Tungsten Carbide- Based HVAF Coatings for Protection of Petrochemical, Oil Drilling and Hydro-Power Equipment Against Wear and Cavitation

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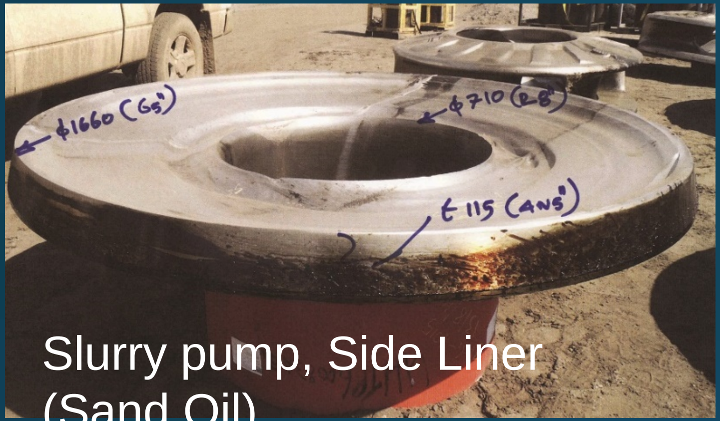
Erosion and Cavitation Damage in Pumps, Compressors and Turbines



Slurry pump, Side Liner (Sand Oil)

Slurry pump impeller: before and after 3-month service

Turbine shaft (Refinery)

Erosion Damage in Hydro Plant Components

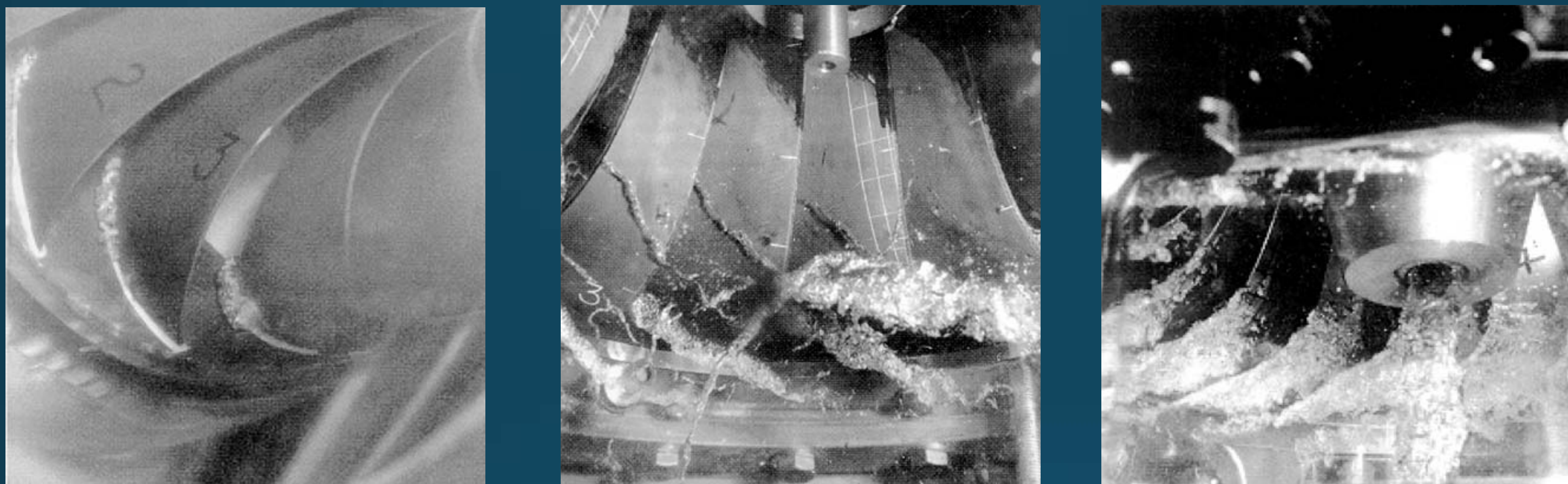
Runner

Guide Vane

Liner Plate

Cavitation Induced Damages in Hydro components.

"Pure" Cavitation



Francis Runner Leading edge, inter blade vortex and traveling bubble

Pelton Bucket
damaged regions

Protective Overlays and Coatings

Rubber lining (polyurethane, etc.):

Good cavitation resistance
Poor erosion resistance
Poor bonding

Stellite 6 (PTA overlays and HVOF coatings):

Moderate cavitation resistance
Moderate erosion resistance
Occasionally – bonding problems (HVOF)

Cr3C2-25NiCr (HVOF)

Poor cavitation resistance
Moderate-to-high erosion resistance

WC-10Co-4Cr (HVOF)

Poor cavitation resistance
High erosion resistance

Adaptation of HVAF for Application of WC-10Co-4Cr Coatings

Attractive improvements of HVAF over HVOF:

Better ductility (crack resistance) of coatings

Lower combustion temperature & concentration of oxygen =>
Reduced oxidation and WC decomposition

Higher coating hardness

Higher spray particle velocity and optimized heating =>
Better cohesion strength and density

Lower cost of application

Better energy efficiency =>
Higher spray rates, lower labor cost and associated expenses

Spray Guns and Materials

HVOF

Gun: JP5000 (150 mm long barrel)

Powder: Durmat 135, 38/15 micron, densified, “super-fine” WC

Cavitation resistance of this coating is 2.5-fold better compared to coatings applied with “conventional” agglomerated/sintered powders

HVAF

Gun: AK06 (275 mm long nozzle)

3 types of nozzles: 5L, 5E, 5O with different degree of expansion

Powder: Amperit 558.059, 30/5 micron, “conventional” agglomerated/sintered, “fine” WC

Samples

Initial substrates: 410 SS, 100 x 100 mm
Test samples of needed size were EDM cut from initial substrates (15 x 15 mm).
Before testing, coating surfaces were ground and polished
As-sprayed coating thickness: 350-400 micron

Spray Parameters
Settings on equipment

JP5000 HVOF			AK06 HVAF	
Barrel Length, inch	6		Barrel length, inch	11
			Chamber	3
Oxygen Flow @ 210 PSIG, SCFH	1850		Air, PSIG	90.3
Kerosene @ 170 PSIG, Gallon/hour	5.8		Propane, PSIG	83.8
Carrier N2 @50 PSIG, SCFH	23		Carrier N2 @140 PSIG, SLPM	21
			H2 Injections @ 140 PSIG, SLPM	20
Combustion pressure, PSIG	108		Combustion pressure, PSIG	75
Stand-off distance, inch	15		Stand-off distance, inch	7
Powder feed rate, g/min	90		Spray rate, g/min	133
Deposition per pass, micron	15		Deposition per pass, micron	28

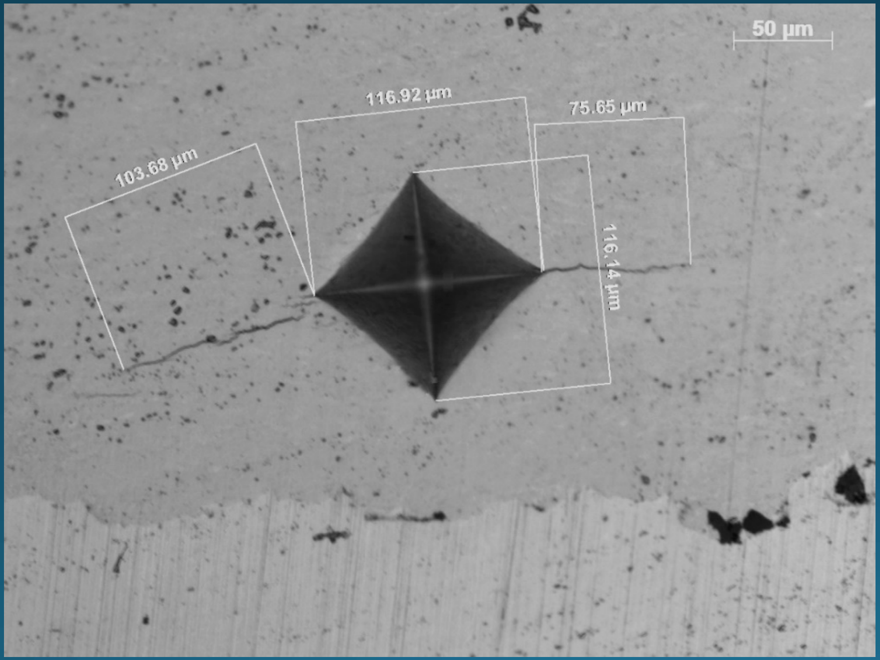
Characterization and Testing Methods

- Spray particle velocity and temperature - AcuraSpray 3GC (Tecnar)
- As-sprayed surface roughness
- Optical metallography
- X-ray analysis
- Vickers hardness at 300 g load (HV_{300})
- Fracture toughness K_{1C} at 10 kg indentation load at cross-section
- Young's modulus by micro-indentation technique
- Cavitation erosion resistance – ultrasonic tester per ASTM G32-03
- Silt erosion resistance – water jet with silica particles
- SEM microscopy of surface after testing

Characterization and Testing Methods

Fracture toughness K_{1C} at 10 kg indentation load at coatings cross-section, calculations according to Evans and Wilshaw equation

$$K_1C = 0.016*(Hv * d)*(E/Hv)^2/5 * a ^ (-0.5)$$



Determination of Young's Modulus by micro-indentation technique

$$\frac{1}{E_r} = \frac{(1-\nu^2)}{E} + \frac{(1-\nu_i^2)}{E_i}$$

$$\sigma_y \approx H/3$$

$$H = P/A$$

$$E_r = \frac{\sqrt{\pi}}{2}\frac{S}{\sqrt{A}}$$

$$A = f(h_c)$$

$$h_c = h - 0.75P/S$$

$$S = \left.\frac{dP}{dh}\right|_{h_{max}}$$

Nomenclature:

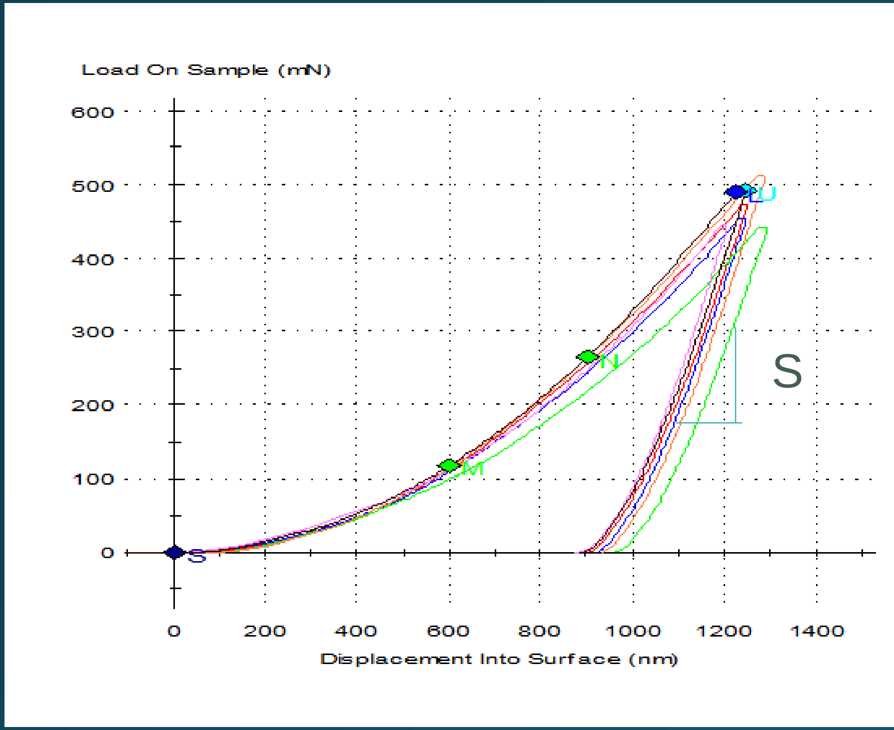
E	Young's modulus
H	hardness
σ_y	Yield stress
E_r	reduced modulus
ν	Poisson's ratio
i	(as subscript) indenter
S	contact stiffness
A	projected contact area
h_c	contact depth
h	displacement
P	applied force (load)

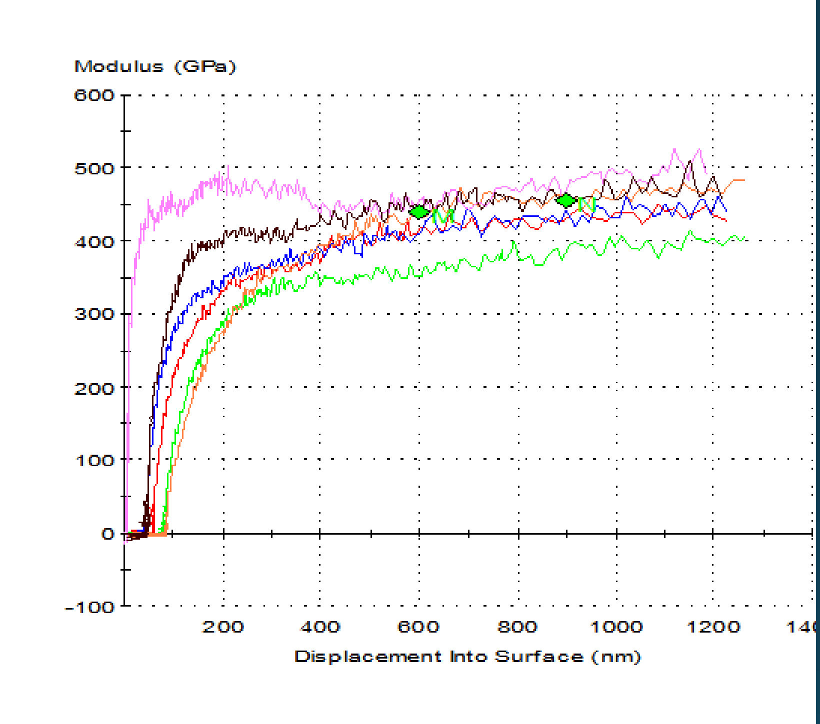
$$S = \left.\frac{dP}{dh}\right|_{h_{max}}$$

$$E_r = \frac{\sqrt{\pi}}{2}\frac{S}{\sqrt{A}}$$

$$\frac{1}{E_r} = \frac{(1-\nu^2)}{E} + \frac{(1-\nu_i^2)}{E_i}$$

Determination of Young's Modulus by micro-indentation technique





Stiffness

$$S = \left.\frac{dP}{dh}\right|_{h_{max}}$$

Reduced modulus

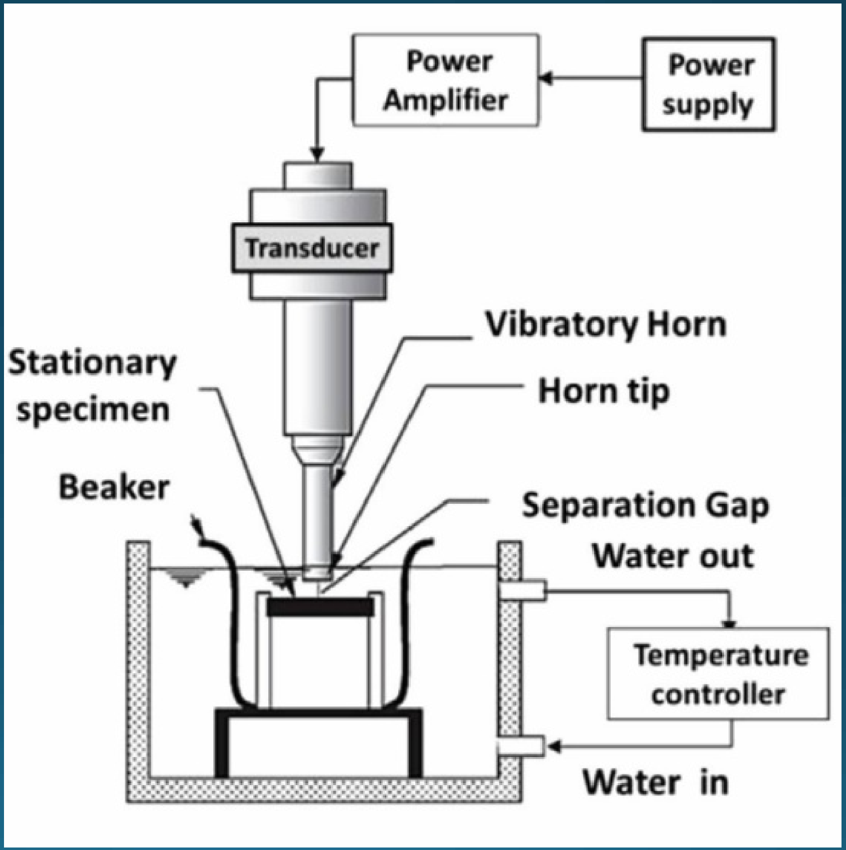
$$E_r = \frac{\sqrt{\pi}}{2}\frac{S}{\sqrt{A}}$$

$$\frac{1}{E_r} = \frac{(1-\nu^2)}{E} + \frac{(1-\nu_i^2)}{E_i}$$

Characterization and Testing Methods

Cavitation erosion resistance – ultrasonic tester* per ASTM G32-03

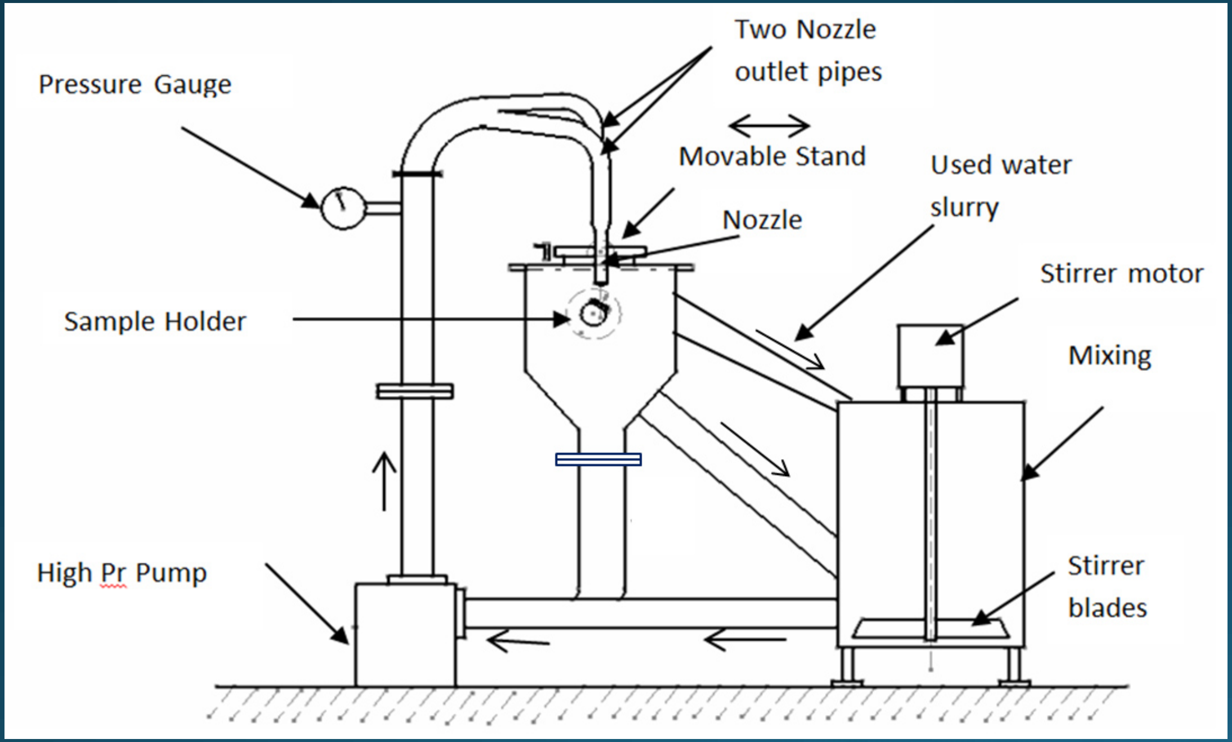
Sample size: 15 x 15 mm
Surface ground and polished
3 samples tested for each coating
Gap between horn tip and sample: 1 mm
Oscillator frequency: 20 kHz
Peak-to-peak amplitude: 100 μm
Liquid: water
Weight measurement with 0.01 mg resolution: each hour
Test duration: up to 13 hours



(*) Tester: VCX 1500, Sonics & Materials, USA

Characterization and Testing Methods

Silt erosion resistance – water jet with silica particles



Sample: 15 x 15 mm

Erodent: silica sand AFS No.70
Concentration: 8%

Nozzle diameter: 19 mm
Particle velocity: 28 m/s
Impact angle: 45 deg.

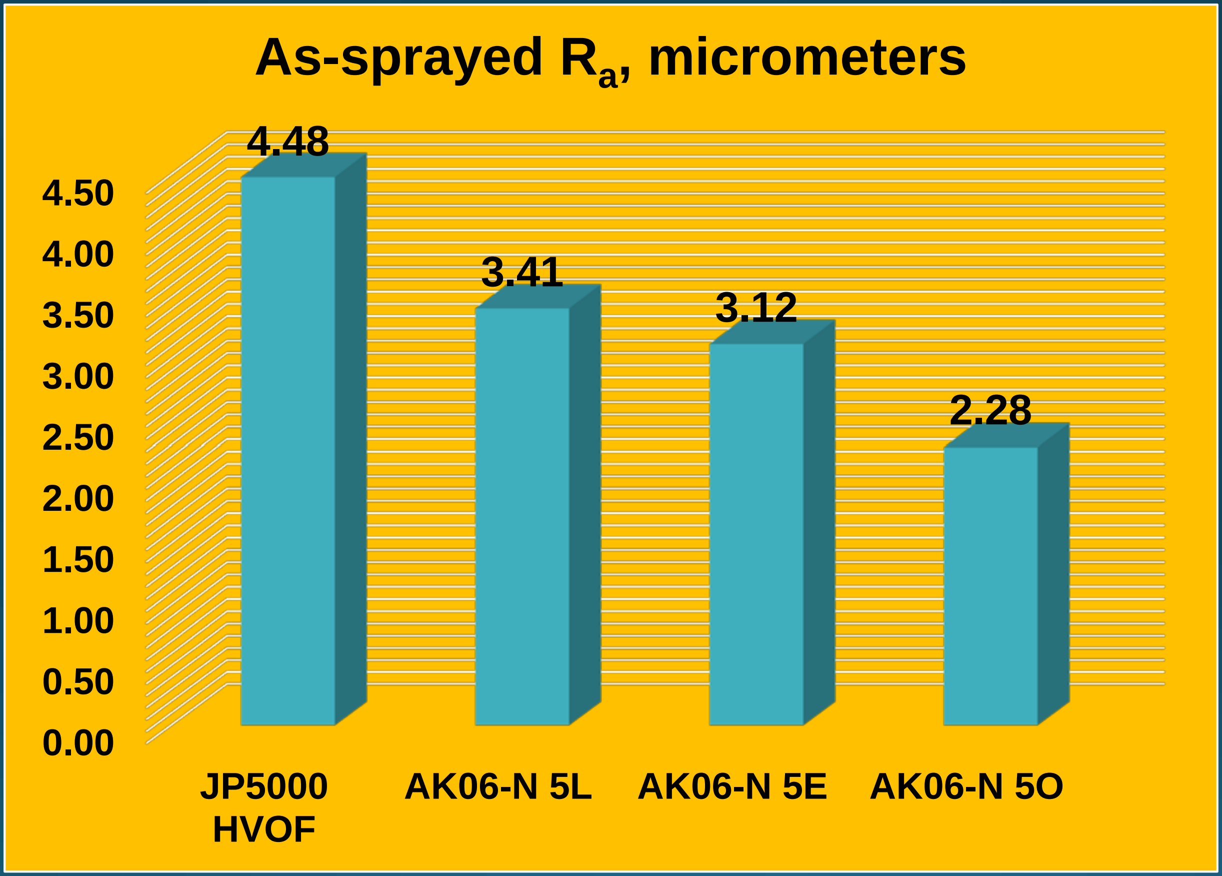
Test duration: 3 hours
Weight measurements: each hour

TEST RESULTS

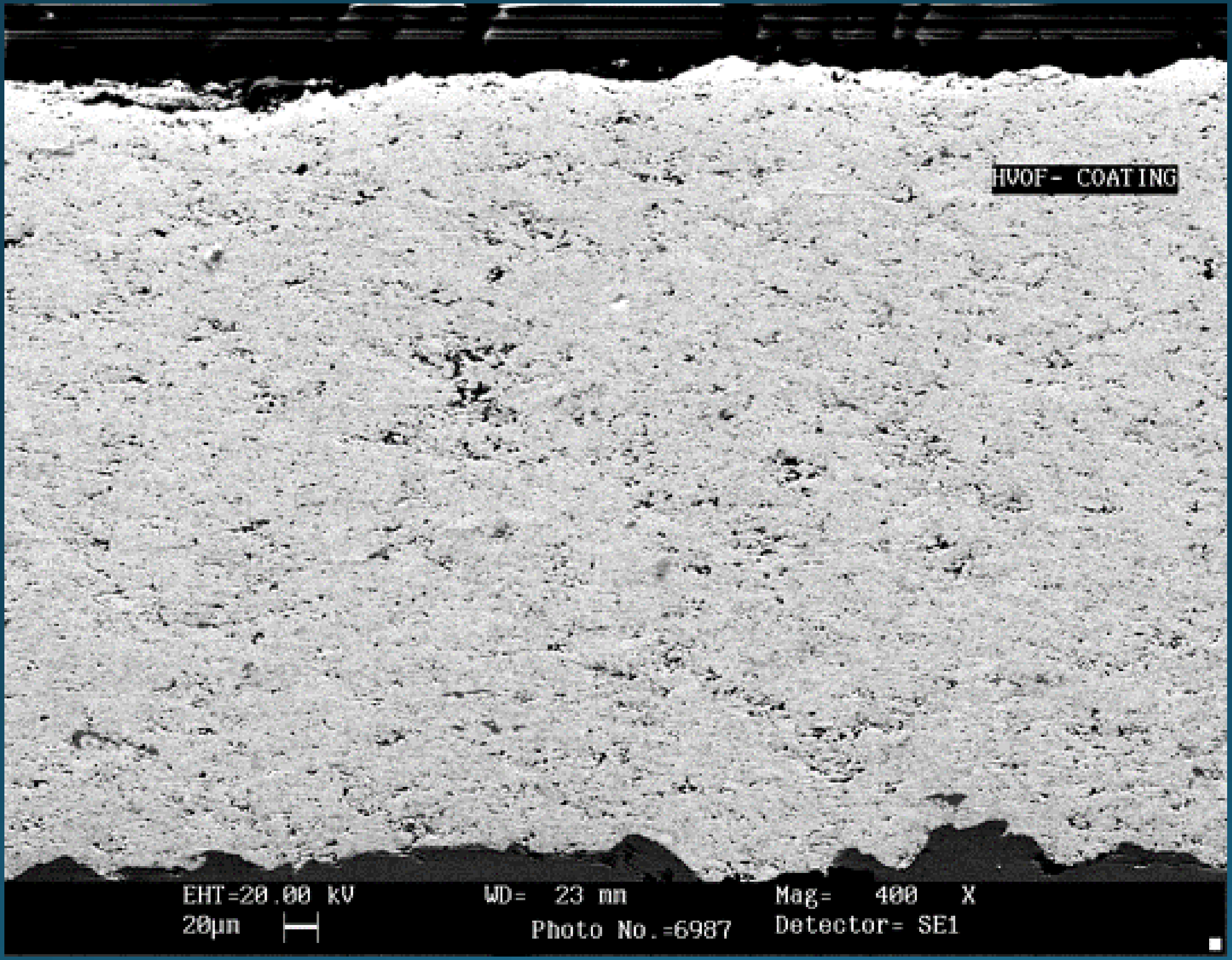
Spray Parameters: Normalized

	JP5000 HVOF	AK06 HVAF		
		Nozzle 5L	Nozzle 5E	Nozzle 5O
Oxidizer flow, SLPM	O2: 873.1	Air: 2,104 (O2: 421.0)		
Fuel, g/sec	5.01	2.65		
O_2/Fuel Ratio vrs. Stoichiometric	1.16 (Oxidizing)	1.03 (~Neutral)		
Carrier Nitrogen, SLPM	10.85	21		
Combustion pressure, Bar	7.56	5.25		
Powder feed rate, g/sec	1.50	2.22		
Particle average size, micron	27	18		
Particle velocity, m/s	740	895 +/-2	960 +/-3	1010+/-4
Particle temperature, ^{o}C	1790-1840	1470 +/-10	1460 +/-10	1470 +/-10
Particle kinetic energy, μJ	29.4	12.7	14.7	16.2
Energy density, GJ/m^3 =GPa	3.8	5.6	6.4	7.1

Surface Roughness of As-Sprayed Coatings

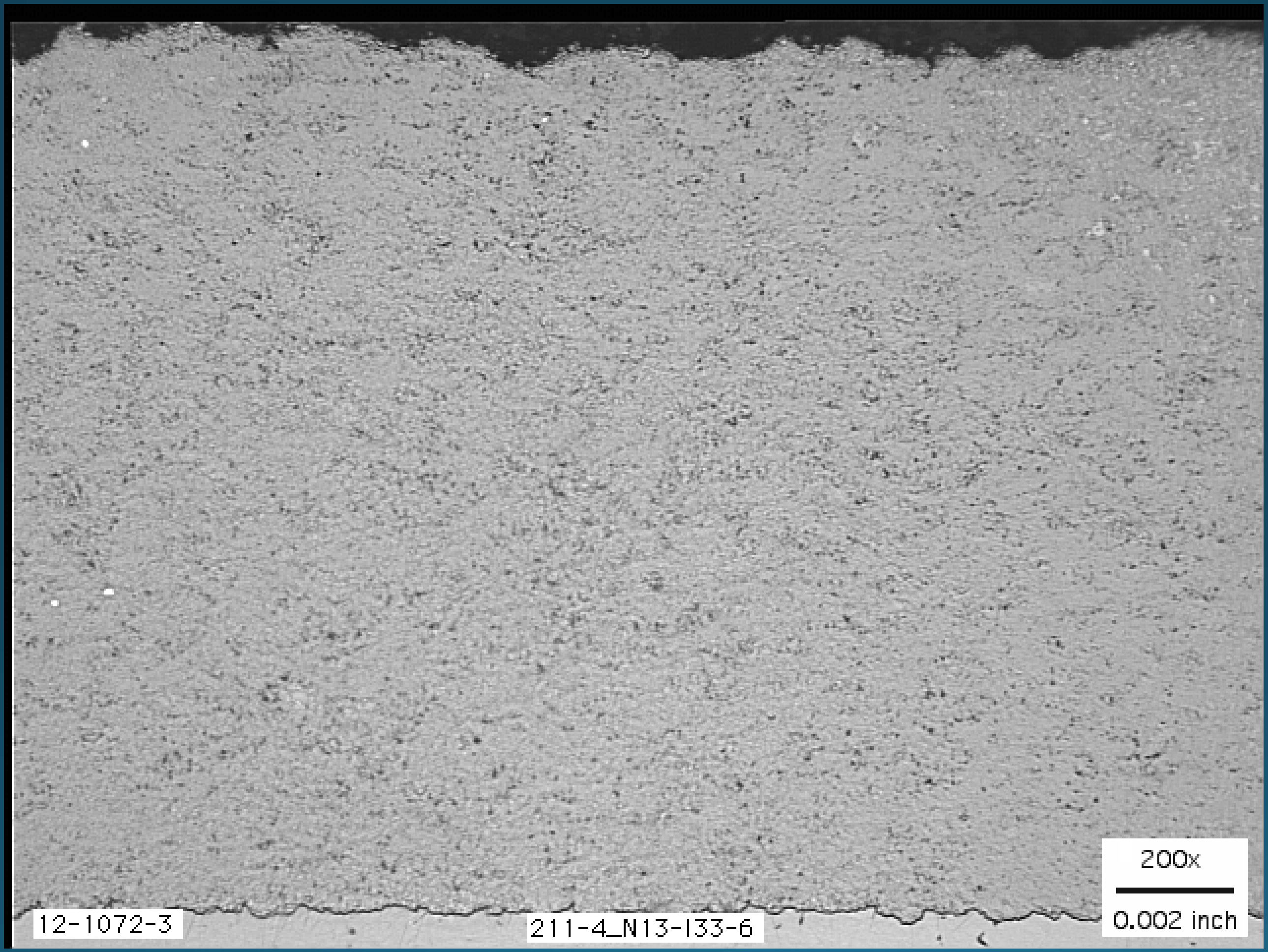


Optical Metallography:
JP5000 HVOF



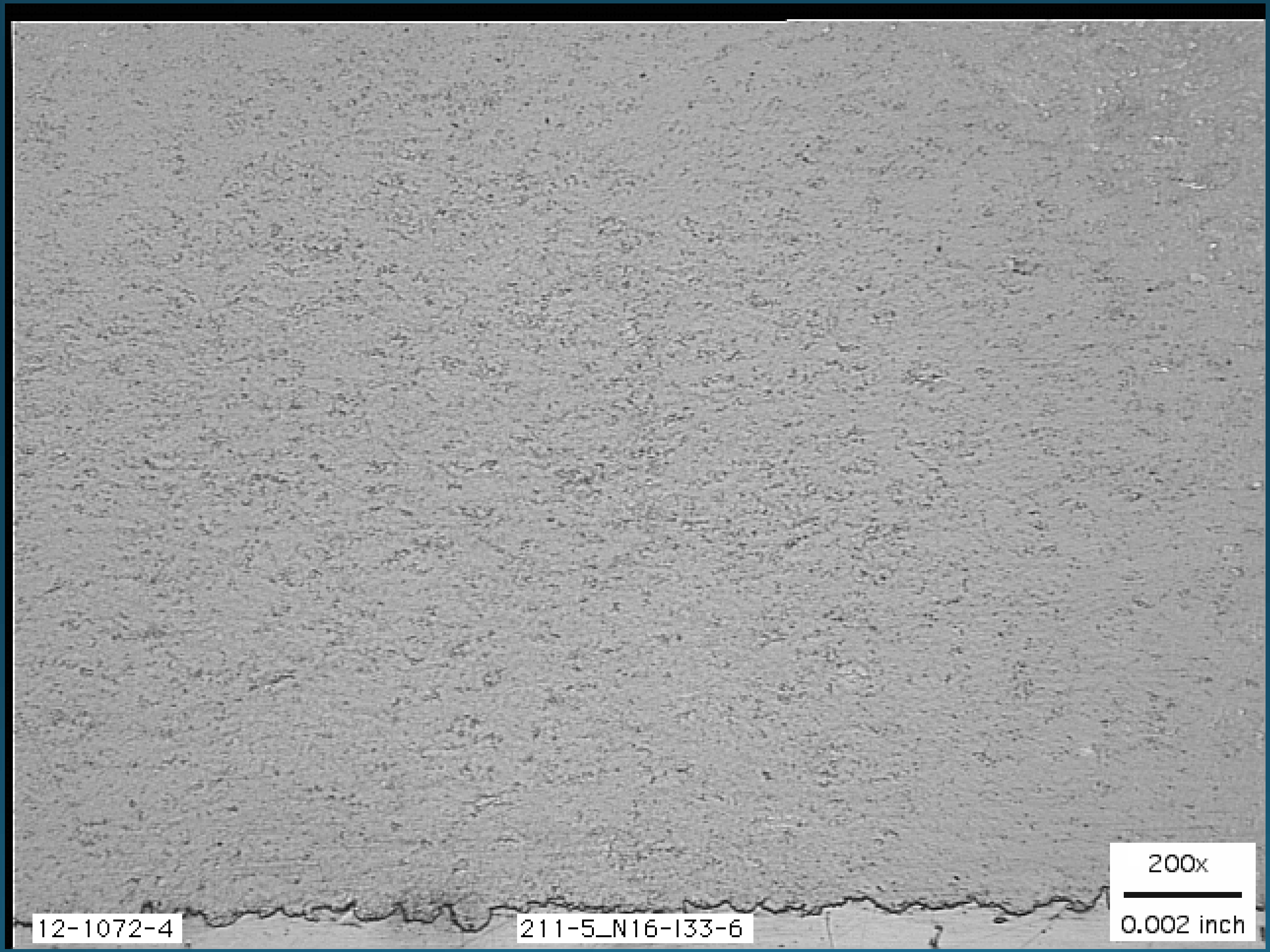
P<0.8%

Optical Metallography:
AK06 HVAF, Nozzle 5L



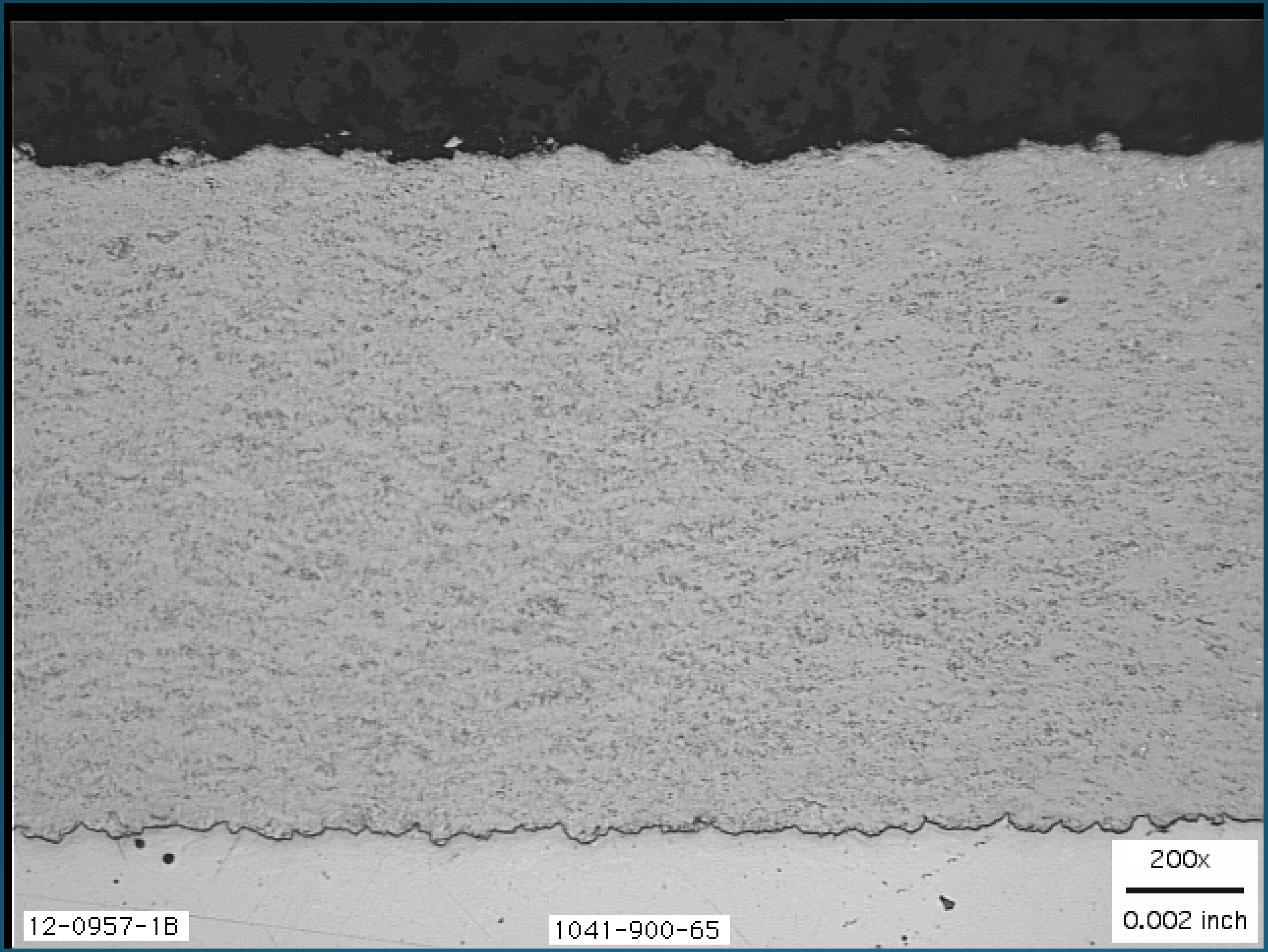
P<0.1%

Optical Metallography
AK06 HVAF, Nozzle 5E



P<0.1%

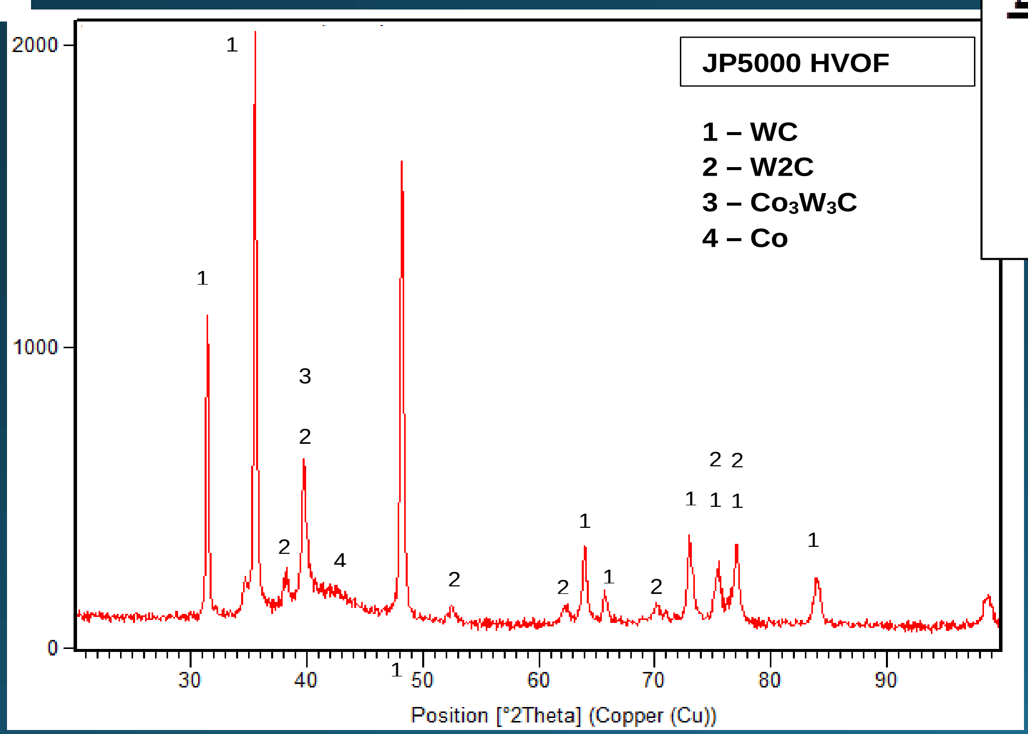
Optical Metallography:
AK06 HVAF, Nozzle 5O

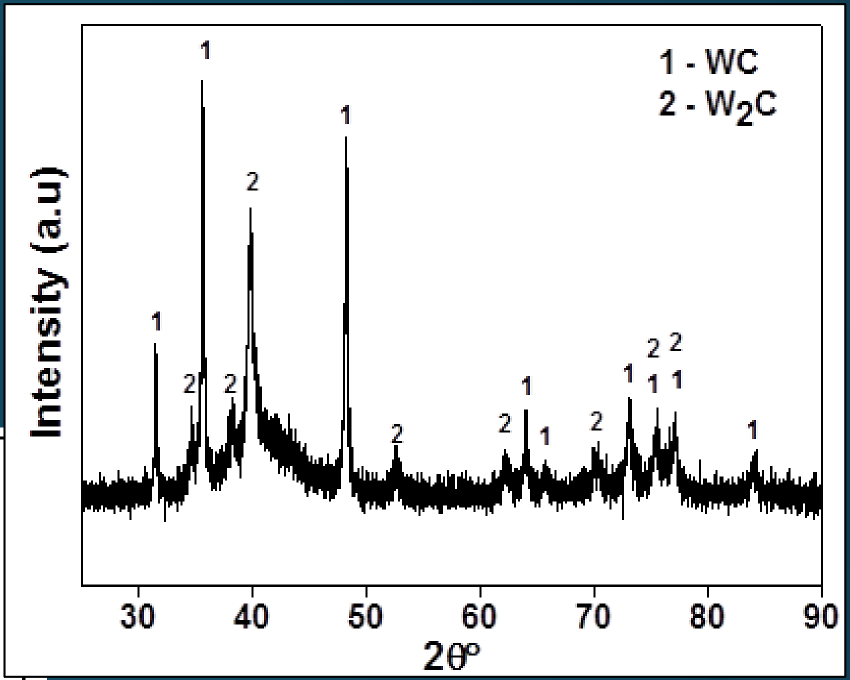


P<0.1%

X-ray Analysis Data
HVOF

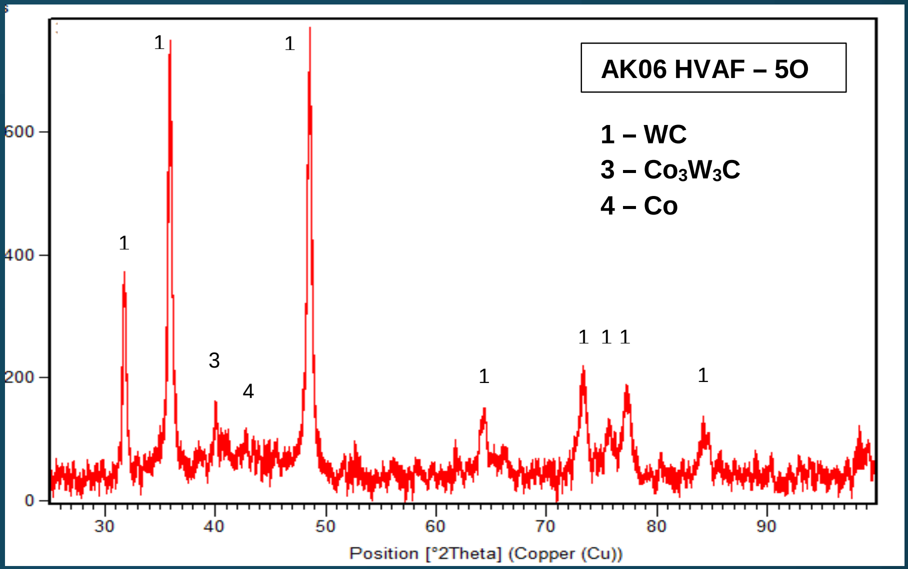
Improved coating: Current study

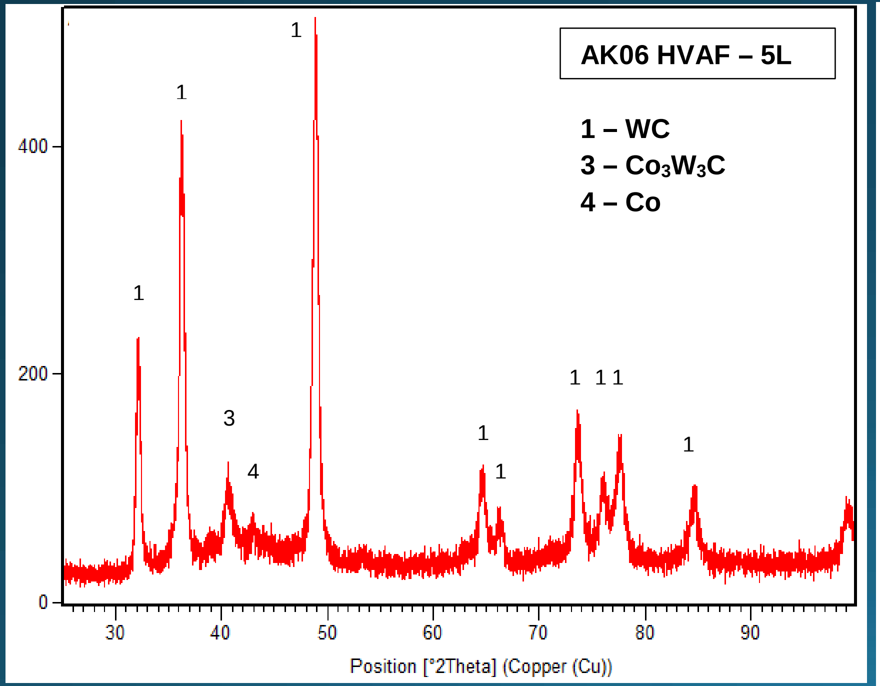


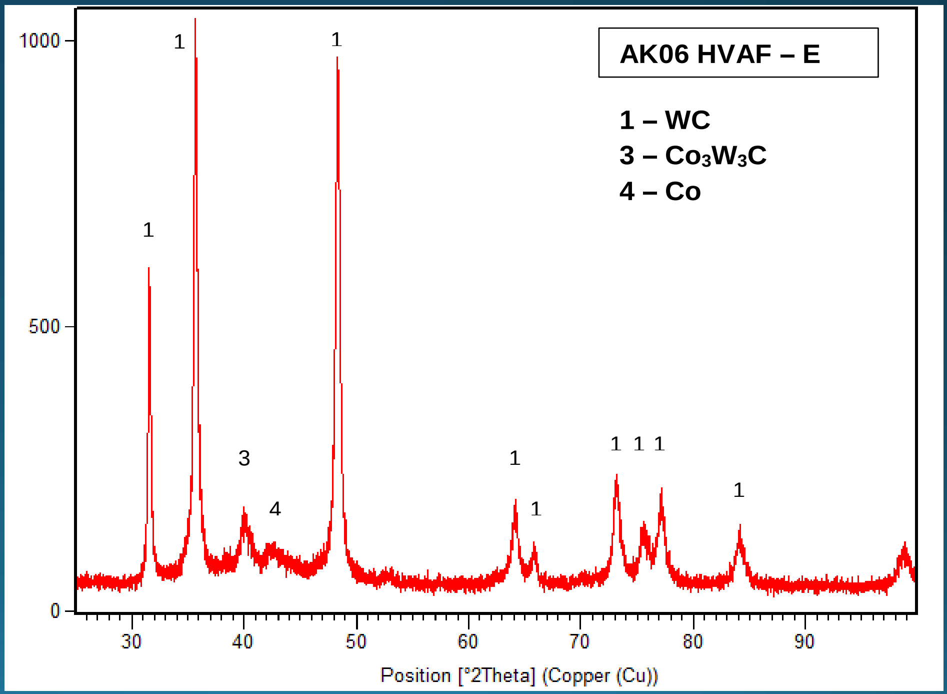


Typical for agglomerated/sintered powders (1350VM powder)

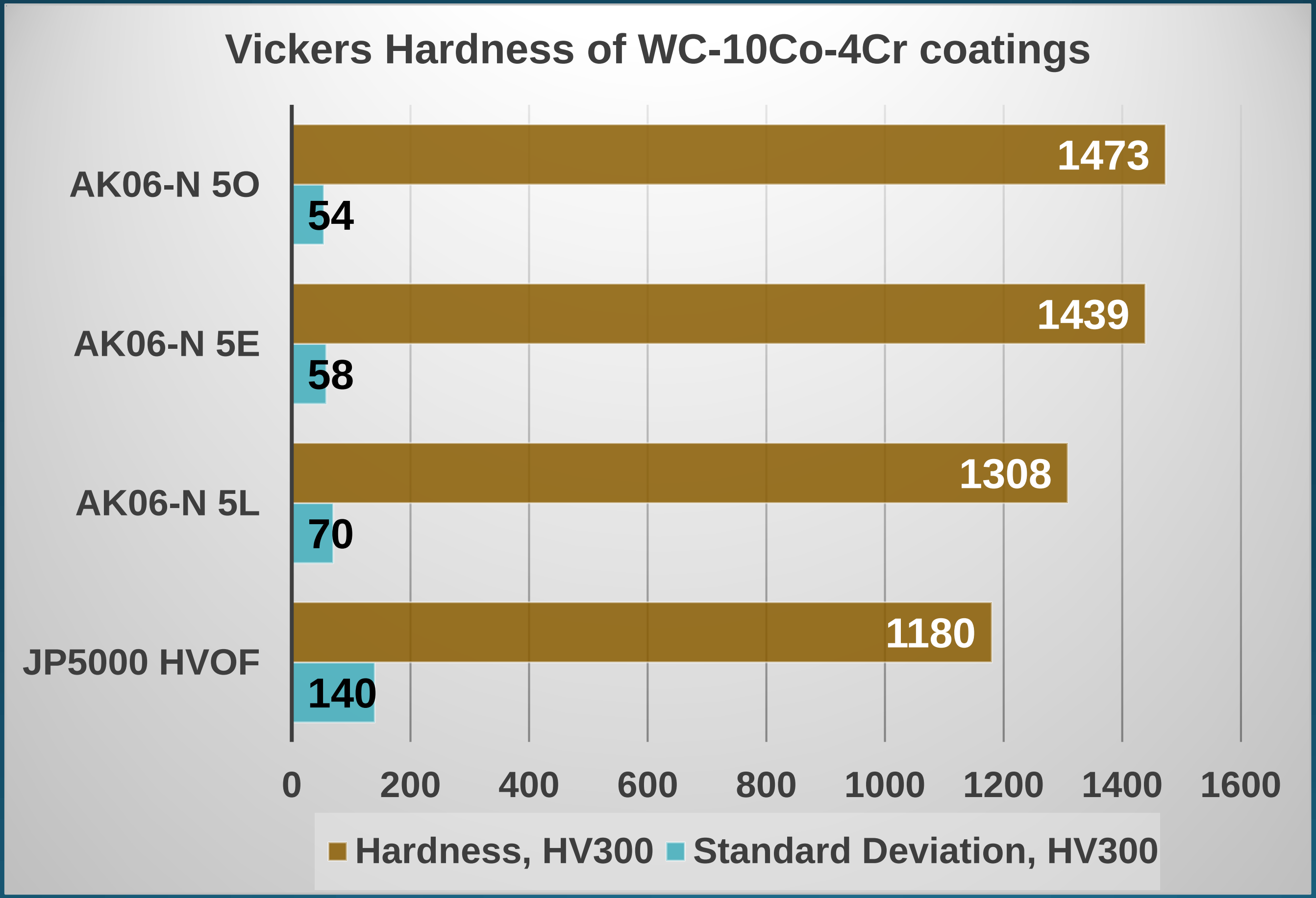
X-ray Analysis Data
HVAF



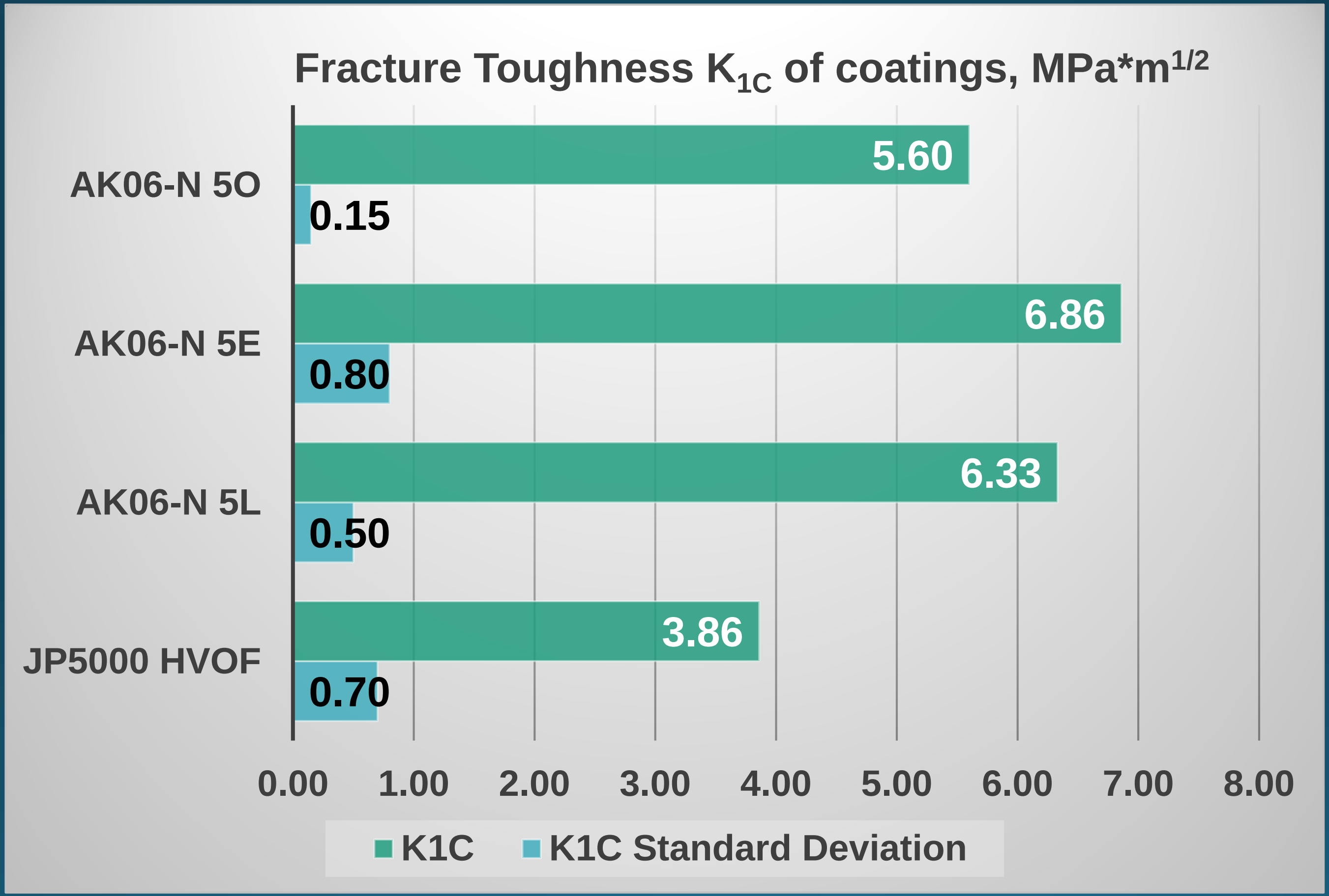




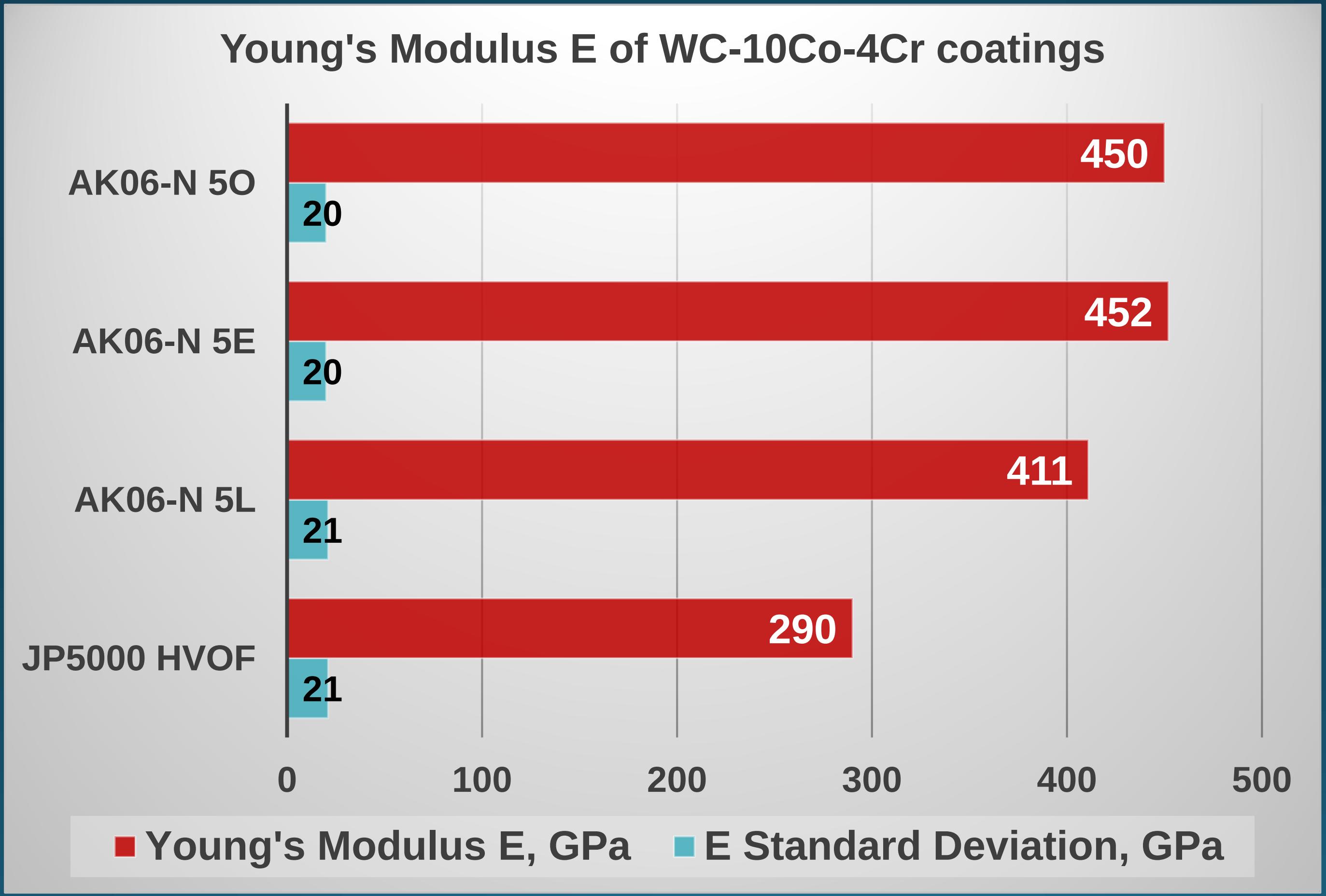
Mechanical Properties



Mechanical Properties



Mechanical Properties



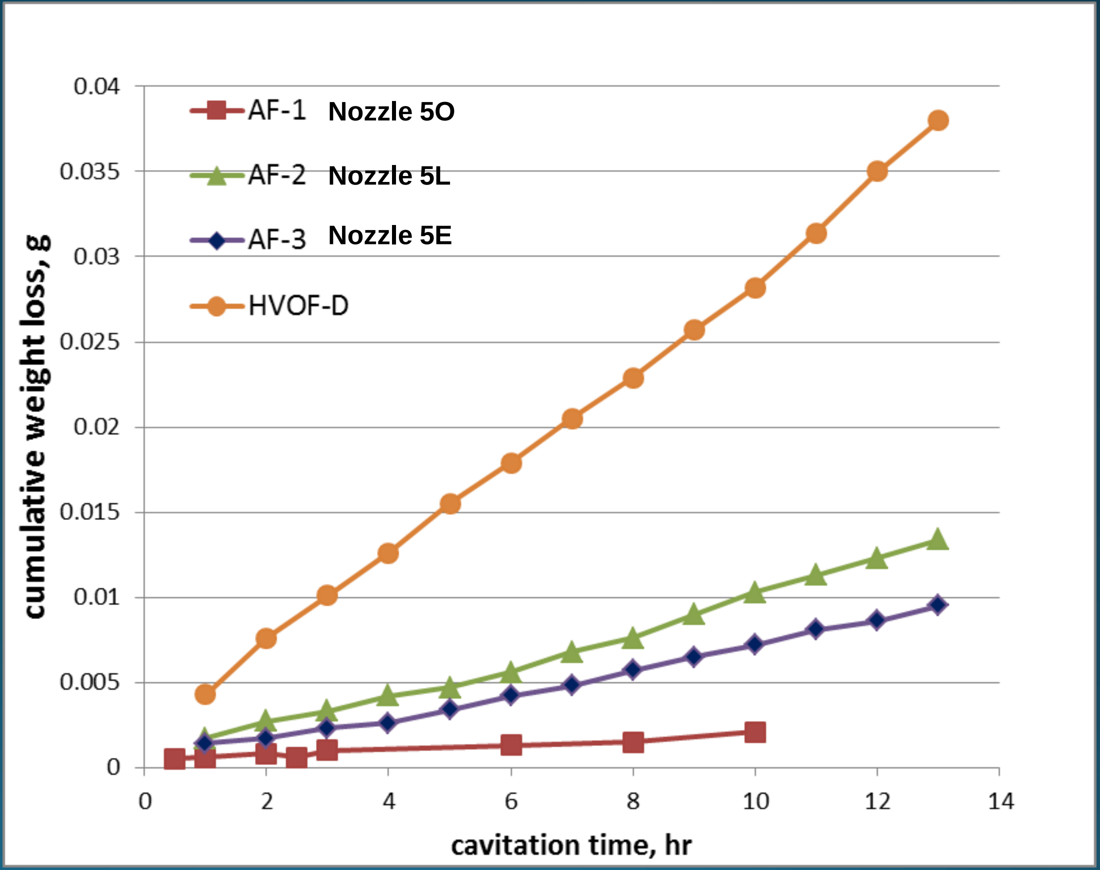
Cavitation Resistance
of WC-10Co-4Cr HVOF and HVAF coatings

(dw/dt) AF1 (5O) = 0.23 mg/h
(dw/dt) AF3 (5E) = 0.71 mg/h
(dw/dt) AF2 (5L) = 0.96 mg/h

(dw/dt) HVOF = > 3.26 mg/h

(dw/dt) 16Cr-5Ni steel = 2.0 - 2.5 mg/h

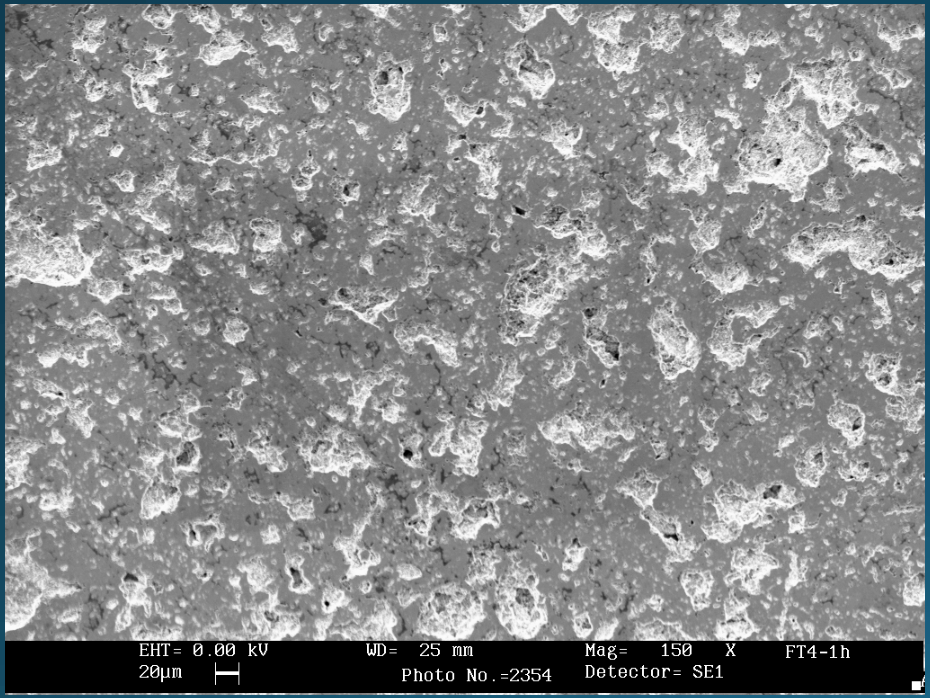
$$\frac{d\,(\,weight\ loss)}{d\,(time)} = dw/dt$$

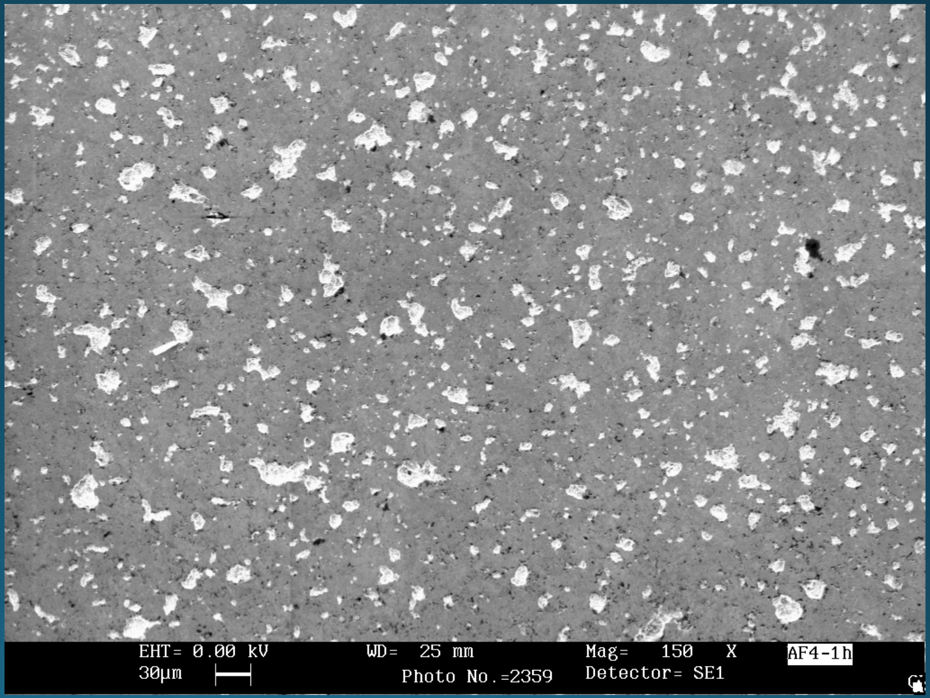


Surface SEM Micrographs of WC-10Co-4Cr Coatings after Cavitation Testing

Test duration: 1 hour

JP5000 HVOF **AK06 HVAF**

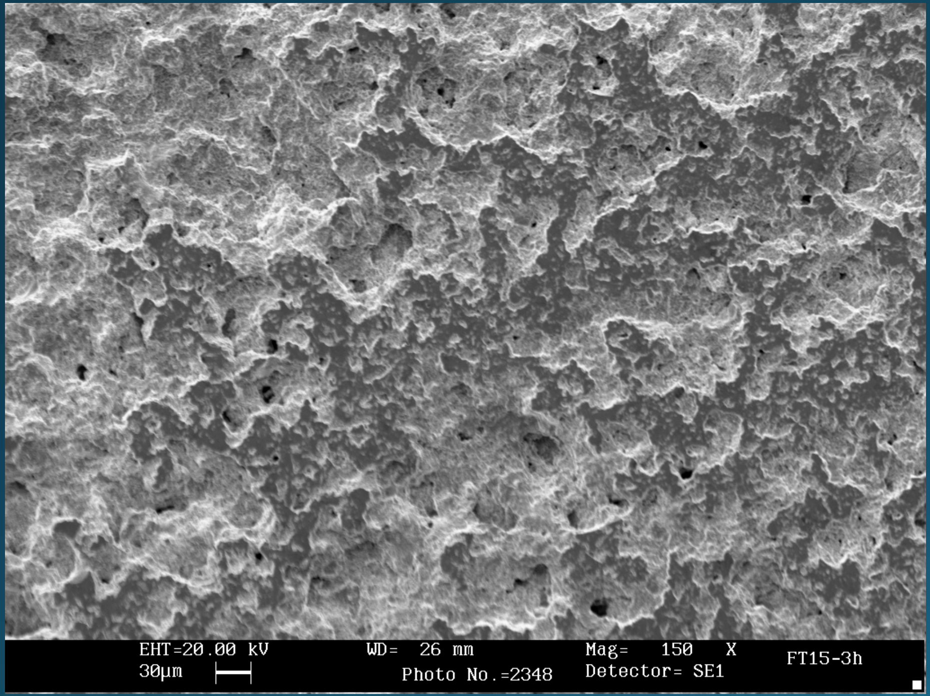


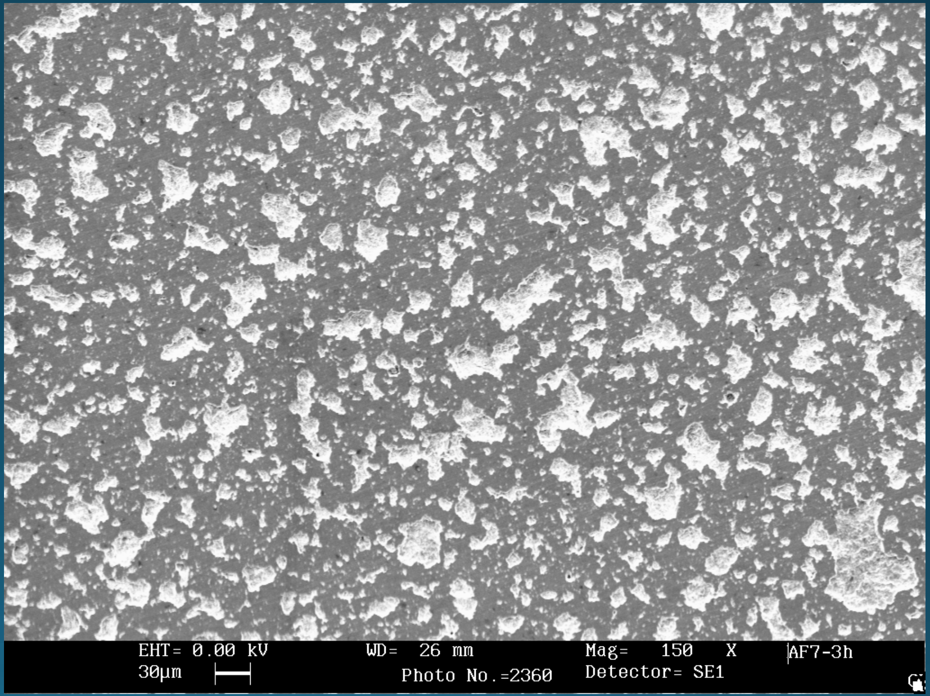


Surface SEM Micrographs of WC-10Co-4Cr Coatings after Cavitation Testing

Test duration: 3 hours

JP5000 HVOF | **AK06 HVAF**

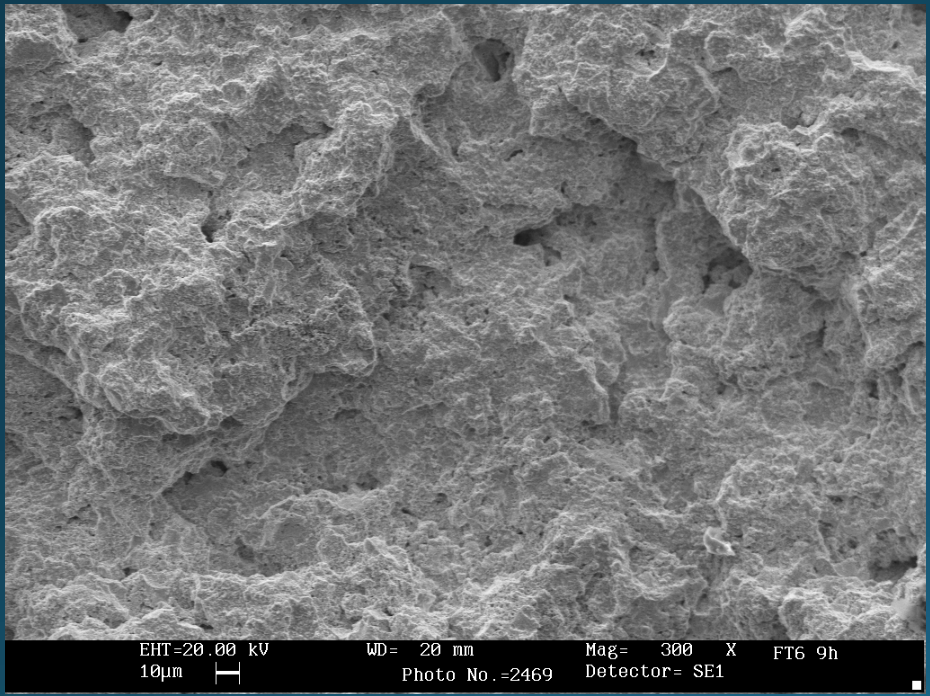




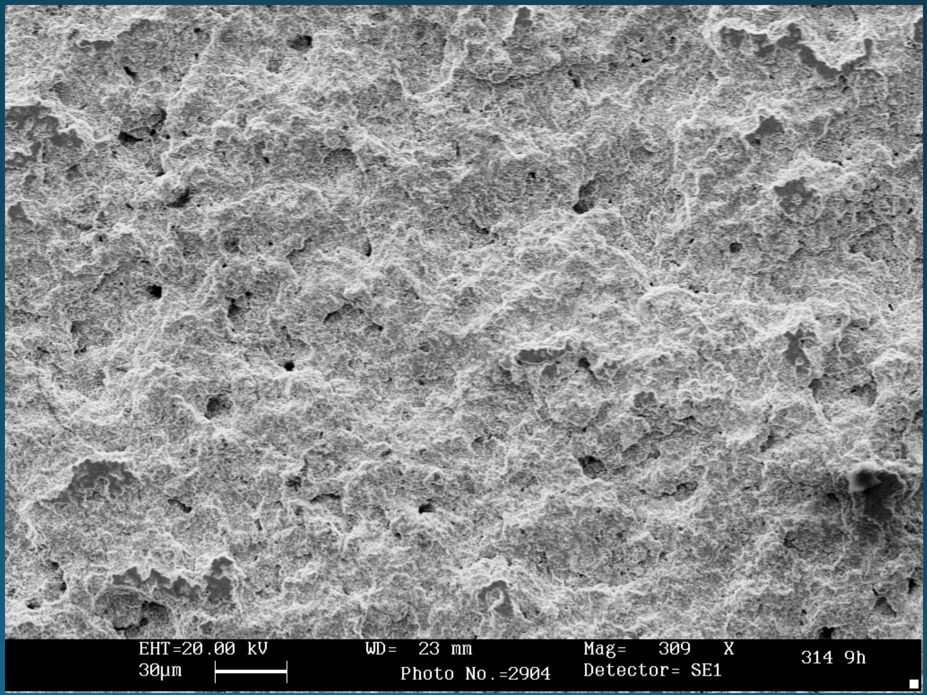
Surface SEM Micrographs of WC-10Co-4Cr Coatings after Cavitation Testing

Test duration: 9 hours

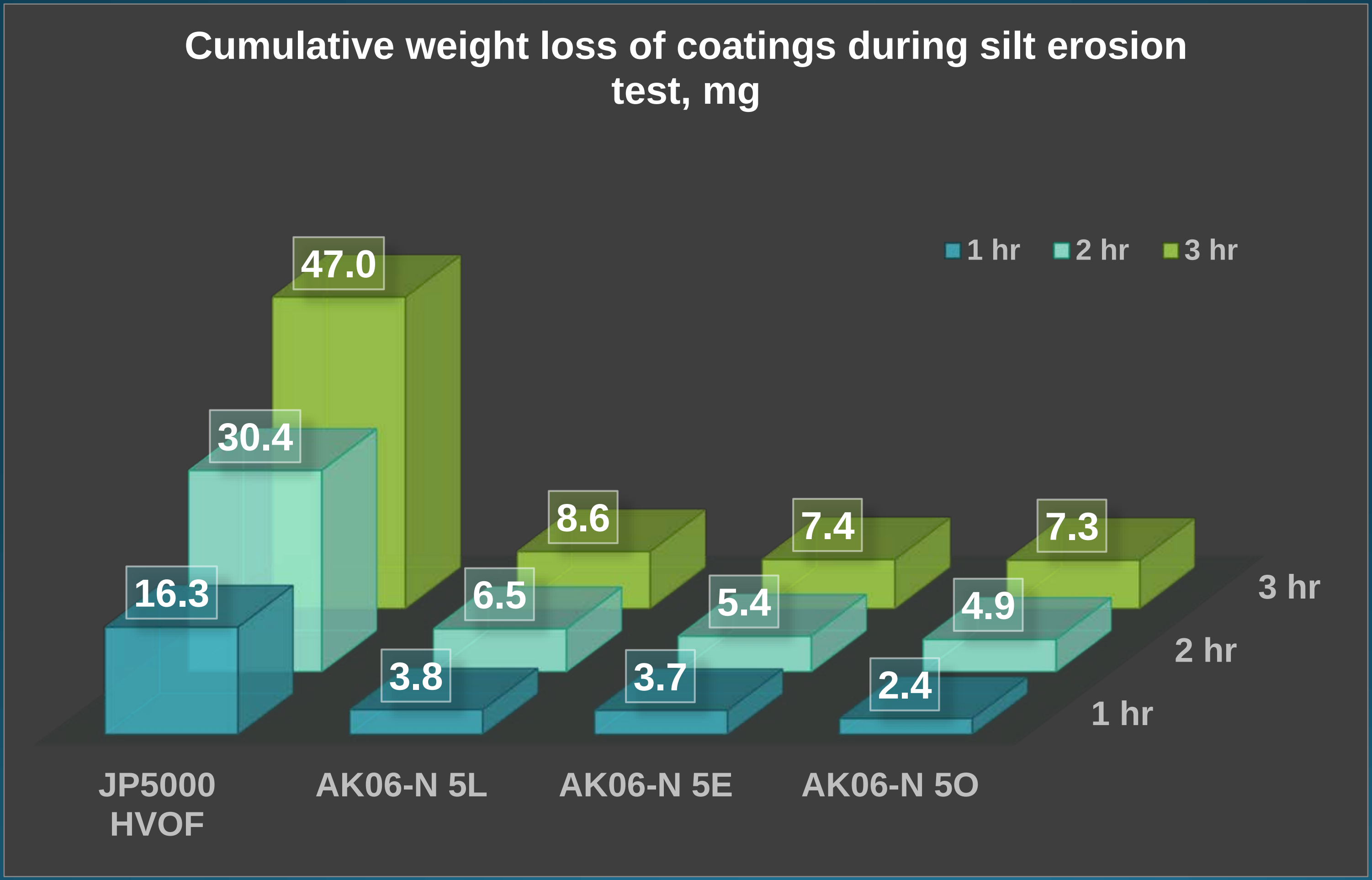
JP5000 HVOF



AK06 HVAF

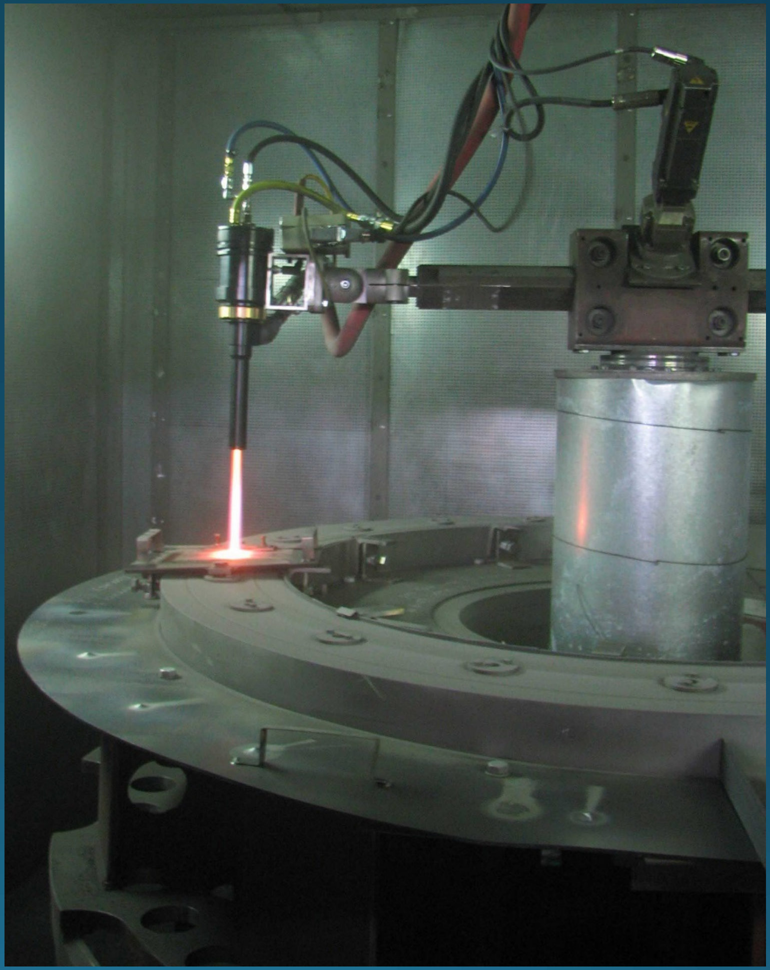


Resistance to Silt Erosion
WC-10Co-4Cr HVOF and HVAF coatings



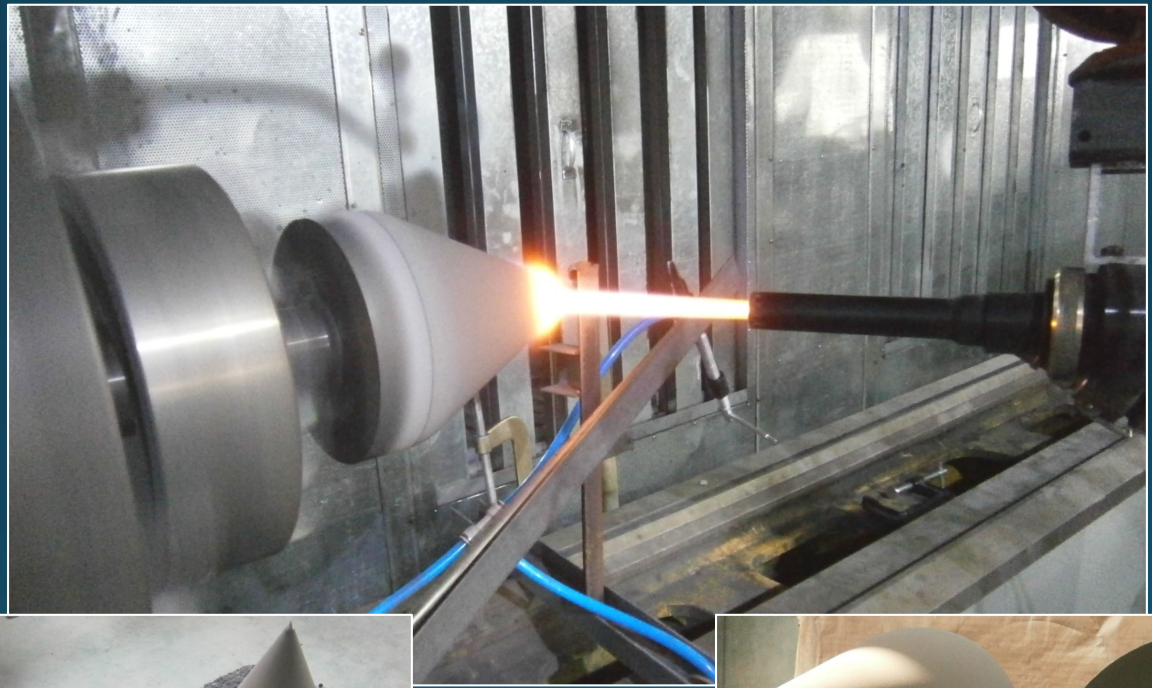
HVAF Applications

Hydro-Power:
Francis Runner and Head Cover
Application by Plackart Ltd., Russia

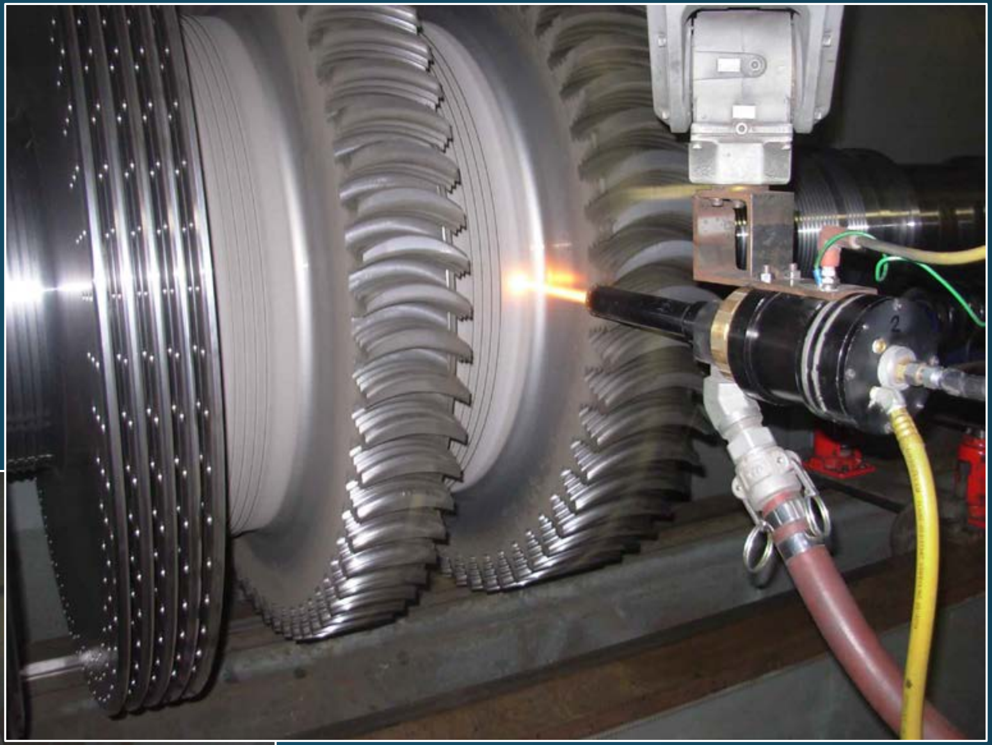


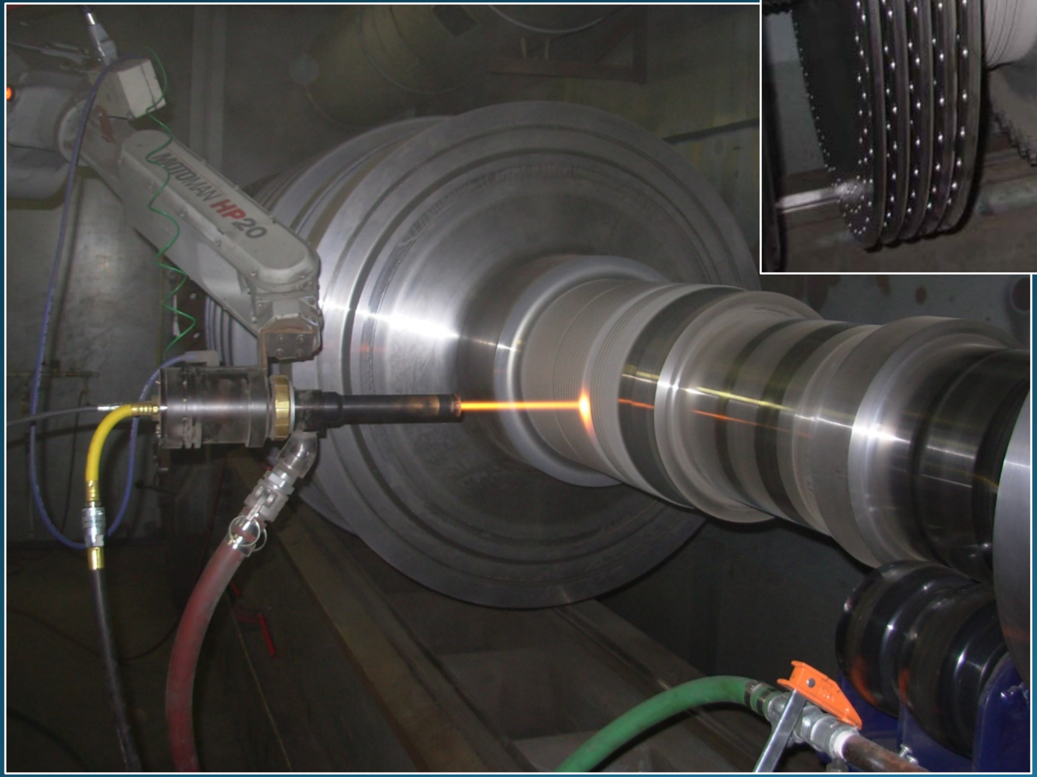
Hydro-Power:
Francis Runner, On-site spraying
Application by Plackart Ltd., Russia

Hydro-Power:
Metering Needle Valve and Seat
Application by RenCoat Ltd., China

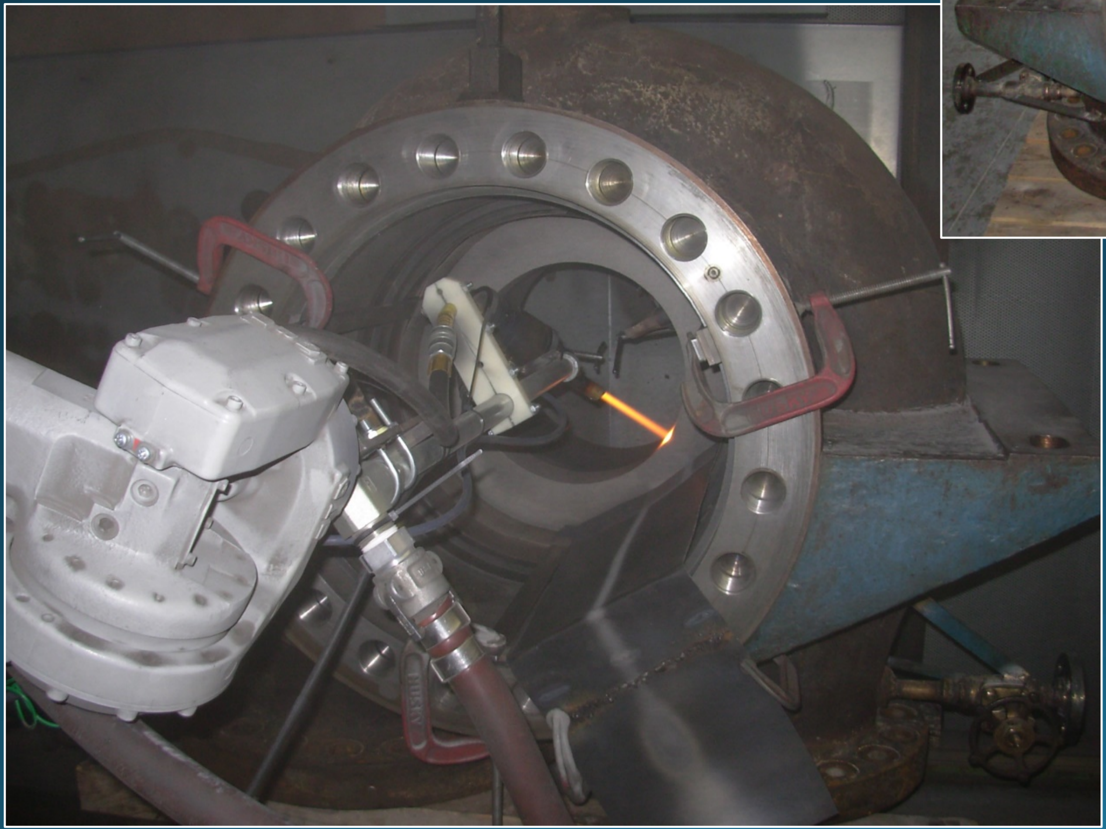


Geothermal Power: Rotor

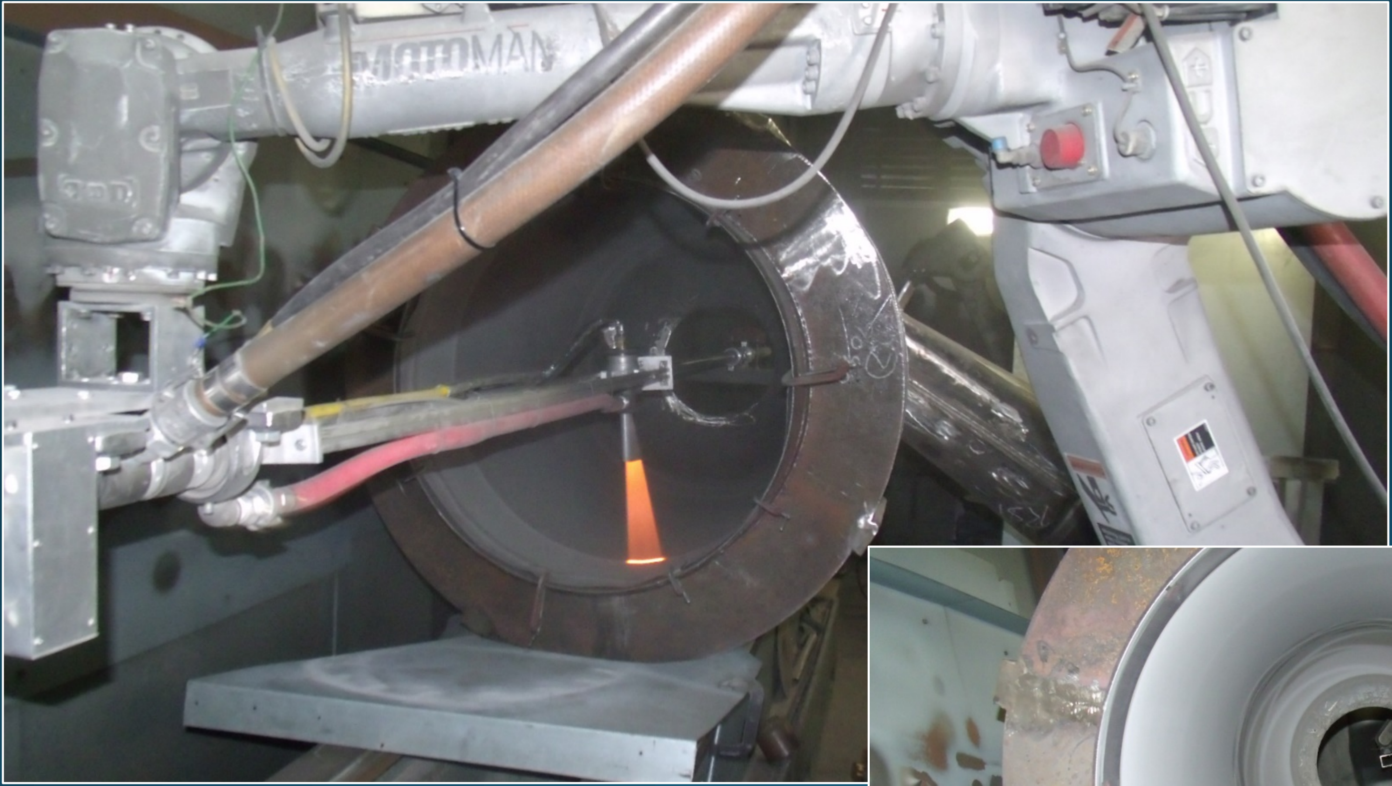




Oil Refinery:
Pump Casing ID spraying

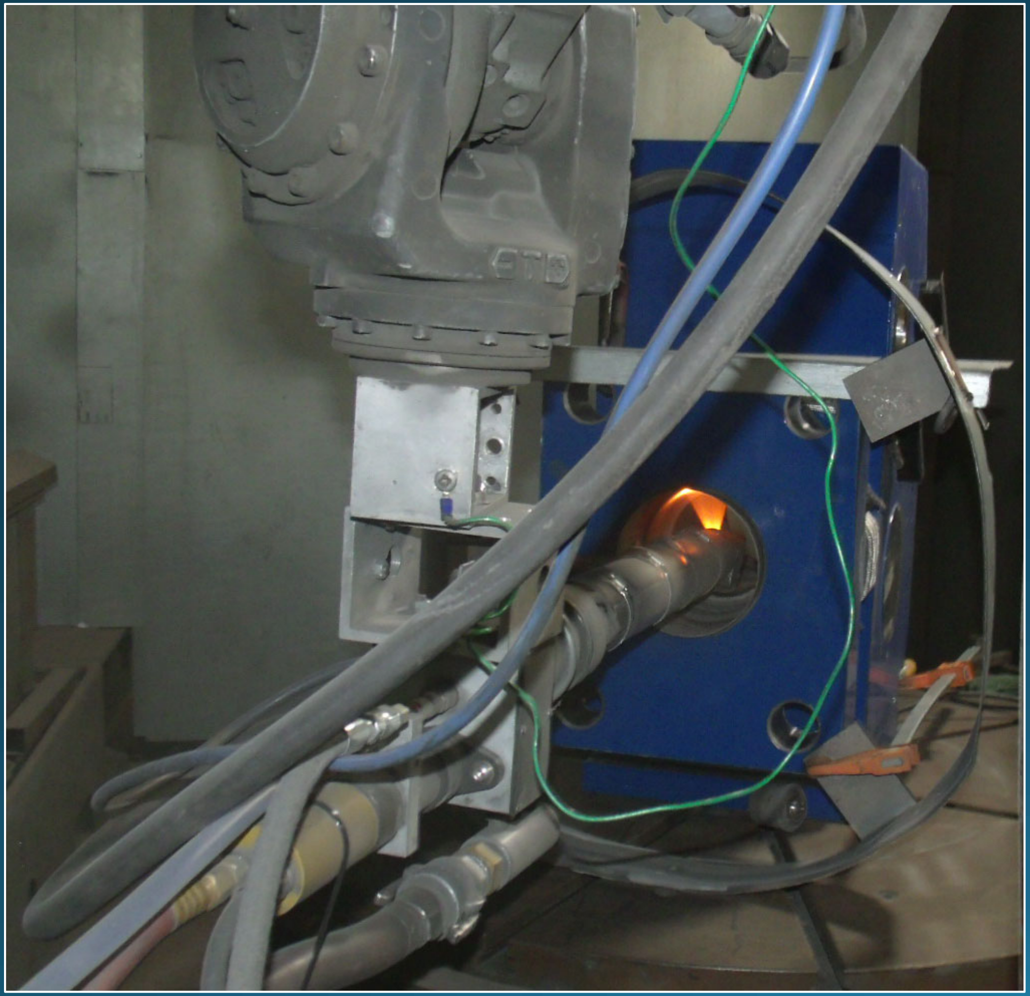


Oil Refinery:
Cyclone ID spraying with Rotating AK5 HVAF Gun



Oil Refinery:
Coke Transport Line Piping: Double-Elbow HVAF ID spraying

Oil Drilling:
Fluid-End Pump Casing, 5-inch ID
Application of coating with AK4-ID rotating gun



Conclusions

Structure and properties of several WC-10Co-4Cr HVAF coatings were compared to the best HVOF counterparts developed for protection of industrial equipment against cavitation and slit erosion.

The HVAF coatings were applied with the same parameters, but different spray particle velocity, varied from 895 to 1010 m/s.

Compared to the HVOF coating, the HVAF coatings had lower as-sprayed surface roughness.

Within the HVAF coatings, the surface roughness was decreasing with the increase of spray particle velocity.

The HVAF coatings revealed denser and more uniform structure and reduced level of WC decomposition during spraying.

Conclusions

All HVAF coatings were substantially harder than the HVOF counterparts and had 2-3 times lower deviation of hardness measurements.

With the increase of spray particle velocity the HVAF coatings hardness increased from 1308 to 1473 HV_{300}.

In spite of high hardness, the HVAF coatings revealed 1.4-1.8 times higher fracture toughness coefficient K1C compared to HVOF coatings.

The HVAF coatings, applied with intermediate spray particle velocity, showed the highest fracture toughness.

Young’s modulus of HVAF coatings was measured 1.5-fold higher than for HVOF coating.

Within the tested HVAF coatings the difference in modulus measurements was negligible.

Conclusions

During testing the HVAF coatings demonstrated 3.5 to 14 times better resistance to cavitation erosion compared to HVOF counterparts.

Within the HVAF coatings, the cavitation erosion improved with increase of spray particle velocity.

In silt erosion testing, the HVAF coatings performed 5.5-6.5 times better than HVOF coatings.

Within the HVAF coatings, the resistance to silt erosion was only slightly improved with the increase of spray particle velocity.

Conclusions

The study demonstrated significant advantages of the WC-10Co-4Cr HVAF coatings over the best HVOF counterparts, apparently important for performance of the coatings in protection of industrial equipment against erosion, silt erosion and cavitation.

Several examples of such applications for protection of hydro-power, geothermal and oil & gas equipment components against erosion and cavitation were presented.