The Effect of Fracture Toughness on the Deposition Efficiency of Ceramic Particles in Cold Spray

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Dr. Gary Fisher
Dr. André G. McDonald

moving life forward
Introduction

Metal Matrix Composites (MMCs)

- High strength
- Low density
- High wear resistance
Introduction

Current Production of MMCs

• Hot pressing or sintering
• Extrusion
• Pressure infiltration
• Reaction processing
• Thermal Spray
Introduction

Cold Spraying

• Benefits of including ceramics in cold spray
  – Higher adhesion strengths \(\rightarrow\) Lee, et al. (2005)
  – Higher cohesion strengths \(\rightarrow\) Spencer, et al. (2012)
  – Higher overall deposition efficiency \(\rightarrow\) Shkodkin, et al. (2006)

• Particle size vs deposition efficiency \(\rightarrow\) Sova, et al. (2009)
  – Small particles promote particle adhesion
  – Larger particles erode the surface

• Minimum velocity required to deposit ceramics \(\rightarrow\) Sova, et al. (2011)
Objectives

- Evaluate the cold spray deposition
  - $B_4C$-Ni
  - TiC-Ni
  - WC-Ni

- Characterize the microstructure

- Deposition efficiency of the carbide
  - Velocity
  - Momentum
  - Fracture toughness
Experimental Methods
Powder Morphology

*Boron Carbide*

Particle Mean Diameter:

\[ 39 \pm 10 \, \mu m \, (n = 42) \]

*Titanium Carbide*

Particle Mean Diameter:

\[ 23 \pm 7 \, \mu m \, (n = 28) \]
Powder Morphology

Tungsten Carbide

Particle Mean Diameter: 
36 ± 11 µm ($n = 56$)

Nickel

Particle Diameter: 
–45 +5 µm
Powder Parameters

Powder Parameters and Properties

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<tr>
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<th>Hardness (kg/mm(^2))</th>
<th>Fracture Toughness (MPa m(^{0.5}))***</th>
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Cold Spray Deposition

*Powder blends*
- 50 wt.%, 75 wt.%, and 92 wt.% carbide
  - With the remaining weight being Ni

*Cold Spray Parameters*
- Pressure, 634 kPa
- Temperature, 550 °C
- Stand off distance, 5 mm
- Traverse speed, 5 mm/s (2.5 mm/s for 92 wt.% B4C)
- Working fluid, air
Coating Characterization

Scanning Electron Microscopy and Image Analysis

- Porosity
- Carbide content
- Carbide particle size

B₄C-Ni coating from 50 wt% B₄C + 50 wt.% Ni blend

TiC-Ni coating from 50 wt% TiC + 50 wt.% Ni blend

WC-Ni coating from 50 wt% WC + 50 wt.% Ni blend
Model developed by Dykhuizen et al. (1998) using

- Principles of dynamics and thermodynamics
  - Compressible fluid flow through
  - Converging-diverging nozzle

**Assumptions**
- 1D, isentropic, and ideal
- Constant specific heat
- Carrier gas source was a large chamber with no velocity
Mathematical Model

Calculate Mach number along nozzle

Determine gas pressure, temperature, velocity, and density

Determine particle drag coefficient and velocity

Determine particle momentum
Results and Analysis
Particle Velocity

- WC particles are slower
  - High density

- $\text{B}_4\text{C}$ and TiC are faster
  - Lower density
  - Smaller size (TiC)
Particle Momenta

- Assumed coefficient of restitution is zero
- High density WC particles have the greatest momentum
- Small TiC particles have low momentum

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<th>Density (g/cm³)</th>
<th>Mean Diameter (µm)</th>
<th>Mean Velocity (m/s)</th>
<th>Mean Momentum (nNs)</th>
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<td>B₄C</td>
<td>2.52</td>
<td>39 ± 10 (n = 42)</td>
<td>485</td>
<td>38</td>
</tr>
<tr>
<td>TiC</td>
<td>4.93</td>
<td>23 ± 7 (n = 28)</td>
<td>493</td>
<td>15</td>
</tr>
<tr>
<td>WC</td>
<td>15.8</td>
<td>36 ± 11 (n = 56)</td>
<td>246</td>
<td>95</td>
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Microstructure
B₄C-Ni

B₄C-Ni coating from 75 wt% B₄C + 25 wt.% Ni blend
Microstructure
TiC-Ni

TiC-Ni coating from 75 wt% TiC + 25 wt.% Ni blend
Microstructure
TiC-Ni

TiC-Ni coating from 92 wt% TiC + 8 wt.% Ni blend
Microstructure
WC-Ni

WC-Ni coating from 75 wt% WC + 25 wt.% Ni blend
Microstructure Porosity

- No B$_4$C results
  - Low contrast

- Particle pull-out
  - Increases porosity

- High momentum particles
  - Matrix densification

![Graph showing relationship between Carbide Content in Coating (vol. %) and Porosity (vol. %)]
Microstructure Deposition Efficiency

- Low deposition efficiency
  - Carbide fracture

![Graph showing Carbide Content in Coating vs. Carbide Content in Powder](image-url)
Microstructure
Carbide Particle Size

• Same distribution for all coatings
• The distribution is shifted towards 1 µm
• 1 µm resolution limit

WC particle size distribution within the WC-Ni coating fabricated from 92wt.% WC + 8 wt.% Ni in the powder blend
## Microstructure

### Carbide Particle Size

<table>
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<th>Carbide</th>
<th>Particle Mean Diameter (µm)</th>
<th>Weighted average particle diameter in the fabricated coatings (µm)</th>
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<td></td>
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<td>50 wt.% carbide + 50 wt.% Ni</td>
</tr>
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<td>B₄C</td>
<td>39 ± 10 (n = 42)</td>
<td>3.3 ± 2.9 (n = 4516)</td>
</tr>
<tr>
<td>TiC</td>
<td>23 ± 7 (n = 28)</td>
<td>2.3 ± 1.9 (n = 2393)</td>
</tr>
<tr>
<td>WC</td>
<td>36 ± 11 (n = 56)</td>
<td>2.7 ± 2.3 (n = 1432)</td>
</tr>
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</table>
Microstructure Deposition Efficiency

- Low deposition efficiency
  - Carbide fracture

- Deposition efficiency
  - WC > TiC > B₄C

- Fracture Toughness
  - WC > TiC > B₄C
Effect of Fracture Toughness

• High impact momentum
  – High impact force and energy

• High fracture toughness
  – More substrate side deformation

• Substrate side deformation

• Increasing particle adhesion
  – Improves deposition efficiency
Conclusion

• Increasing carbide content in the powder blend
  – Higher the carbide content in the coating

• High momentum of the carbide particles
  – High impact force of the carbide particles
  – Reduces porosity
  – Fractures carbide particles

• Fracture toughness of the carbide particles
  – Deposition efficiency of the carbide particles
Thank You

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