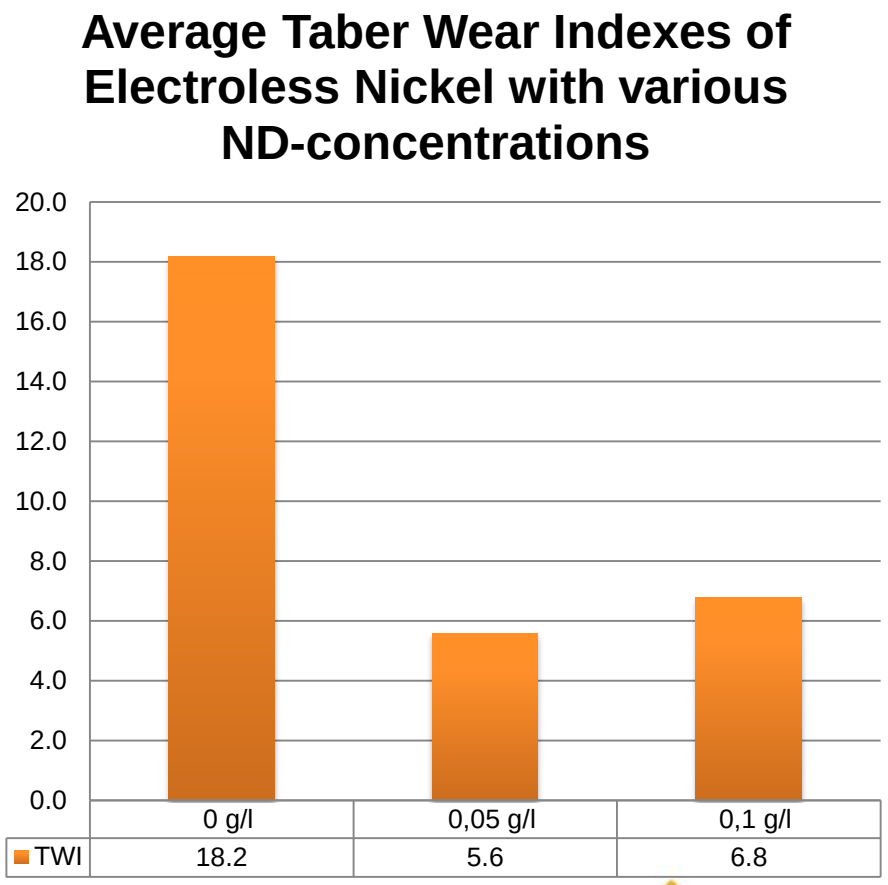
Electroless Nickel – Preliminary in-house test results

- Medium phosphorous (P = 5-9%)
- No heat treatment
- Wear resistance measured using Taber 5135, CS-10 rolls ,1 kg load
- TWI = average weight loss [mg] / 1000 revolutions
- Small change in hardness, large change in wear resistance
- Diamond composition in the plating is approx 0.2-0.4wt%
- Diamond cost is lower than the Nickel cost



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Example Coating Application
NanoDiamond-Fluoropolymer Coatings

Over 500 samples made and tested to date.

Suspension grade:

Improvements made, based on around 2wt% addition.

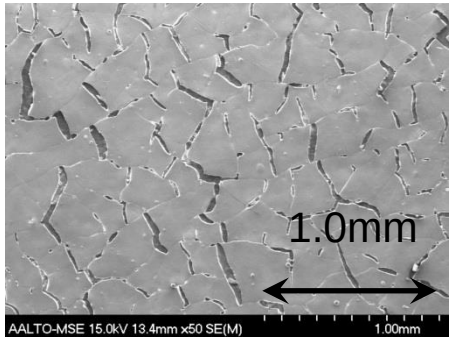
Dispersion grade:

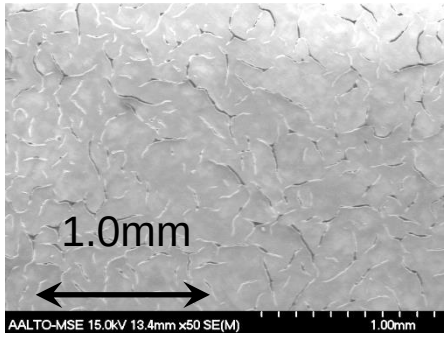
Matching improvements made using 0.05-0.25wt%

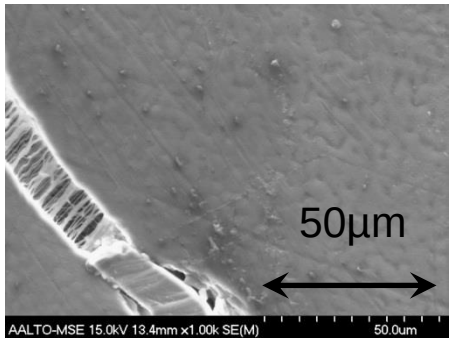
Friction, Wear and Surface Finish Improvements

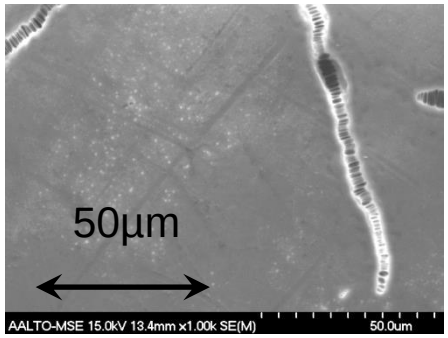
Reference

With ND's









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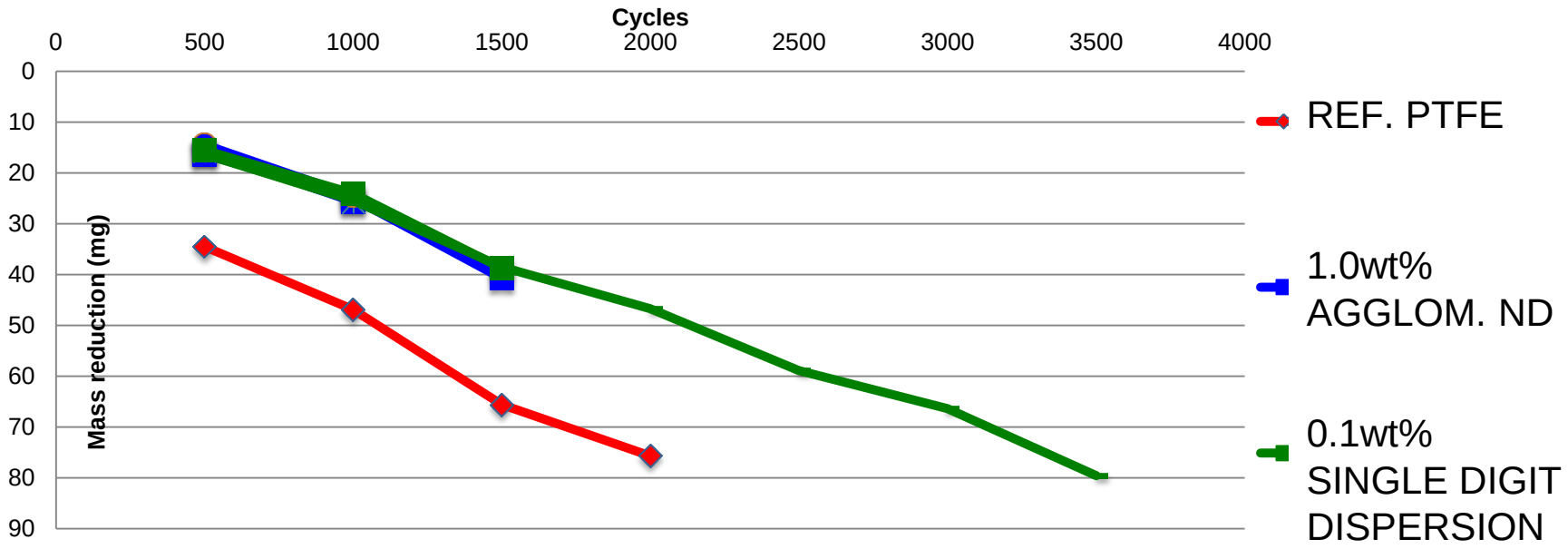
Wear Properties – PTFE (Aqueous)

Taber analyses



- ND concentrations, in final coatings
  - Agglomerating grade, 1 wt.%
  - Single Digit grade, 0.1 wt.%
- Wear properties studied up to 2000-3500 cycles
- Up to 50% improvement in wear properties , up to 66% friction reduction

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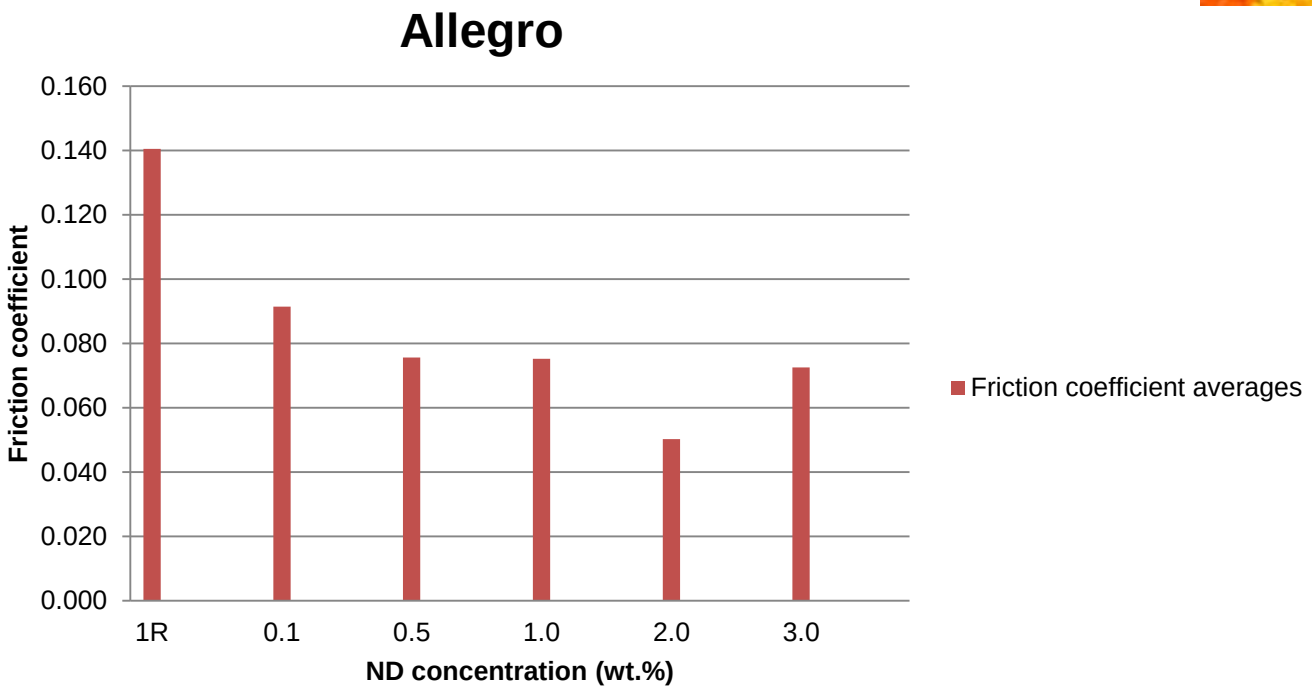
Friction Properties – PTFE (Aq) Example



- Friction tests with Allegro ND – **not the latest single digit dispersion**
- ND concentrations varied between 0.1 to 3.0 wt.%
- Significant improvements already with very low ND additions
- 66% reduction received with 2 wt.% ND concentration

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Friction - Wear Collection

Plating, coatings, nanocomposites

- Powertrain components (friction, wear)
- Chassis components (friction, corrosion, elastomer properties)
- Interior & Exterior (wear resistant resins & coatings, high performance composites)

- Automotive, Aerospace & Defence, Industrial, Electronics etc.

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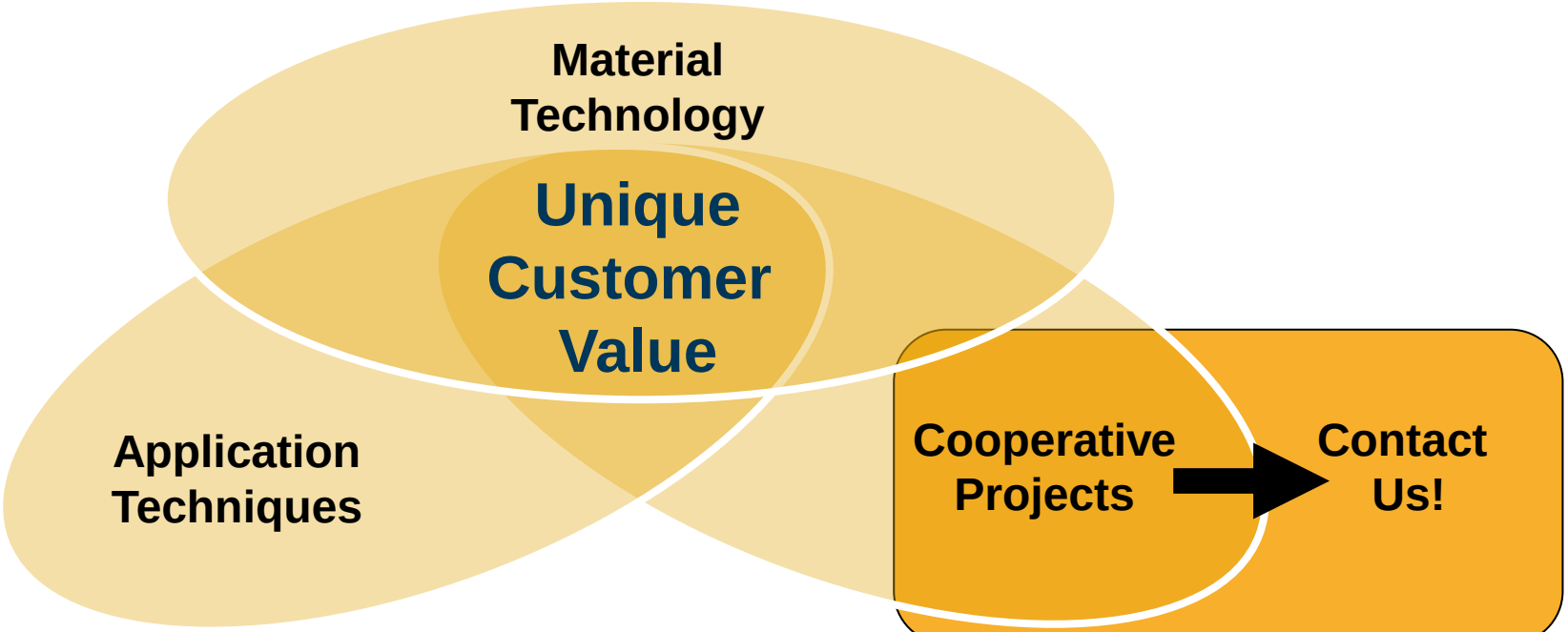
Carbodeon – Providing You a Unique Advantage through New Materials



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