Overlay Technologies for Wear and Corrosion Applications

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Presentation Outline

• Introduction to ARC
• Wear and Corrosion Applications
• Engineering Solutions to Wear/Corrosion
• Overlay Technologies
• Thermal and Plasma Spray Processes
• Welded Overlay/Cladding Processes
• Case Studies
  – Flue Gas Desulphurization Unit - Cladding & Overlay Welding
  – Development of an Impact Test Rig for Overlay Materials
• Conclusion
• Acknowledgments and References
The Alberta Research Council

- **Canada’s 1st provincial research organization (1921)**
  - 500 employees with $80M annual operating budget
  - Locations at Edmonton, Calgary, Devon & Vegreville

- **Advanced Materials Business Unit**
  - 26 Staff (including 13 PhD’s, 2MSc’s)
  - R&D and Technical Services for:
    - Oilfield & Oil Sands
    - Pipeline, Manufacturing, & Infrastructure
    - Transportation (automotive & aerospace)
    - Alternative Energy
  - Areas of Expertise:
    - Mechanical Testing
    - Wear & Corrosion
    - Welding & Failure Investigations
    - Non-Metallics
    - Computer Modelling (FEA, CFD)
Overview of Wear & Corrosion
Mechanisms and Applications

Overlay Technologies for Wear and Corrosion Applications
Introduction to Tribology & Wear

- **Definition of Tribology**:
  - “The science and technology of interacting surfaces in relative motion” [Ref 1]
  - Includes consideration of friction, wear, and lubrication

- **Industrial Wear**
  - No uniform designation system for wear mechanisms
  - Wear mechanisms are very application specific
  - A “hard surface” does not always equal optimum wear resistance - other factors must be considered
Overview of Wear Mechanisms

WEAR

- Abrasion (Two or Three-body)
  - Low stress
  - High stress
  - Slurry
  - Gouging
  - Polishing
  - Sliding
  
- Erosion
  - Solid impingement
  - Fluid impingement
  - Cavitation
  - Slurry Erosion
  - High Temperature

- Adhesion
  - Fretting
  - Adhesive
  - Seizure
  - Galling
  - Oxidation wear

- Surface Fatigue
  - Pitting
  - Spalling
  - Impact
  - Brinelling
  - Contact
  - Delamination
  - Percussive

- Corrosion – Assisted
  - Uniform
  - Galvanic
  - Pitting
  - Crevice
  - Environmental\(^{(a)}\)
    - Oxidation
    - High-temp

**Mechanism**
- Require interaction between sharp or hard surfaces on softer surfaces
- Require fluid or slurry action
- Interaction between mating surfaces
- Require repetitive, cyclic stresses
- Synergistic effect that accelerates wear

NOTE (a): Environmental corrosion includes stress-corrosion cracking (SCC), hydrogen embrittlement, microbial assisted corrosion, etc.

References: [1,2,3,4,5,6,7]
Introduction to Corrosion

• **NACE Definition:**
  - “The deterioration of a material, usually a metal, that results from a reaction with its environment”

• **Occurrence of Corrosion is Application Specific**
  - Hydrotransport of Oil Sands – erosion-corrosion
  - Upstream & Upgrading – CO₂/H₂S corrosion
  - Refineries – Stress Corrosion Cracking

• **Factors Affecting Corrosion**
  - **Materials** – type, microstructure, flaws
  - **Stress** – magnitude, static/dynamic
  - **Geometry** – stress concentrations, design
  - **Temperature** – surface temperature
  - **Time** – service or material properties changes
  - **Environment** - corrodent concentration, fluid velocity, wear, phases, deposits
Introduction to Corrosion

• No internationally accepted *Corrosion Mechanism* designation system
  – “Original 8”: Uniform, galvanic, crevice, pitting, intergranular, selective leaching, erosion-corrosion, and stress corrosion
  – Four Intrinsic Corrosion Modes:

  - Uniform Corrosion
  - Pitting (localized) Corrosion
  - Intergranular Corrosion
  - Stress Corrosion Cracking

Ref [8,9]

**Corrosion Mechanisms**

Complex corrosion mechanisms, such as stress corrosion cracking, require a combination of factors.

### ENVIRONMENTALLY INFLUENCED
- Stress Corrosion Cracking
- Liquid Metals
- Molten Salts
- Aqueous, Non-Aqueous, Gases
- Pitting/Crevvice
- Corrosion Under Insulation
- Corrosion Under Deposits
- Filiform
- Condensate Corrosion
- Microbial Assisted Corrosion
- Hydrogen Damage (Blisters & Cracks)

### METALLURGICAL
- Galvanic
- Intergranular
- Sensitization/Knife-Line
- Dealloying/Selective Leaching
- Exfoliation

### MECHANICALLY ASSISTED
- Stress-Corrosion Cracking
- Corrosion Fatigue
- Corrosive Wear
- Erosion-Corrosion
- Fretting Corrosion
- Impingement/Cavitation

**References:** [6,8,9,10]
## Solutions to Wear & Corrosion

### Corrosion
- Modify service conditions
- Materials selection & upgrades
  - Corrosion resistant alloys (CRA)
- Corrosion inhibitors
- Cathodic protection
- Anodic protection
- Design, inspection & maintenance

### Wear
- Modify service conditions
- Materials selection & upgrades
  - Wear resistant materials (WRM)
- Design & operate for wear
  - Identify actual mechanism(s)
  - Appropriate component design
  - Periodic replacement

### Surfacing Techniques
- Surface treatment
- Overlay techniques
- Cladding techniques

![PTA overlay welding](PTA_overlay_welding)
Surfacing and Overlay Techniques

- **Two broad categories:** *surface treatments* & *surface coatings*
  - **Surface treatments**
    - Inherent substrate composition is used to obtain desired properties
    - Diffusion of elements into surface, e.g. carbon or nitrogen for hardening
  - **Surface coatings**
    - Deposit & form a new surface onto a substrate backing
    - Coating properties dictate component’s function and lifespan

<table>
<thead>
<tr>
<th>Surface Processes and Treatments</th>
<th>References: [3,4,11]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Surface Treatments</strong></td>
<td><strong>Surface Coatings</strong></td>
</tr>
<tr>
<td>Nitriding</td>
<td>Chemical Treatments</td>
</tr>
<tr>
<td>Carburising</td>
<td>Plastic Coating</td>
</tr>
<tr>
<td>Nitrocarburizing</td>
<td>Carbonitriding</td>
</tr>
<tr>
<td>Metallizing</td>
<td>Boronizing</td>
</tr>
<tr>
<td>Thermal Hardening</td>
<td>(Induction, Flame, Laser)</td>
</tr>
<tr>
<td>Thermal/Plasma Spraying</td>
<td></td>
</tr>
</tbody>
</table>
Overlay Technologies for Wear and Corrosion Applications

Thermal Spray Techniques
Technologies, Applications, and Comparisons
Thermal Spray Techniques

- **Spray Surfacing Fundamentals**
  - Surfacing materials are melted, propelled at high velocity and mechanically bond to substrate
  - Low surface temperatures < 200ºC
  - Substrates: metallic & non-metallic

- **Typical Flaws:** voids, oxidized or un-melted particles
- **Mechanical Bond:** can limit applications
- **Large variety of applicable materials**

References: [4,5,12,13]
### Thermal Spray Techniques

#### Gas Combustion Processes

<table>
<thead>
<tr>
<th>Process</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxy-fuel wire (OFW)</td>
<td>Oxy-fuel rod</td>
</tr>
<tr>
<td>Oxy-fuel powder (OFP)</td>
<td>Oxy-fuel jet powder</td>
</tr>
<tr>
<td>Detonation gun (D-Gun)</td>
<td>High-velocity oxyfuel (HVOF)</td>
</tr>
</tbody>
</table>

#### Arc/Plasma Processes

<table>
<thead>
<tr>
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<tr>
<td>Plasma arc powder (PA)</td>
<td>Electric arc wire (EAW)</td>
</tr>
<tr>
<td>Atmospheric plasma spraying</td>
<td>Inert Plasma Spraying (IPS)</td>
</tr>
<tr>
<td>(APS)</td>
<td></td>
</tr>
<tr>
<td>Vacuum Plasma Spraying</td>
<td></td>
</tr>
<tr>
<td>(VPS)</td>
<td></td>
</tr>
<tr>
<td>Low Pressure Plasma Spraying</td>
<td></td>
</tr>
<tr>
<td>(LPPS)</td>
<td></td>
</tr>
<tr>
<td>High-Power Plasma Spraying</td>
<td></td>
</tr>
<tr>
<td>(HPPS)</td>
<td></td>
</tr>
<tr>
<td>Cold Spraying</td>
<td></td>
</tr>
</tbody>
</table>

### Process selection considerations

- Surface quality, productivity, costs
- Often subtle differences, e.g. plasma spray variants
- Selection guidelines: Industrial handbooks, standard practices, & texts

### Techniques common for pressure equipment:

- OFW/OFP, electric arc, plasma spray and HVOF

References: [3,4,5,12,13,14]
Oxy-Fuel Spray Processes

**Oxy-Fuel Process Overview**
- Fuel mixtures: acetylene, MAPP, propane, natural gas & hydrogen
- Air stream – atomizes consumables
- Combustion energy & resulting gas pressure dictates particle velocity
- High heat input process – consumables & substrate

**Oxy-fuel wire spray**
- Also called wire flame spraying & combustion wire process
- Low capital cost
- Large range of consumables

**Oxy-fuel powder spray**
- Process similar to wire spraying
- Powder feed allows for wider range of consumable, i.e. carbides & complex mixtures

References: [4,12,13,14]
High Velocity Oxy-Fuel (HVOF)

- **HVOF Process Overview**
  - **State-of-the-art** in fuel-gas processes
  - Extremely high kinetic energy
    - Supersonic nozzle flame velocity (2100 m/s)
    - Particle velocities (up to 650 m/s)

  References: [4,12,13,14,15]

- **Spray materials must suit application & component**
  - Corrosion applications: exchanger tubesheets, amine units, boilers
  - Wear application: valve seats, pipe fittings

HVOF spraying of an Exchanger Tubesheet

WC-Co-Cr coating produced via HVOF

HVOF Shock Diamonds

www.materials.drexel.edu
Electric Arc Wire Spraying

**EAW Process Overview**
- Electric arc temp > 5500ºC (10,000ºF)
- Air stream atomizes & sprays melted wire

- Wire speeds control deposition rates
- Environment: inert gases or vacuum
- Energy efficient process
  - Energy used directly to melt wires
  - Low substrate temperatures

**Twin Wire - Development of New Surfacing Materials**

- Metal Matrix Wire (e.g., Fe, Ni, Co)
- Composite Wire (e.g., carbides, borides)
- MMC Coating

References: [4,5,12,13]
Plasma Arc (PA) Spraying

• **PA Process Overview**
  – Constricted arc process: plasma temps of 10,000-20,000°C
  – Carrier gas mixtures of Ar, He, N₂ and/or H₂ transports powder
  – High-energy plasma jet propels consumables
  – Similar to PTA welding (non-transferred mode)

• **Process Variants:**
  – Atmospheric Plasma Spraying (APS)
  – Inert Plasma Spraying (IPS)
  – Vacuum Plasma Spraying (VPS)
  – Low Pressure Plasma Spraying (LPPS)
  – UPS, HPPS & ‘cold spraying’ under development

References: [4,5,12,13,15]
## Comparison of Spray Processes

### Typical Operating Parameters & Productivity:

<table>
<thead>
<tr>
<th>Process</th>
<th>Gas flow</th>
<th>Flame/plasma temp</th>
<th>Particle impact velocity</th>
<th>Relative adhesive strength</th>
<th>Adhesive Strength</th>
<th>Inter-particle cohesive strength</th>
<th>Oxide content</th>
<th>Porosity</th>
<th>Relative process cost</th>
<th>Max. spray rate</th>
<th>Power</th>
<th>Energy required to melt</th>
</tr>
</thead>
<tbody>
<tr>
<td>OFP</td>
<td>11 m³/h</td>
<td>2200 °C</td>
<td>30 m/s</td>
<td>3</td>
<td>8</td>
<td>Low</td>
<td>6</td>
<td>10-15</td>
<td>3</td>
<td>7 kg/h</td>
<td>25-75 kW</td>
<td>11-22</td>
</tr>
<tr>
<td>OFW</td>
<td>71 m³/h</td>
<td>2800 °C</td>
<td>180 m/s</td>
<td>4</td>
<td>10</td>
<td>Medium</td>
<td>4</td>
<td>10-15</td>
<td>3</td>
<td>9 kg/h</td>
<td>50-100 kW</td>
<td>11-22</td>
</tr>
<tr>
<td>EAW</td>
<td>71 m³/h</td>
<td>5500 °C</td>
<td>240 m/s</td>
<td>6</td>
<td>12</td>
<td>High</td>
<td>0.5-3</td>
<td>10</td>
<td>1</td>
<td>16 kg/h</td>
<td>4-6 kW</td>
<td>0.2-0.4</td>
</tr>
<tr>
<td>APS</td>
<td>4.2 m³/h</td>
<td>5500 °C</td>
<td>240 m/s</td>
<td>6</td>
<td>4 to &lt;70</td>
<td>High</td>
<td>0.5-1</td>
<td>1-10</td>
<td>5</td>
<td>5 kg/h</td>
<td>30-80 kW</td>
<td>13-22</td>
</tr>
<tr>
<td>VPS</td>
<td>8.4 m³/h</td>
<td>8300 °C</td>
<td>240-610 m/s</td>
<td>9</td>
<td>&lt;70</td>
<td>Very high</td>
<td>ppm level</td>
<td>&lt;0.5</td>
<td>10</td>
<td>10 kg/h</td>
<td>50-100 kW</td>
<td>11-22</td>
</tr>
<tr>
<td>HVOF</td>
<td>28-57 m³/h</td>
<td>3100 °C</td>
<td>610-1060 m/s</td>
<td>8</td>
<td>&gt;70</td>
<td>Very high</td>
<td>0.2</td>
<td>1-2</td>
<td>5</td>
<td>14 kg/h</td>
<td>100-270 kW</td>
<td>22-200</td>
</tr>
</tbody>
</table>

**NOTE:** (a.) 1 (low) to 10 (high)

**References:** [3,4,5,12,13,17,18,19]
## Comparison of Spray Processes

### Process contrasts & typical applications:

<table>
<thead>
<tr>
<th>Process</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Typical uses</th>
</tr>
</thead>
<tbody>
<tr>
<td>OFP</td>
<td>Lowest-cost; light, compact equipment; pressurized powder feed for high rates</td>
<td>Lower bond strengths; higher porosity; lower cohesive strength; slow deposition rate</td>
<td>Machinery maintenance; gas turbine engines;</td>
</tr>
<tr>
<td>OFW</td>
<td>Inexpensive equipment and setup; optimizable for metallic coatings</td>
<td>Lower bond strengths; higher porosity; high heat transfer to substrate; n/a for high alloy or ceramics</td>
<td>Corrosion protection for bridges/tanks; machinery repair; dimensional restoration</td>
</tr>
<tr>
<td>EAW</td>
<td>Highest spray speed-deposition; large spray pattern (50-300 mm); mobile; low cost</td>
<td>Poor adhesive strength; high porosity and oxide content; expensive and complex equipment</td>
<td>Heavy coating buildup; large surfaces; corrosion protection</td>
</tr>
<tr>
<td>APS</td>
<td>High quality deposit; minimized oxidation; low porosity; portable</td>
<td>Many process parameters must be optimized; highest equipment costs; complex, bulky equipment</td>
<td>Cermet/MMC for wear; ceramics for turbines</td>
</tr>
<tr>
<td>VPS</td>
<td>Highest quality deposit; improved bonding; low porosity; high efficiency</td>
<td>Special coating material storage required; highest costs; workpiece limited by chamber size</td>
<td>Turbine airfoils, blade tips, shroud segments; refractory materials</td>
</tr>
<tr>
<td>HVOF</td>
<td>Highest bond strength; low porosity/oxide; thick coatings; good machinability; automation; low distortion</td>
<td>Capital investments; rocket-like hazardous torch; extremely loud process</td>
<td>Carbides; oxides; composites; repair; corrosion &amp; wear protection</td>
</tr>
</tbody>
</table>

### Process Selection:
- Consideration of process technical limitations and costs
- References and consulting available

References: [3,4,5,12,13,17,18,19]
Overlay Technologies for Wear and Corrosion Applications

Weld Overlay & Cladding Techniques
Technologies, Applications, and Comparisons
Cladding and Overlay Welding

**Fundamentals:**
- Metallurgical bond between surface & substrate
- Controlled arc environment = fewer flaws
- Manual, semi-automatic, fully-automatic/robotic

**Cladding or Overlay Welding?**
- Cladding:
  - Coating material bonded to a substrate via mechanical force
  - Clad & base material are not melted during fusion
  - Common for highly corrosive applications, e.g. reactors, vessels
- Overlay:
  - Fusion of a coating to a substrate surface via a welding process
  - Applicable for essentially all corrosion and wear applications
  - Overlay “restoration” welds used during clad fabrication projects
Weld Overlay & Cladding Processes

• **Process selection considerations**
  – Productivity, costs and applications
  – Consumable forms, i.e. wire, strip, powder, sheet (plate)
  – Selection guidelines: Industrial handbooks, standard practices, & texts

• **Common techniques for pressure equipment**
  – Overlay welding via manual & wire-feed processes, PTA overlay welding
  – Hot roll & explosive bonding

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### Arc Welding Processes

<table>
<thead>
<tr>
<th>Process</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas Tungsten Arc Welding (GTAW)</td>
<td></td>
</tr>
<tr>
<td>Gas Metal Arc Welding (GMAW)</td>
<td></td>
</tr>
<tr>
<td>Submerged Arc Welding (SAW)</td>
<td></td>
</tr>
</tbody>
</table>

### Plasma Transferred Arc Welding (PTAW)

### Other Fusion Processes

<table>
<thead>
<tr>
<th>Process</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxy/fuel gas (OFW)</td>
<td></td>
</tr>
<tr>
<td>Electron Beam Welding (EBW)</td>
<td></td>
</tr>
<tr>
<td>Furnace Brazing (FB)</td>
<td></td>
</tr>
<tr>
<td>Spray and Fuse (SF)</td>
<td></td>
</tr>
</tbody>
</table>

### Laser Beam Welding (LBW)

### Electroslag welding (ESW)

### Explosive Welding (EW)

---

### Cladding Techniques

<table>
<thead>
<tr>
<th>Plate</th>
<th>Pipe</th>
<th>Fittings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot Roll Bonding</td>
<td>Seamless (extruded)</td>
<td>Hot Isostatic Pressing (HIP)</td>
</tr>
<tr>
<td>Cold Roll Bonding</td>
<td>Longitudinal seam</td>
<td>Manufactured from plate/pipe</td>
</tr>
<tr>
<td>Explosive Bonding</td>
<td>Explosive Bonding</td>
<td>Weld Overlay</td>
</tr>
<tr>
<td>Hot Pressing</td>
<td>Weld Overlay</td>
<td></td>
</tr>
</tbody>
</table>

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**References:** [3,4,5,12,14,20]
Overview of Cladding Techniques

- **Hot Roll Bonding Process**
  - Typically produced by the “sandwich” technique
  - 85-90% of clad plate produced via hot roll bonding
  - Significant savings over solid CRA products

- **Common CRA materials with steel backing:**
  - Stainless steel, e.g. 316SS, 317SS, or duplex
  - Nickel alloys, e.g. Inconel 625, 825 or C-276
  - Titanium & specialty alloys

References: [20,29]
Overview of Cladding Techniques

- **Explosive Bonding**
  - High energy, explosive impulse drives and bonds metal layers together
  - Surface oxides are expelled = metallurgical bond
  - Bond line has characteristic “wavy” shape

- **Construction Materials**
  - Stainless steels, coppers and nickel alloys
  - Preferred technique for refractory metals, such as titanium, tantalum & zirconium

References: [20,29]; www.dynamicmaterials.com

25 ft by 120 ft Autoclave Leaching Vessels - 3 inch steel lined with 6mm titanium

Explosive Bonding Process
Overlay Welding Processes

- **Common wire-feed process**
  - Gas Metal Arc Welding (GMAW)
  - Submerged Arc Welding (SAW)
  - Flux Cored Arc Welding (FCAW)
  - Gas Tungsten Arc Welding (GTAW)
    with hot or cold wire addition

- **Areas of Development**
  - Overlay consumables
    - Wear – carbides in wire form
    - Corrosion – higher metallurgy
  - Motion control & robotic systems
  - Advanced processes & inverter power sources

**Process considerations:**
- Balance deposition rate & dilution
- Reactivity of base material & coating
- GMAW systems for vessel repairs & restorations;
  SMAW common for minor manual repairs
PTA Welding & Overlays

**Process Fundamentals**
- Constricted Arc Process:
  - High Current Density
  - High Temperature Profile
  - High Energy Density
- Semi-automated for small & large components
- Capital investments required

{\-century
  - High Deposition Rate
  - Low Dilution
  - Low degree of carbide degradation

NiCrSiBFe-WC overlay deposited by PTA – Exhibiting shear crack formation from repeated impacts
PTA Weld Overlaying

**Areas of Development**
- **Consumables**
  - Powder allows for complex metallurgies
  - Developments for wear & corrosion service (e.g., oil sands)
- **Process Investigations**
  - Effective heat input: current, voltage, motion, powder feed-rate
  - Gas mixtures
  - Torch designs
  - Automation and control systems

PTA welding of a MMC overlay  

Carrier Gas Variations
Comparison of Overlay Welding

- Typical Operating Parameters & Productivity:

<table>
<thead>
<tr>
<th>Process</th>
<th>Deposit thickness (mm)</th>
<th>Deposition rate, kg/h</th>
<th>Dilution(a) %</th>
<th>Deposit efficiency, %</th>
<th>Consumable Material Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>OAW</td>
<td>1-1.5</td>
<td>0.5-2</td>
<td>1-5</td>
<td>85-95</td>
<td>Bare cast rod; tube rod; powder</td>
</tr>
<tr>
<td>SMAW</td>
<td>3</td>
<td>0.5-6</td>
<td>15-30</td>
<td>60-65</td>
<td>Flux covered cast/tube rod</td>
</tr>
<tr>
<td>GTAW</td>
<td>1-2</td>
<td>0.5-4</td>
<td>5-10</td>
<td>90-95</td>
<td>Bare cast rod; tube rod</td>
</tr>
<tr>
<td>PTAW</td>
<td>0.5-5</td>
<td>0.5-12</td>
<td>2-10</td>
<td>85-95</td>
<td>Powder; bare tube wire</td>
</tr>
<tr>
<td>GMAW</td>
<td>2</td>
<td>3-9</td>
<td>10-30</td>
<td>85-95</td>
<td>Bare tube wire; strip</td>
</tr>
<tr>
<td>FCAW</td>
<td>2</td>
<td>3-6</td>
<td>15-30</td>
<td>85-95</td>
<td>Cast/tube rod with internal flux</td>
</tr>
<tr>
<td>SAW</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wire</td>
<td>3</td>
<td>10-30</td>
<td>15-30</td>
<td>90-95</td>
<td>Bare tube wire (up to 4 simult.); strip; powder</td>
</tr>
<tr>
<td>Strip</td>
<td>3-5</td>
<td>10-40</td>
<td>10-25</td>
<td>90-95</td>
<td></td>
</tr>
<tr>
<td>LBW</td>
<td>0.5-6</td>
<td>0.5-1.5</td>
<td>3-15</td>
<td>85-95</td>
<td>Powder</td>
</tr>
</tbody>
</table>

Note (a): Acceptable single-pass levels of dilution are typically less than 15%.

References: [3,4,12,17,19,22,23,24,25,26,27,28]
## Process contrasts & typical applications:

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<tr>
<td>OAW</td>
<td>Low dilution</td>
<td>Automation difficult; low deposition rate</td>
<td>Small area deposits on light sections</td>
</tr>
<tr>
<td>SMAW</td>
<td>Portability (field repair); simple setup/equipment; multiple positions</td>
<td>Slag removal; low deposition; limited materials</td>
<td>Multilayers on heavier sections</td>
</tr>
<tr>
<td>GTAW</td>
<td>Controllable heat input; high quality welds; amenable to automation</td>
<td>Relatively slow process; deposition rate low</td>
<td>Small components, low-dilution work</td>
</tr>
<tr>
<td>PTAW</td>
<td>Amenable to automation; high quality deposition; low deformation; narrow heat affected zone</td>
<td>Overspray (powder loss); complicated and expensive equipment</td>
<td>High-quality, small and large components</td>
</tr>
<tr>
<td>GMAW</td>
<td>Good deposition rates; amenable to automation</td>
<td>Relatively high dilution; bulky equipment setup</td>
<td>Faster than SMAW, no stub-end loss; positional work possible</td>
</tr>
<tr>
<td>FCAW</td>
<td>High deposition rates; Amenable to automation</td>
<td>Slag removal; low deposit efficiency; limited materials</td>
<td>Similar to GMAW; MMC wire</td>
</tr>
<tr>
<td>SAW</td>
<td>High deposition rate and efficiency; amenable to automation; variable electrical configurations</td>
<td>High heat input and dilution; limited material selection; horizontal position only</td>
<td>Heavy section work; Corrosion-resistant cladding of large areas</td>
</tr>
<tr>
<td>LBW</td>
<td>Amenable to automation; high quality deposition; low deformation; narrow heat affected zone</td>
<td>Very expensive equipment</td>
<td>High-quality, low-dilution work</td>
</tr>
</tbody>
</table>

References: [3,4,12,17,19,22,23,24,25,26,27,28]
Case Study: Alloy 59 for FGD Unit

- **Wet Flue Gas Desulfurization Unit – Syncrude UE-1**
  - Remove sulphur dioxide by reaction with ammonium sulfate
  - Also produces ammonium sulfite crystals (fertilizer product)
  - “Most corrosive application in Syncrude’s operations”

- **FGD Unit Design**
  - 70 ft diameter at bottom & 20 ft at top; total height of 310 ft
  - Carbon steel - Alloy 59 clad plates (770 t), solid Alloy 59, & FRP

- **Alloy 59**
  - Nickel-chromium-molybdenum alloy
  - Nicrofer® 5923 hMo - Alloy 59 (UNS N06059) manufactured by ThyssenKrupp VDM
  - Excellent corrosion resistance and thermal stability

References: [30,31]; Photograph credits: www.thyssenkruppvdm.com/
Case Study: Alloy 59 for FGD Unit

- Fabrication of the FGD Unit
  - Solid Alloy 59 plate
  - Clad plate by hot roll bonding
  - Backing Weld: SAW or GMAW
  - Clad Restoration: GMAW stringer beads

- Technical Challenges
  - Selection of welding processes & procedures
  - Corrosion testing – “Green Death” solution
  - Controlling weldment dilution – maintain corrosion resistance
  - Post Weld Heat Treatment (PWHT) requirements
  - Impurity & iron contamination
    - Source of in-service pitting
    - Proper handling and weld preparation techniques were required

References: [30,31]
Case Study: MMC Impact Tester

- **Abrasive & Impact Wear in Oil Sands**
  - Abrasion Test: ASTM G65 standard method
  - Impact Test: No method for assessing *only* impact properties

- **Suncor and ARC joint-development project**
  - Computer-aided model design → test rig commissioning
  - Low energy impact regime (5 – 10J)
  - Design parameters: rotational velocity, hammer weight, number of specimens & specimen spacing

**Modeling of the Impact Rig**
Case Study: MMC Impact Tester

- **Test Method Results:**
  - Reproducible test method for metallics and non-metallics
  - Determined key materials parameter affecting impact performance
    - WC-MMC overlays – matrix toughness
    - Chromium carbide overlays - carbide content
    - Polymers – failure mode unique for different grades

Detailed results to be published at NACE Corrosion 2007
Conclusions

• **Wear and Corrosion Applications**
  – Many possible synergistic modes and mechanisms
  – Preventative techniques are application specific

• **Thermal and Plasma Spray Processes**
  – Simple or sophisticated technologies
  – Mechanical bond can limit applications

• **Cladding Processes**
  – CRA cladding used many for corrosion applications
  – Overlay welding used for restoration welds and repairs

• **Overlay Processes**
  – Selection is largely influenced by quality and productivity
  – PTA is the process of choice for wear-resistant materials

• **Selection of overlay materials and the surfacing technique should be assessed on a case-by-case basis**
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# References


