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

Andrew A. Verstak
Kermetico Inc. , Benicia, CA (USA)

R.K. Kumar
Materials Technology Dpt., Central Power Research Institute, Bangalore (India)
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

<table>
<thead>
<tr>
<th></th>
<th>JP5000 HVOF</th>
<th></th>
<th>AK06 HVAF</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Barrel Length, inch</strong></td>
<td>6</td>
<td><strong>Barrel length, inch</strong></td>
<td>11</td>
</tr>
<tr>
<td><strong>Chamber</strong></td>
<td></td>
<td><strong>Combustion pressure, PSIG</strong></td>
<td>108</td>
</tr>
<tr>
<td><strong>Air, PSIG</strong></td>
<td>90.3</td>
<td><strong>Carrier N2 @140 PSIG, SLPM</strong></td>
<td>21</td>
</tr>
<tr>
<td><strong>Propane, PSIG</strong></td>
<td>83.8</td>
<td><strong>H2 Injections @ 140 PSIG, SLPM</strong></td>
<td>20</td>
</tr>
<tr>
<td><strong>Combustion pressure, PSIG</strong></td>
<td>108</td>
<td><strong>Spray rate, g/min</strong></td>
<td>133</td>
</tr>
<tr>
<td><strong>Stand-off distance, inch</strong></td>
<td>15</td>
<td><strong>Deposition per pass, micron</strong></td>
<td>28</td>
</tr>
<tr>
<td><strong>Powder feed rate, g/min</strong></td>
<td>90</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Deposition per pass, micron</strong></td>
<td>15</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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

$$K_{1C} = 0.016 \times (H_v \times d) \times (E/H_v)^{2/5} \times a^{-0.5}$$
Determination of Young’s Modulus by micro-indentation technique

\[ \frac{1}{E_r} = \frac{\left(1-\nu^2\right)}{E} + \frac{\left(1-\nu_i^2\right)}{E_i} \]

\[ \sigma_y \approx H/3 \]

\[ H = \frac{P}{A} \]

\[ E_r = \sqrt{\frac{\pi}{2}} \frac{S}{\sqrt{A}} \]

\[ A = f(h_c) \]

\[ h_c = h - 0.75P/S \]

**Nomenclature:**

- \( E \): Young’s modulus
- \( H \): hardness
- \( \sigma_y \): Yield stress
- \( E_r \): reduced modulus
- \( \nu \): Poisson’s ratio
- \( i \): (as subscript) indenter
- \( S \): contact stiffness
- \( A \): projected contact area
- \( h_c \): contact depth
- \( h \): displacement
- \( P \): applied force (load)

\[ S = \frac{dP}{dh}_{h_{\text{max}}} \]

\[ E_r = \sqrt{\frac{\pi}{2}} \frac{S}{\sqrt{A}} \]

\[ \frac{1}{E_r} = \frac{\left(1-\nu^2\right)}{E} + \frac{\left(1-\nu_i^2\right)}{E_i} \]
Determination of Young’s Modulus by micro-indentation technique

Stiffness: $S = \frac{dP}{dh}\bigg|_{h_{\text{max}}}$

Reduced modulus:

\[
E_r = \frac{\sqrt{\pi}}{2} \frac{S}{\sqrt{A}}
\]

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

<table>
<thead>
<tr>
<th></th>
<th>JP5000 HVOF</th>
<th>AK06 HVAF</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Nozzle 5L</td>
<td>Nozzle 5E</td>
</tr>
<tr>
<td>Oxidizer flow, SLPM</td>
<td>O2: 873.1</td>
<td>Air: 2,104 (O2: 421.0)</td>
</tr>
<tr>
<td>Fuel, g/sec</td>
<td>5.01</td>
<td>2.65</td>
</tr>
<tr>
<td>O$_2$/Fuel Ratio vs. Stoichiometric</td>
<td>1.16 (Oxidizing)</td>
<td>1.03 (~Neutral)</td>
</tr>
<tr>
<td>Carrier Nitrogen, SLPM</td>
<td>10.85</td>
<td>21</td>
</tr>
<tr>
<td>Combustion pressure, Bar</td>
<td>7.56</td>
<td>5.25</td>
</tr>
<tr>
<td>Powder feed rate, g/sec</td>
<td>1.50</td>
<td>2.22</td>
</tr>
<tr>
<td>Particle average size, micron</td>
<td>27</td>
<td>18</td>
</tr>
<tr>
<td>Particle velocity, m/s</td>
<td>740</td>
<td>895 +/-2</td>
</tr>
<tr>
<td>Particle temperature, °C</td>
<td>1790-1840</td>
<td>1470 +/-10</td>
</tr>
<tr>
<td>Particle kinetic energy, µJ</td>
<td>29.4</td>
<td>12.7</td>
</tr>
<tr>
<td>Energy density, GJ/m$^3$ =GPa</td>
<td>3.8</td>
<td>5.6</td>
</tr>
</tbody>
</table>
Surface Roughness of As-Sprayed Coatings

As-sprayed $R_a$, micrometers

- JP5000 HVOF: 4.48
- AK06-N 5L: 3.41
- AK06-N 5E: 3.12
- AK06-N 5O: 2.28
Optical Metallography:
JP5000 HVOF

P<0.8%
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

AK06 HVAF – 50
1 – WC
3 – Co₃W₃C
4 – Co

AK06 HVAF – 5L
1 – WC
3 – Co₃W₃C
4 – Co

AK06 HVAF – E
1 – WC
3 – Co₃W₃C
4 – Co
Mechanical Properties

Vickers Hardness of WC-10Co-4Cr coatings

- AK06-N 5O: 1473 (54)
- AK06-N 5E: 1439 (58)
- AK06-N 5L: 1308 (70)
- JP5000 HVOF: 1180 (140)

Hardness, HV300  Standard Deviation, HV300
Mechanical Properties

Fracture Toughness $K_{1C}$ of coatings, MPa$\cdot$m$^{1/2}$

- **AK06-N 5O**: 5.60, 0.15
- **AK06-N 5E**: 6.86, 0.80
- **AK06-N 5L**: 6.33, 0.50
- **JP5000 HVOF**: 3.86, 0.70

K1C  K1C Standard Deviation
Mechanical Properties

Young's Modulus E of WC-10Co-4Cr coatings

- **AK06-N 5O**: 20 GPa, 450 GPa
- **AK06-N 5E**: 20 GPa, 452 GPa
- **AK06-N 5L**: 21 GPa, 411 GPa
- **JP5000 HVOF**: 21 GPa, 290 GPa
Cavitation Resistance of WC-10Co-4Cr HVOF and HVAF coatings

\[ \frac{d}{d\text{time}} \frac{d\text{weight loss}}{dt} = \frac{d\text{weight loss}}{dt} \]

(\( \frac{dw}{dt} \)) AF1 (5O) = 0.23 mg/h
(\( \frac{dw}{dt} \)) AF3 (5E) = 0.71 mg/h
(\( \frac{dw}{dt} \)) AF2 (5L) = 0.96 mg/h
(\( \frac{dw}{dt} \)) HVOF = > 3.26 mg/h
(\( \frac{dw}{dt} \)) 16Cr-5Ni steel = 2.0 - 2.5 mg/h
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

Cumulative weight loss of coatings during silt erosion test, mg

- JP5000 HVOF: 16.3, 30.4, 47.0
- AK06-N 5L: 3.8, 6.5, 8.6
- AK06-N 5E: 3.7, 5.4, 7.4
- AK06-N 5O: 2.4, 4.9, 7.3
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.