ANALYSIS OF THERMAL SPRAYING IN THE INDUSTRIES OF WESTERN CANADA

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DISCLAIMER

The contents of this study are meant to supply information on the industries and markets in Western Canada that utilize thermal spraying for coating fabrication. The report is not meant to be the sole resource used in any project or analysis. The author is not attempting to render any type of engineering or other professional services. Should these services be required, an appropriate professional engineer should be consulted. The author assumes no liability or responsibility for any uses made of the material contained and described herein.
Chapter 1  Introduction

Market studies on the thermal spraying industry have focused heavily on the general global market or on niche markets in the aerospace, automotive, and/or heavy equipment sectors. Currently, there are limited studies that have focused on niche markets outside of the aerospace and automotive sectors that are specific to the sectors in Western Canada. The overarching goal of this report is to provide a technical market analysis of thermal spraying in the mining and oil and gas industries of Western Canada. The features of the report will include basic information on the major thermal spraying processes in the region, an overview of the global thermal spraying market, the thermal spray market and opportunities for thermal spraying in Western Canada, and emerging technologies and research in thermal spraying that may have direct applications in the mining and oil and gas industries of Western Canada.

1.1  Overview of Thermal Spray Processes

Thermal spraying is a process in which a high-temperature heat source is used to melt and accelerate micron-sized metal, ceramic, or alloy particles to build protective coatings on industrial machine components. Molten and semi-molten particles impact and spread on the component surfaces until several layers of the coating are fabricated. These coatings provide protection against degradation caused by corrosion, erosion, or high temperatures. The versatility and cost-efficiency of thermal-sprayed coatings have increased their use in diverse industrial applications in aeronautics, automotives, biomedical, mining, forestry, and the oil and gas sector.
Thermal spray coating deposition involves the use of a torch to heat a material (see Figure 1-1), in powder or wire form, to a molten or near-molten state, and the use of a gas to propel the material to the target substrate, creating a completely new surface. The coating material may be a single element, alloy or compound with unique physical properties that are, in most cases, achievable only through the thermal spray process. It is typical that the torch will be operated by a robot in order to ensure safety and repeatability during the coating fabrication process. Furthermore, there are many torches available, with a selection from the four major thermal spray processes available: flame spraying, high-velocity oxy-fuel spraying (HVOF), air plasma spraying, and cold-gas dynamic spraying.

![Figure 1-1 Schematic of the thermal spray deposition process [1]](image-url)
1.1.1 Flame Spraying

Flame spraying is a versatile, low-cost thermal spraying process in which heat from the combustion of fuel gases is used to melt and accelerate powder particles to form a coating. The fuel, commonly acetylene, propane, or hydrogen, is burned in oxygen to produce a combustion flame. The temperature of the flame is usually on the order of 3,000°C [2, 3]. The use of powder as the stock material for the flame spray process permits the use of a large variety of materials, including metals, alloys, and some ceramics or cermets. Figure 1-2 shows an image of a flame spray torch in operation.

![Image of an oxy-acetylene flame spray torch in operation](image.png)

Figure 1-2 Image of an oxy-acetylene flame spray torch in operation

The coatings fabricated by powder flame spraying will have porosities between 5 to 15%, depending on the material that is deposited. The low flame temperatures of approximately 3,000°C contribute to the high levels of coating porosity. The porosity of the coating may be reduced by using the flame spray torch to melt the coating to fuse it. The direct flame interaction with metal powder particles, coupled with the entrainment of
air into the flame, will induce oxidation and the inclusion of oxide content in the final coating.

1.1.2 High-velocity Oxy-fuel Spraying

High-velocity oxy-fuel (HVOF) spraying uses a combustible mixture of a fuel and oxygen under high pressure in a combustion chamber to produce a continuous flame. The flame and combustion products exit the torch nozzle at high speed (with supersonic velocity). Powder particles are injected into the flame. The high speed of the flame ensures that the powder particles have high velocities, resulting in improved coating characteristics. Depending on the design of the HVOF torch, the fuel can be propylene, acetylene, propane, hydrogen, or liquid kerosene. The flame temperature in HVOF spraying is usually on the order of 2,500 °C. HVOF spraying is used primarily in some industries to fabricate wear resistant coatings, typically of tungsten carbide-cobalt-based (WC-Co) or chrome carbide/nickel chrome (Cr3C2/NiCr) materials. Due to the high speeds of the molten powder particles upon impact on the substrate, the fabricated coatings are generally very dense, with porosities lower than 2%. In addition to the coatings being dense, the coatings tend to adhere well to the underlying substrate and have lower oxide content than those deposited by powder flame spraying.

1.1.3 Air Plasma Spraying

Plasma spraying is a process in which a high-temperature ionized gas jet is used to melt and accelerate micron-sized powder particles to fabricate hard-faced coatings. Plasma temperatures can be on the order of 9,700 °C to 29,700 °C [2], depending on the
gas properties and its physical characteristics. Powders may be fed into the plasma jet stream by way of internal injection through the nozzle wall of the plasma spray torch or by external injection through ports outside the torch. Powder injection and conditions will have an influence on overall coating quality, porosity levels, and the levels of oxide inclusions. Active research has shown that small powder particles that are deposited via external powder injection will improve the quality of plasma-sprayed coatings by reducing the levels of porosity [5].

1.1.4 Cold-gas Dynamic Spraying

Developments in thermal spraying have resulted in a new process known as cold-gas dynamic spraying ("cold spraying"). Cold spraying is a process of applying a coating layer by depositing fine, micron-sized particles at high speeds (100 to 1200 m/s) onto metallic substrates (see Figure 1-3) and utilizing a pressurized gas to remove the requirement for a high heat source. The high impact speeds of the particles promote rapid spreading, plastic deformation, and the deposition of a highly dense layer of particles. Bonding between the deposited particles is typically metallurgical, coupled with mechanical interlocking. The absence of high temperature particle heating during the deposition process eliminates oxidation, promotes retention of the properties of the original stock powder, induces low residual stresses in the coating, permits the deposition of thermally sensitive materials such as polymers, and facilitates the deposition of highly dissimilar materials. Due to the need for plastic deformation upon impact of the particles, metals and metal alloys are the usual materials that are deposited by cold spraying. However, ceramic or cermet-based materials that are blended with a metal binder may be deposited via this process to form metal matrix composite (MMC) coatings.
Figure 1-3  Schematic of the cold spray deposition process [4]

The various thermal spraying processes that have been described will have unique attributes that characterize them. These attributes will be based generally on the process gas, powder, and the properties of the final coatings that are produced. Table 1 summarizes some of the attributes of each of the aforementioned thermal spraying processes.
Table 1-1  Typical Attributes of the Thermal Spraying Processes [2, 4, 6, 7]

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Flame Spraying</th>
<th>HVOF Spraying</th>
<th>Plasma Spraying</th>
<th>Cold Spraying</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gas</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature, K</td>
<td>3,500</td>
<td>2,500 – 5,500</td>
<td>15,000</td>
<td>500 – 1,000</td>
</tr>
<tr>
<td>Velocity, m/s</td>
<td>50 – 100</td>
<td>500 – 1,200</td>
<td>300 – 1,000</td>
<td>300 – 1,200</td>
</tr>
<tr>
<td>Gas Flow, SLM</td>
<td>100 – 200</td>
<td>400 – 1,100</td>
<td>100 – 200</td>
<td>1,000 – 2,000</td>
</tr>
<tr>
<td>Gas Types</td>
<td>C₂H₂, O₂</td>
<td>CH₄, C₃H₆, H₂, O₂</td>
<td>Ar, He, H₂, N₂</td>
<td>Air, N₂, He</td>
</tr>
<tr>
<td>Power Input, kW</td>
<td>20</td>
<td>150 – 300</td>
<td>40 – 200</td>
<td>5 – 25</td>
</tr>
<tr>
<td><strong>Powder Feed</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max. Particle Temperature, °C</td>
<td>2,500</td>
<td>3,300</td>
<td>&gt; 3,800</td>
<td>200 – 700</td>
</tr>
<tr>
<td>Particle Velocity, m/s</td>
<td>50 – 100</td>
<td>200 – 1,000</td>
<td>200 – 800</td>
<td>300 – 900</td>
</tr>
<tr>
<td>Feed Rate, g/min</td>
<td>30 – 50</td>
<td>15 – 50</td>
<td>50 – 150</td>
<td>80 – 240</td>
</tr>
<tr>
<td><strong>Coating</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Density, %</td>
<td>85 – 95</td>
<td>&gt; 95</td>
<td>90 – 95</td>
<td>95 – 99</td>
</tr>
<tr>
<td>Bond Strength, MPa</td>
<td>7 – 18</td>
<td>68</td>
<td>&lt; 68</td>
<td>60</td>
</tr>
<tr>
<td>Oxide Level</td>
<td>High</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Negligible</td>
</tr>
</tbody>
</table>
REFERENCES


Chapter 2  Thermal Spray Market and Opportunities

2.1  Overview of the Global Market

In the current global market, thermal spraying continues to be a leading surface technology solution. The process offers advantages due to its high throughput, ease of operation, and versatility. The thermal spray process is used in a wide variety of industries, including aero and industrial gas turbines, automotive, biomedical, and in Western Canada, the pulp and paper and oil and gas industries. Globally, the thermal spray industry is valued at approximately $6.5 billion, with the majority of revenue generated in the coating services segment of the industry [1]. Figure 2-1 shows that 77% of the market share in thermal spraying originates from the service segment [1].

![Figure 2-1  Thermal Spray Markets: Breakdown by Industry [1]](image)
Geographical distribution of the $6.5 billion thermal spray industry is heavily concentrated in North America and Europe, with North America accounting for 32% or $2.1 billion of the thermal spray market as shown in Fig. 2-2 [1].

![Thermal Spray Markets: Breakdown by Geography](image)

**Figure 2-2**  Thermal Spray Markets: Breakdown by Geography [1]

The regional distribution of global thermal spray activities results in market segmentation based on the service/supply industries in which thermal spraying are applied. Figure 2-3 shows that the majority of thermal spraying activities are dedicated to the aero and industrial gas turbines (IGT) industries at 60%, the automotive industry at 15%, and other industries at 25%. These other industries may include those in oil and gas, pulp and paper (forestry), mining, and biomedical, to name a few. The industrial gas turbine, aero, and automotive industries have seen the application of developed and mature thermal spraying solutions. Future growth of the thermal spray market in the industrial gas turbine, aero, and automotive industries will depend on the development of
novel thermal spray solutions and/or wider penetration into new geographical markets. Opportunities and potential for growth exist in the other industries that constitute 25% of the thermal spray market (see Fig. 2-3). According to Dorfman and Sharma [2], infiltration of thermal spraying in these other areas, in particular the conventional and renewable energy sectors, is low, and with advanced technology and material/process control, the stringent requirements of these industries may be fulfilled with thermal-sprayed coatings. Novel coating solutions that employ new consumables, new equipment such as cold spraying and suspension plasma spray torches, and new deposition methodologies will be useful to enable further penetration of thermal spray technology into specific segments of the oil and gas and forestry industries of Western Canada. Based on a study by Krömmer [3], the annual growth rate of the thermal spray industry is approximately 10% and the incorporation of new advanced technology into thermal spraying, coupled with penetration into new areas of application will secure and/or increase this current growth rate. Other studies have suggested similar growth rates of about 8% for the North American market [4].

![Figure 2-3](image.png)  
**Figure 2-3** Thermal Spray Markets: Breakdown by Type of Service Customer [1]
The end use application of thermal-sprayed coatings and the needs of local industries will dictate the type of equipment and consumables that will be required. For example, in Europe, approximately 61% of thermal-spray systems are combustion flame spray, followed by 18% of wire arc spray systems (see Fig. 2-4) [3]. These systems produce corrosion resistant coatings or are used for dimensional restoration of pre-existing parts. To support these equipment systems, 65% of the spray materials used in Europe is wire-based, with the remaining as powder-based [3]. However, in the oil and gas industry of Alberta, HVOF and flame spraying (with fusing) are the predominant thermal spray equipment systems used. These systems produce dense coatings with high adhesion strengths for the highly erosive oil sand slurry environment in which they will be exposed.

![Figure 2-4](image_url)  
**Figure 2-4**  Thermal Spray Systems in German-speaking Europe as of 2011 [3]
2.2 Mining and Oil & Gas Industry Markets

2.2.1 Coatings and Processes for the Mining and Oil & Gas Industries

In the mining and oil & gas industries, wear, which causes physical material removal, and corrosion, which causes chemical degradation, are the two main surface degradation mechanisms. A practical solution to mitigate the effects of these processes has been the deposition of hard-faced thermal-sprayed coatings [5].

Tungsten carbide (WC)-based cermet materials are used extensively to fabricate wear resistant coatings in the oil and gas industry. The most commonly used carbide materials are:

- WC-12Co (for example, Sulzer Metco 72F-NS)
- WC-10Co-4Cr (for example, Eutectic 5586)

The WC hard phase material provides resistance against abrasive and erosive wear (for example, in oil sands slurry transport and processing) and the cobalt (Co) and/or chromium (Cr) metal acts as a ductile matrix to provide support for the WC particles and increase the toughness of the overall coating. These materials are usually deposited by HVOF spraying. An example of a HVOF-sprayed WC-based coating is shown in Figure 2-5. Notice the absence of a significant amount of pores in the coating.
The flame spraying process may also be used to fabricate WC-based coatings. In this case, WC-12Co is blended with self-fluxing nickel (Ni) and deposited using flame spraying. An example of this type of powder material may be the Sulzer Metco 32C (WC-12Co + 14Ni + 3.5Cr + 0.8B + 0.8Fe + 0.8Si + 0.1C). In this powder blend, there is 14 wt.% self-fluxing Ni. After flame spray deposition, there will likely be many pores in the coating, that is, the coating will have high porosity. This will reduce the quality and longevity of the coating and will not provide a suitable barrier to fluid penetration during application. Therefore, the torch is used to melt the coating after deposition to fuse it, reducing coating porosity and redistributing the particles in the coating to homogenize it. Fusing could also be done:

- in a furnace,
- with a laser,
- with an electron beam, or
- with induction heating.

Figure 2-6 shows images of flame-sprayed NiCrBSi alloy coatings before and after fusing. The figure shows that after fusing the amount of fine and coarse porosity has decreased and the coating is denser compared to sample immediately after deposition.

![Image of flame-sprayed NiCrBSi coating before fusing](image1.png)

(a) After deposition

![Image of flame-sprayed NiCrBSi coating after fusing](image2.png)

(b) After fusing

**Figure 2-6** Self-fluxing of a flame-sprayed NiCrBSi coating [7]
Corrosion resistant coatings can also be fabricated for use in the mining and oil and gas industries. If corrosion resistance is required for applications in which wear will not occur, a flame-sprayed Colmonoy 6 coating may be used. Colmonoy 6 consists of Ni-13.5Cr-4.7Fe-4.2Si-3.0B-0.75C. The use of Ni and Cr aids to increase the corrosion resistance of the coating. Where wear will be a surface degradation process, in conjunction with corrosion, a HVOF-sprayed WC-Ni-based coating may be utilized. Table 2-1 shows typical target performance values that are required of thermal-sprayed coatings that are used for wear and corrosion protection in the mining and oil and gas industries.

<table>
<thead>
<tr>
<th>Metric</th>
<th>HVOF-sprayed: WC-Co-Cr</th>
<th>Flame-sprayed: Colmonoy 6</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Minimum</td>
<td>Aggressive</td>
</tr>
<tr>
<td>Thickness</td>
<td>200 – 300 μm</td>
<td></td>
</tr>
<tr>
<td>Porosity</td>
<td>&gt; 3%</td>
<td>&gt; 1%</td>
</tr>
<tr>
<td>Hardness</td>
<td>800 – 1000 HV</td>
<td>900 – 1200 HV</td>
</tr>
<tr>
<td>ASTM C633</td>
<td>&lt; 10,000 psi</td>
<td>&lt; 11,000 psi</td>
</tr>
<tr>
<td>ASTM G65</td>
<td>&gt; 0.2 g</td>
<td>&gt; 0.15 g</td>
</tr>
<tr>
<td>Corrosion test</td>
<td>No rusting</td>
<td>No rusting</td>
</tr>
</tbody>
</table>

### 2.2.2 Market Analysis of the Mining and Oil & Gas Industries

The mining and oil and gas industries of Western Canada have an estimated $200 million market for thermal spraying supply/services [8]. Of this market:

- $32 million of services are rendered to the down hole drilling sub-market for coatings for pump impellers, pump casings, valves, etc.
- $150 million of services are purchased by above-ground applications
$18 million of services are rendered to sub-markets outside of oil sands upgrading.

This market and the demand for thermal spray services are expected to grow at a rate of 2.5 to 3% per annum. This growth is on the same order of magnitude as that predicted by McWilliams [4] for the global thermal spray market. In the mining and oil and gas markets of North America, the growth and demand for coatings has been due to the advent of hydraulic fracturing (“fracking”) and exploitation of the oil sands of Western Canada. Particularly, HVOF-sprayed coatings and PTA overlays have entered the oil and gas market of Western Canada as a competitive alternative to hard chrome plating. Typically, these coatings are applied to ball valves, screens, storage barrels, crusher tips, pumps, hydraulic cylinder rods, mandrels and risers, hydrotransplant and tailings lines, buckets, latches, and teeth of digging shovels, to name a few. While, in general, applications in the mining and oil and gas industries are in terms of wear and corrosion, the oil sands of Western Canada are even more abrasive on equipment, making HVOF-sprayed coatings and PTA overlays more attractive as coating solutions. As the demand for energy resources continues to increase, placing greater demand on mining and oil and gas extraction, thermal spraying will continue to be an attractive alternative in these industries.

Figure 2-4 has shown that for European market, where aerospace, heavy machinery, and the automotive industries dominate, flame spraying and wire arc spraying are the most widely used thermal spraying equipment in that market. The demand for wear resistant and corrosion resistant coatings in the mining and oil and gas industries have
predicated the need for hard, dense, adherent coatings that are fabricated by HVOF spraying and flame spraying with fusing. Figure 2-7 shows that for the Western Canadian thermal spray market, HVOF spraying and flame spray and fuse represent 80% of the market.

![Pie chart showing thermal spray systems in Western Canada](image)

**Figure 2-7** Thermal Spray Systems in Western Canada [8]

Plasma-transfer arc (PTA) welding is also used in the mining and oil and gas industries to produce thick overlay coatings based on tungsten carbide for wear and corrosion resistance. However, typical of high-temperature deposition processes, decarburization of the tungsten carbide (WC) will occur, which reduces the mechanical integrity of the overlay. In addition, carbon monoxide and carbon dioxide formed during the decarburization process may cause the formation of large pores in the coating overlay, further reducing the strength of the coating.
The rigorous environments in the mining and oil and gas industries in which the coatings are applied require that a portion of this study be dedicated to presenting information on the life of coatings in service and compare that longevity with the cost of the coatings. Figure 2-8 shows the typical life span (in days) of various coatings and bare steel (control) that are exposed to oil sand slurries during the upgrading of bitumen in the Alberta market. The figure shows that PTA overlays have the longest life span of nearly 200 days, compared with a life span of nearly 100 days for HVOF-sprayed coatings.

**Figure 2-8**  Life Span of Various Coatings [8]

The cost of the coating solutions presented in Fig. 2-8 will be proportional to the longevity of the coating. As expected, the cost of PTA overlays is approximately twice that of HVOF-sprayed coatings, as shown in Fig. 2-9.
The cost of the various coatings may be indexed on their life span. Indexing, by dividing the cost by the life span, will provide a normalized or average price relative to facilitate direct comparison of the different coating solutions. Figure 2-10 shows the cost index of the various coating solutions that are used in the mining and oil and gas industries. It shows that HVOF-sprayed coatings have the lowest price index, which suggests that HVOF-sprayed coatings may provide the best value for the cost that is required to fabricate them.
A recent report by Thintri Inc. [9] has suggested HVOF-sprayed coatings may be 0 to 25% more costly than other processes such as chrome plating. The higher cost structure of HVOF-sprayed coatings are derived from the fact that the process may not be best suited for deposition on inner diameters, flange faces, and complex geometries that require repositioning and multiple rearrangement during spraying. That being said, Fig. 2-10, which shows a lower price index for HVOF-sprayed coatings, coupled with longer life span and the capability to deposit environmentally friendly coatings other than chrome-based coatings, make HVOF-spraying a competitive alternative in the mining and oil and gas industries.
In the oil sands sub-market of Western Canada alone, $45 billion in capital projects are expected for 2015. These capital projects will serve to support the upgrading and processing of an average of 2 tonnes of mined oil sand to produce 1 barrel (159 L) of synthetic crude oil. The Economist [10] has estimated that output from the Canadian oil sands will be nearly 3.5 million barrels per day by 2025, up from 1.5 million barrels per day in 2011. If the application of HVOF-sprayed coatings and PTA overlays continue to grow in this market, the demand for consumables such as powders will rise in tandem. However, instabilities in powder costs due to fluctuation of base commodity prices will temper growth in the thermal spray market. According to the study by Thintri Inc. [9], the price of tungsten has varied over time by a factor of 3 and the cost of nickel tripled in one year, only to fall nearly 50% the next year. Tungsten carbide-based powders for the HVOF spray market in the mining and oil and gas industries of Western Canada are worth about $7 million, which represents approximately 100 tonnes of powder per annum. This is based on prices that are $70 - $75 per kilogram, where prices could be as high as $95 per kilogram [8]. Stabilization and reduction of powder prices will be paramount to the continued success of thermal spraying in the mining and oil and gas markets of Western Canada. However, research has shown that end-users of thermal-sprayed coatings found that adverse quality issues resulting from the use of less expensive, low-quality powder consumables outweighed any cost savings that were gained [9]. Most participants in the thermal spray industry that service the mining and oil and gas markets believe that prices of carbide-based powders will decrease significantly if suppliers consolidate operations to the point where only a few major companies control the entire supply chain, from mining to powder production, and who focus on very high volumes. This premise is based on stable commodity prices.
Powders that are used for coatings in wear applications currently dominate the thermal spray powder market at 35% [9]. Carbide-based powders pervade that segment of the market. It is expected that as wear and corrosion resistant thermal-sprayed coatings penetrate the chrome plating market, the demand for powders for wear applications will increase. It has been stipulated that the wear coating powder market will more than double over the next 7 years [9]. In terms of producers/suppliers of these wear coating powders, Sulzer Metco (38%) and Praxair (34%) have the largest market share, combined, with H.C. Starck (12%) and Stellite (6%) owning smaller shares of the market [9]. The market for thermal spray equipment (i.e., torches, consumables, and parts) to deposit the coating powders is also dominated by Sulzer Metco and Praxair, with a combined market share of 91% [9]. Specifically, for HVOF spray torches and their auxiliary support equipment, Praxair has a 55% market share, with Sulzer Metco at 36%. Other smaller companies who supply tools for specialized jobs or who introduce advanced or novel technology will likely be able to increase their market share and begin to have an impact on the overall market in the next few years.
REFERENCES


Chapter 3  Emerging Technologies and Research

3.1 Opportunities in the Mining and Oil & Gas Industry Markets

In the mining and oil and gas industries, various opportunities for the application of thermal-sprayed coatings exist. A few of these potential opportunities are outlined below.

- In the hydrotransplant process during the upgrade of bitumen from oil sand slurries, chrome overlays on the tips of crushers have been found to have a life span of approximately 16 weeks (112 days) in the winter. According to Fig. 2-8, the life span for overlays is typically 200 days. Chrome-based coatings that can last longer on crusher tips would find a niche market in this industry.

- At present, hot water at a temperature of 80 – 90°C is mixed with oil sands as a part of the upgrading process. The slurry mixture will have a normal operating temperature of 55°C, with a maximum temperature of 95°C. The mixture will usually contain solid sand particles with sizes that are on the order of 2 to 3 inches and will have velocities between 4 m/s and 5.5 m/s (13 ft/s and 18 ft/s). The mixture will also contain chlorides on a concentration of 150 – 200 ppm, which causes corrosion of carbon steel pipes. The high-velocity transport of an abrasive, corrosive sand-water mixture in long 24 to 40-inch diameter carbon steel pipes, results in replacement of 60% of typical pipelines per year.

- In mining applications, an average fleet will include 100 trucks and 30 shovels. A truck will cost approximately $5 – 6 million, with shovels having slightly higher costs. The major surface degradation issues on the equipment are erosion of the undercarriages, cleaning of the components, hard-particle impact on the truck beds, and stress-corrosion cracking. Depending on the component in question, a
repair can cost from $100,000 to $500,000. At present, an estimated $40 million is spent on machine shop repairs annually.

- In froth treatment facilities, erosion and corrosion are the main surface degradation issues. Epoxy and polymer-based coatings and liners have been used as solutions. However, these coatings and liners have spalled and failed under service. Thermal-sprayed coating solutions in this area are still in the early stages of development, with opportunities for growth through proper material selection and deposition protocols.

- Boiler feedwater tanks and heat exchangers are equipment of concern for operators due to the high levels of corrosion that are induced by the higher operating temperatures in the equipment. Life expectancy of a boiler feedwater heat exchanger in the field is approximately 2 years. Recovery boilers in the pulp and paper industry of Western Canada also experience similar issues. Cracking of the recovery boiler floor, walls, and tubes has contributed to a reduction in continuous operation of this equipment. This cracking may be due to stress corrosion cracking and/or thermal fatigue [1]. Ferritic-martensitic steels have good resistance to stress corrosion cracking, but are inadequate for resisting corrosion and oxidation. On the other hand, austenitic steels and nickel-based alloys provide acceptable resistance against oxidation, but poor resistance against stress corrosion cracking. Therefore, the pulp and paper industry have used high-velocity oxy-fuel (HVOF) thermal-sprayed coatings of stainless steel or Alloy 625 to provide resistance against corrosion [1]. However, these coatings often crack and peel (spallation) from the coated surfaces after 12 months (or less) in operation, necessitating expensive repairs. In addition, alloy 625 is expensive,
resulting in a desire to find other alternative coatings that will either be low-cost, eliminate cracking and spallation, or both.

3.2 Emerging Solutions for the Mining and Oil & Gas Industries

High-velocity oxy-fuel (HVOF) spraying is currently one of the dominant thermal spray processes in the mining and oil and gas industries of Western Canada. However, the high temperature of the flame in HVOF spraying results in phase transformations, oxidation, and in the case of carbides, decarburization. Decarburization of carbides, in particular tungsten carbide (WC), produces hard brittle phases with low impact and fracture toughness. This reduces the performance and longevity of the coatings and overlays when they are exposed to the highly erosive environments in the mining and oil and gas industries. To that end, research and product development have been underway to produce coatings and equipment in which the adverse effects of temperature during the spraying process will be mitigated.

One such equipment technology development is high-velocity air fuel (HVAF) spraying. Similar to HVOF spraying, HVAF spraying utilizes a fuel that is combusted to produce a flame that is used to melt and accelerate the powder particles to high speeds that are on the order of 4,000 ft/s. However, unlike HVOF spraying where oxygen gas is used as the oxidant, in HVAF spraying, air is used as the source of oxygen for the combustion reaction. Given that air contains approximately 21 vol.% oxygen, the HVAF spray flame temperature is lower than that of HVOF spraying, heating the particles less, and mitigating the occurrence of oxidation and decarburization when WC-based coatings are fabricated. HVAF-sprayed coatings are typically dense and adhere well to the
substrate, similar to HVOF-sprayed coatings. This technology is well-suited for WC-based coatings on pump casings that are used in the oil and gas industry. Currently, HVAF spraying is used as a repair technology in the mining and oil and gas industries. Given the novelty of the HVAF process, it is a technology that has yet to gain full penetration into the thermal spray market of the mining and oil and gas sectors.

Investigations on the use of cold spray deposition to fabricate metal matrix composite (MMC) coatings based on WC have recently been initiated by several academic researchers. Cold spraying does not use high temperatures to melt the powder particles, but rather accelerates them to high velocities and relies on plastic deformation and adiabatic shear heating at the interface between the particles and the substrate to promote adhesion and densify the coatings. However, cermets and ceramics do not deform plastically, fracturing upon high-speed impact on the substrate. Therefore, cermet or ceramic powders may be bonded with a metal binder or mechanically blended with a metal powder that will deform upon impact, with the cermet or ceramic powder particle embedded within the metal matrix. Kim et al. [2] have shown that it is possible to fabricate cold-sprayed WC-Co coatings, with the Co phase deforming plastically and acting as the matrix for embedment of the hard WC phase. However, their use of an expensive high-pressure N₂/He cold spray system to deposit the hard Co metal binder phase may restrict extensive use of their methodology in industry. Use of a low-pressure system based on air would reduce costs while increasing the possibility of commercialization of the coatings. To that end, Melendez et al. [3, 4] used cold spraying at low pressure (150 psig) with a cold spray system from SST Centerline Ltd. to fabricate WC-Ni MMC coatings with WC content of nearly 70 wt.%, porosity of 0.3 vol.%,
hardness of about 550 HV$_{0.3}$, and wear rate under ASTM Standard G65 testing of $20 \times 10^{-6}$ mm$^3$/N-m. Figure 3-1 shows a scanning electron microscope (SEM) image of the cross section of a typical WC-Ni MMC coating fabricated by cold spraying at low pressure. HVOF-spraying usually produces coatings with WC content in excess of 80 wt.% and Table 2-1 shows that the minimum target for hardness and porosity for WC-based coatings fabricated by HVOF spraying for the mining and oil and gas industries should be 800 – 1000 HV and less than 3 vol.%, respectively. According to Guilemany et al. [5], HVOF-sprayed WC-Ni coatings should have a wear rate on the order of $18 \times 10^{-6}$ mm$^3$/N-m. The comparable wear rate and low porosity of the cold-sprayed WC-Ni coatings suggest that there is potential in the thermal spray market for cold-sprayed coatings in the mining and oil and gas sectors. However, further research will be needed to quantify and characterize the performance of these coatings fully.

Figure 3-1  Cold-sprayed WC-Ni Coating (white particles = WC) [3]
The harsh corrosive environments of boiler feedwater tanks and heat exchangers used in the oil and gas industry of Western Canada may be candidates for thermal-sprayed environmental barrier coatings (EBC’s). Environmental barrier coatings have been developed and designed to protect machine components from harsh environmental conditions. These coatings are usually deposited by using high-temperature thermal spraying processes such as air plasma spraying (APS), high-velocity oxy-fuel (HVOF) spraying, or direct-current radio frequency plasma spraying, to name a few. The EBC’s may be a single layer of coating or they may consist of multiple layers of different coating materials, with each layer having a specific function or meeting a prescribed requirement. The topmost layer will usually provide direct protection against the harsh environmental conditions, while the innermost layers will complement the properties of the substrate to increase coating properties such as adhesion strength. The choice of coating structure and materials will depend on the area of application, the surface degradation process, and coating integrity issues such as cohesion and adhesion to the substrate. EBC’s may be considered similar in their design to thermal barrier coatings (TBC’s). However, unlike EBC’s, TBC’s serve primarily to reduce the adverse effects of high temperature on component parts thereby extending the longevity of the component part. Oxidation and corrosion are usually the two main degradation processes that characterize harsh environments for which EBC’s provide protection. Without the EBC’s, significant chemical degradation of the substrate components would occur. EBC’s provide protection from such chemical degradation that is caused by solutions of gases or solid material dissolved in water, molten salts, or other reactive species. Table 3-1 shows a listing of examples of degradation mechanisms that may occur in boilers and heat exchangers in the oil and gas industry and typical coating materials that have been used.
to combat them. The table also shows the thermal spray deposition process that could be used to fabricate the coating. Some of the solutions, in particular those that combat molten salt corrosion, can be applied to recovery boilers in other industries such as the forestry and pulp and paper industries.

Table 3-2  Degradation Processes, Coating Materials, and Processes

<table>
<thead>
<tr>
<th>Degradation Mechanism</th>
<th>EBC Material</th>
<th>Deposition Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxidation</td>
<td>Alumina (Al₂O₃)</td>
<td>Direct-current radio frequency (DC-RF) plasma spraying</td>
</tr>
<tr>
<td>Calcium-magnesium alumino-silicate (CMAS) melts</td>
<td>Ba₁₋ₓSrₓAl₂Si₂O₈ (BSAS)</td>
<td>Air plasma spraying</td>
</tr>
<tr>
<td>Corrosion</td>
<td>Functionally-graded material (FGM) coatings of Al₂O₃ and Ni-20Cr</td>
<td>High-velocity oxy-fuel (HVOF) spraying</td>
</tr>
<tr>
<td>Hot corrosion</td>
<td>Mullite (3Al₂O₃-2SiO₂) and BSAS</td>
<td>Air plasma spraying</td>
</tr>
<tr>
<td>Molten salt corrosion</td>
<td>Ni-20Cr</td>
<td>Cold spraying</td>
</tr>
<tr>
<td>Molten salt corrosion</td>
<td>Yttria-stabilized zirconia (YSZ)/Ni-Cr-Al-Co-Y₂O₃</td>
<td>Air plasma spraying</td>
</tr>
<tr>
<td>Hot corrosion in molten salt</td>
<td>YSZ/LaMgAl₁₁O₁₉ or lanthanum zirconate (La₂Zr₂O₇)</td>
<td>Air plasma spraying</td>
</tr>
<tr>
<td>Hot corrosion and oxidation</td>
<td>Zircon (ZrSiO₄)</td>
<td>Low-pressure plasma spraying (LPPS)</td>
</tr>
</tbody>
</table>

Future trends in the development and application of EBC’s have focused primarily on new spraying techniques and materials. For example, cold gas dynamic spraying has been used recently to fabricate metal-based coatings to act as environmental barriers [6]. Suspension plasma spraying of small nanostructured powders [7] and small-particle plasma spraying [8] have also been explored to fabricate dense EBC’s. The use of smaller particles has been shown to produce denser coatings since they are easier to melt and accelerate in the plasma jet [8, 9]. In terms of materials development, zircon (ZrSiO₄) is an example of a promising candidate for use as an EBC because of its excellent high
temperature properties [10]. However, it is very difficult to fabricate ZrSiO₄ because it has a dissociation line at 1,676°C [11]. Suzuki et al. [12] deposited a dense coating by plasma spray deposition of a ZrO₂ + SiO₂ powder blend and heating the substrates; however, no ZrSiO₄ was present in the coating. The coatings that were subjected to heat treatment at 1400°C for approximately 24 hours had a significant amount of ZrSiO₄ and the coating porosity was high. The porosity formed due to the volume shrinkage when ZrSiO₄ was formed. Although the desired material, ZrSiO₄, was present in the coating, the increased porosity made the coating unsuitable. Therefore, further work will be necessary to optimize this coating to be a suitable EBC for application in boilers and heat exchangers.

In the mining and oil & gas industries, the majority of the thermal-sprayed coatings that are produced are fabricated to impede wear and/or corrosion. However, thermal-sprayed coatings may be utilized as functional coatings in other areas in the mining and oil and gas industries. Recent efforts by some oil & gas producers and end-users of thermal-sprayed coatings have involved the use of fiber-reinforced polymer (FRP) pipes or pipe sections, in lieu of steel-based pipes. FRP pipes are advantageous because the material is corrosion resistant, wear resistant, and eliminates the need for complex steel chemistries to combat corrosion and/or wear. Structural integrity monitoring of the pressurized FRP pipes, as well as heat tracing may be difficult since FRP material is not highly thermally conductive to permit monitoring and heating by conventional methods. Several investigators [13 - 15] have recently begun to deposit thermal-sprayed metal coatings onto FRP surfaces, and voltage difference and/or resistance across the coating are used as indicators of the level of damage of the FRP material. As the FRP is
damaged, the coating will also experience damage, resulting in higher voltage difference and resistance across the coating. Figure 3-2 shows a typical process to deposit flame-sprayed coatings onto FRP pipes. Heating may be achieved through the use of Joule heating in which the coating acts as a heat tracer to ensure that freezing of material contained within FRP pipes does not occur. Further investigation on the use of thermal-sprayed coatings as heating elements are currently being explored by other researchers [14, 16, 17].

**Figure 3-2** Deposition of Flame-sprayed Coatings on FRP Pipes
REFERENCES


