Evaluation of Tungsten Carbide Coatings Sprayed with High Velocity Plasma using a Process Map

R. McCullough, R. Molz, D. Hawley
Sulzer Metco (US) Inc. Westbury, NY, USA

Abstract

Process mapping is an ideal method for tracking coating characteristics in the thermal spray process. With the increased utilization of in-flight particle diagnostic tools in recent years it is now possible to quickly and effectively characterize in-flight powder particle properties. With industries’ increasing understanding of the relationship of these properties and coating characteristics, it is now possible to rapidly understand the implications of in-process changes with respect to coating performance.

This paper is an exploratory exercise that describes the utilization of process mapping [1] of in-flight particle velocity and temperature characteristics to optimize tungsten carbide (WC) coatings sprayed with a High Velocity Plasma torch (HVP).

Key performance factors of WC coatings include high inherent hardness, low porosity and neutral to compressive stress conditions. The combination of these factors all contribute to the coatings’ overall success in its intended application and elude to its toughness, wear resistance, corrosion resistance and general ability to protect the required components. Presently, the High Velocity Oxygen Fuel (HVOF) and High Velocity Liquid Fuel (HVLF) combustion processes are the favored method of applying dependable and commercially viable WC coatings that meet all of these criteria.

Introduction

Over the past decade, High Velocity Combustion (HVC) applied WC coatings have evolved to their current state of popularity, where they are essentially the standard method of WC application in all but Aerospace specific applications that require conformance to certain established specifications.

HVC applied WC coatings are generally applied to components requiring good wear and corrosion resistance as well as a good degree of toughness and impact resistance. This therefore dictates that the coatings generally require good hardness properties, uniform carbide distribution and ideally, neutral residual stresses.

The effective use of diagnostic tools in recent years [2; 3] has provided industry with an improved understanding as to why the HVC coatings excel in these areas. Tools such as the DPV2000, Accuraspray and Spraywatch, have been useful in understanding the particle states at any given point in the spray stream. Present characterization of good WC coatings associates these coating properties with particle conditions that have high levels of kinetic energy that are exposed to lower temperatures – when compared with the plasma process.

While the HVC process produces excellent WC coatings it has gained certain notoriety due to its relatively low efficiencies, high operating costs, high heat input into the components, and inability to spray a broad range of materials. Increasing numbers of OEM's and end users are seeking solutions to some of these limitations which has resulted in exploratory work being performed with various other processes to improve their performance in applying these coatings.

It is universally accepted that the plasma process can apply a broad range of materials. Currently, many Aerospace specifications exist for plasma sprayed WC however many of them were developed in the years preceding the advent of the HVC process. While the coatings are acceptable for these aerospace applications, they do not compare favorably to most HVC applied WC coatings. Many of the plasma applied WC coatings suffer from high levels of residual stresses thereby limiting their thickness capabilities and often suffer from residual stress cracking.

Due to certain limitations in the plasma spray process, application of WC coatings requires aggressive parameters that severely inhibit gun component life and day to day repeatability.
Considerable research has been performed on the behavior and limitations of existing plasma technology that has demonstrated plasma arc drift, due to high frequency pulsation, hardware erosion and subsequent instabilities in the plasma gas flow dynamics [4] and their resultant affect on particle conditions and coatings. These limitations severely limit the capability of generating high levels of kinetic energy in the process. As a result of this research, the Sulzer Metco Triplex Pro 200 plasma gun (TP200) design incorporates various features that potentially allow for operation into regimes never before possible with current commercially available technology.

The ability to isolate the arc attachment from the gas dynamics in the TP200 allows for gun operation in high pressure and flow regimes similar to the HVC process. This will potentially aid in increasing the availability of kinetic energy to the process.

These developments have resulted in some obvious questions. Can HVP potentially produce a dense WC coating with an acceptable micro-hardness, microstructure and stress condition? Is this coating comparable to an HVC applied WC coating? Is this a potentially economic, effective and efficient solution for WC application and even other materials in the future? Can process mapping techniques assist in quickly establishing key parameter relationships in the development of this process? Can in-flight particle characteristics be used as a guide to accurately predict plasma sprayed WC coating properties?

These questions will be addressed by experimental evaluation using process maps to define and isolate key influential parameter influences of HVP that could potentially result in further research into this process as a viable thermal spray tool.

**Experimental Methods**

The intended method for carrying out this evaluation would require benchmarking of a current HVC applied WC coating for comparison purposes. All HVP sprayed coatings would be evaluated against this benchmark coating.

Various WC material compositions and size distributions would be tested however the benchmark was completed with standard HVC type material. Sulzer Metco Woka 3202 (-45+15 WC-17%Co) powder was applied through a WokaStar 600 HVLF spray gun using standard parameters. Particle in-flight properties were measured using the DPV2000 for effective comparison to the initial plasma spray work.

Thereafter a 1st stage Design of Experiment (DoE) was developed to establish an operating window of particle temperature and velocity conditions using the TP200 with a standard 5mm convergent/divergent nozzle and the SM Woka 3202 material.

As no previous WC data exists for this new technology, certain boundary conditions were specified for the 1st stage DoE. Boundary conditions were based on existing equipment setup limitations and used current conventional plasma spray WC parameter data (power levels, gas types, gas flows etc) as a starting point.

To maintain a manageable number of spray runs, the following variables were established for generating particle in-flight characteristics for the 1st stage DoE:
1. Gas types (argon, helium, nitrogen, hydrogen);
2. Gas flows;
3. Plasma power;

All other parameter variables such as powder feed rates, carrier gas conditions and application rates were set constant. Plasma power, arc voltages and resultant parameters (plasma conditions determined by parameter inputs) were also recorded for diagnostic and future reference purposes.

The data gathered from all of the spray runs was evaluated to isolate the key influential parameters in HVP WC coating formation. Comparison of coating properties produced with specific in-flight particle conditions with the HVLF process were compared to the coating properties attained for each individual parameter condition measured with the TP200.

**Coating Characterization**

Coated samples (75mm x 25mm) were sectioned and polished for micro-structural evaluation. General evaluation of carbide content, and porosity was completed using optical microscopy and porosity measurements were determined using analySIS Opti software Version 3.2.

**Micro-Hardness**

Vickers micro-hardness was measured with a Wilson Series 200 hardness tester with a 300grm load. Measurement of the indentations was determined with analySIS Opti software Version 3.2.

**Residual Stress**

Determination of residual stress was performed by coating almen strips for each parameter and determining their upward (compressive) or downward (tensile) deflection (stress) condition using an Almen Gauge. Aerospace grade “N-1S” almen strips were coated with approximately 150µm (0.006”) coating thickness and measured at ambient temperature.

While more sophisticated evaluation procedures and equipment were available, these methods proved useful in determining the core differences between each processes treatment of powder particles in a reliable and expeditious manner.

Favorable coating properties obtained during the 1st stage DoE were then evaluated to isolate trends and generate theoretical
direction for the 2nd stage process maps. This included certain parameter modifications as well as alternative WC powder types. Variations to chemistries, manufacturing methods and particle size distributions were sprayed. The following alternate materials were tested:
1. Sulzer Metco Woka 3104 (-30+10µm)
2. Sulzer Metco 71VF-NS-5 (-30+5µm).

Results

HVOF Benchmark
Benchmarking the HVC process produced expected results. The coating exhibited excellent micro-structural characteristics and compressive stress conditions as exhibited on the almen strip deflection.

Figure 1 illustrates the HVLF applied WC coating. The coating exhibits good carbide distribution, low porosity, high micro-hardness and considerable compressive stress conditions. DPV2000 measurements of this coating indicated that the particles achieved an average V of 671m/sec and an average T of 1734°C.

Figure 1: SM Woka 3202 coating applied with the Sulzer Metco WokaStar 600 using a standard parameter.

1st Stage HVP Characterization
The 1st stage DoE results produced using the HVP and the SM Woka 3202 provided a quantitative description of the particle conditions for each measurement point in the plume.

Particle in-flight characterization: The results indicate that it is possible for the HVP to produce supersonic particle velocities at certain parameter conditions. The particle temperature measurements for all of these parameters indicated that, as might be expected, they are higher than those produced with the HVC process.

Figure 2 demonstrates the 1st order process map results based on the DoE factors and boundary conditions previously determined. This illustration demonstrates the potential of isolating influential variables by using process maps. Superimposed over the T and V data are the argon gas flow values representing their influence on particle velocity.

Figure 2: Graph representing 1st order process map for HVP applied SM Woka 3202 with key influencing parameters.

The greatest factor affecting kinetic energy and subsequent particle velocities was the total gas flow. Increases also resulted in high back pressure conditions in excess of 8.5bar (120psi).

Figure 3 illustrates the influence of argon and helium gas flows on particle V. The graph clearly demonstrates the dependence of kinetic energy on total gas flow through the system.

Figure 3: Argon and Helium flow relationship to particle velocities for each parameter.

Figure 4 illustrates the relationship of argon and helium gas flows and their affect on particle T. Increases in argon flow clearly increase particle velocities and therefore reduce the dwell time and subsequent particle temperature. The graph clearly illustrates the importance of helium gas to balance the kinetic energy and its contribution of thermal energy to the process.

Figure 4: Matrix Plot of Temp vs Velocity

<table>
<thead>
<tr>
<th>Argon Gas Flow (NLPM)</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>1800</td>
</tr>
<tr>
<td>150</td>
<td>1900</td>
</tr>
<tr>
<td>200</td>
<td>2000</td>
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</tbody>
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<thead>
<tr>
<th>Argon Gas Flow (NLPM)</th>
<th>Velocity (m/s)</th>
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<tr>
<td>100</td>
<td>400</td>
</tr>
<tr>
<td>150</td>
<td>500</td>
</tr>
<tr>
<td>200</td>
<td>600</td>
</tr>
</tbody>
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Micro-hardness: 1296HV300
Porosity: <1%
Almen: compressive
DE: ~46%
This contradicts the expected theory relating to the properties of these gases [1]. While theory states that helium should accelerate and achieve higher velocities through the convergent divergent nozzle, this data confirms the affect is not carried to the particles. In fact, increases in argon flow appeared to accelerate the particles at a greater rate than the helium. This may be due to the higher density of argon having a significant impact at these extreme temperatures or the properties in the plasma state are different than in the gaseous state. Further evaluation would be warranted.

Measurement of particle velocity and temperature decreased as the spray distance increased. However, as dwell time of the particles is a function of the particle velocity and the distance it travels, longer spray distances subjected particles to greater dwell times.

Table 1 details the average particle conditions for each of the three spray distances measured for a given parameter. The dwell time was calculated by dividing the exact distance from the point of injection by the average velocity of the particles. As the velocity data generated by the DPV is an average, the resultant data was used for comparative purposes only.

Table 1: Particle condition measurement averages for each spray distance point measured for a given parameter. For each parameter measured, the values decreased.

<table>
<thead>
<tr>
<th>Spray Distance (mm)</th>
<th>Average Particle T (°C)</th>
<th>Average Particle V (m/sec)</th>
<th>Average Dwell Time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>110</td>
<td>2076.5</td>
<td>545.5</td>
<td>0.000205</td>
</tr>
<tr>
<td>130</td>
<td>2053.8</td>
<td>535.4</td>
<td>0.000251</td>
</tr>
<tr>
<td>150</td>
<td>2035.6</td>
<td>527.6</td>
<td>0.000299</td>
</tr>
</tbody>
</table>

While are current affected the overall plasma power and efficiency, the amperage boundary conditions set in the DoE study were not shown to have any significant affect on particle in-flight conditions.

1st stage DoE coating characterization: Micro-structural examination of the coatings indicated that, regardless of particle velocity, all coatings produced with particle temperatures below 2100°C exhibit high levels of porosity (>5-6%) with low coating integrity. The coatings produced with the highest recorded particle temperatures (>2150°C) exhibited the most favorable microstructures however they were not comparable to the benchmarked HVC coating.

1st stage DoE residual stresses characterization: Analysis of the residual stress conditions for each parameter indicated that neutral stress conditions were possible only with high levels of kinetic energy and low levels of thermal energy. As determined by micro-structural analysis, these coatings were not acceptable.

It was clear from these results that, even though particle temperature recordings were higher than those measured in the HVC process, the particle conditions required higher levels thermal energy.

Therefore subsequent 2nd stage testing would include attempts to increase the amount of thermal energy to the particles. This would theoretically improve coating structures however, as the 1st stage process map results indicated, particles with elevated temperatures resulted in tensile residual stresses. Therefore improvements to the kinetic energy of the process would also be evaluated.

The alternate WC materials were tested to evaluate the effect of chemistry and particle size on particle thermal and kinetic energy.

2nd Stage HVP Characterization
To avoid large amounts of spray work, the finer WC materials were sprayed using the 1st stage process map window as a starting point. Diatomic gas was added to increase the available thermal energy in the plasma plume at the extreme parameters and the two alternate materials were tested.

Particle in-flight characterization: DPV 2000 measurements for each of the finer materials indicated significant increases in particle energy states. The SM71VF NS-5 material was able to achieve significantly higher particle temperatures than the SM Woka 3104 material. Diatomic gas was utilized to increase the SM Woka 3104 particle temperatures to a level acceptable enough to apply a potentially acceptable coating.

While are current affected the overall plasma power and efficiency, the amperage boundary conditions set in the DoE study were not shown to have any significant affect on particle in-flight conditions.
2nd stage DoE coating characterization: Micro-structurally satisfactory coatings were produced for each material. The SM71VF NS-5 required particle temperature conditions to be approximately 2300°C. Microstructures produced with particles at 2100°C showed excessive porosity and microstructures produced with particles at 2600°C exhibited high levels of decarburization. The Woka 3104 material exhibited excellent coating structures when sprayed with a parameters including diatomic gas. The added thermal energy of these parameters resulted in the excellent micro-structural properties. No significant decarburization was evident. Coatings sprayed at higher particle velocities exhibited higher levels of porosity, similar to the results obtained in the 1st stage DoE.

Figure 6 is the microstructure of the SM71VF NS-5 material. This coating exhibited excellent micro-structural properties. DPV2000 measurements of this coating indicated that the particles achieved an average V of 620m/sec and an average T of 2300°C.

Figure 7 is an acceptable microstructure of the SM Woka 3104 material. The coating remains tensile stressed. DPV2000 measurements of this coating indicated that the particles achieved an average V of 580m/sec and an average T of 2275°C.

2nd stage DoE residual stress characterization: Analysis of the residual stress conditions for the SM71VF-NS-5 coatings indicated similar trends to the results found in the 1st stage DoE. Coatings sprayed with high particle temperature conditions produced tensile stresses and micro-cracking. The coating produced in figure 6 exhibited neutral stresses.

The SM Woka 3104 coating followed a similar trend to the 1st stage DoE results. All of the coatings produced were tensile indicating a requirement for higher kinetic energy. Due to the current boundary conditions determined by the current equipment setup, higher velocity parameters were not tested.

Discussion

As recorded with the 1st stage process map results, the particle conditions in the HVP process were distinctly different than those recorded with the HVC process. The 1st DoE process map results indicated that it is indeed possible for the HVP plasma to produce supersonic particle velocities. As expected, due to the nature of the process, the particle temperatures were higher than the HVC process.

It is understood within the Thermal Spray industry that high velocity applied carbides depend on the following key attributes:

1. Kinetic energy (particle velocity);
2. Particle temperature exposure;
3. Time of temperature exposure (dwell time).

HVC applied WC coatings exhibit favorable properties because of the high levels of kinetic and thermal energy exposure of the particles as they accelerate in the continuously
combusting flame. This flame generally does not exceed a specific temperature (defined by the fuel type and stoichiometric ratio), usually not more than 3000°C and therefore ensures long residence times at low temperatures. This dictates that, provided the correct parameter conditions are established, the particles see sufficient soaking without complete melting thereby causing some of the carbide to go into solution.

Evaluation of the results in this paper, describe how the HVP process may differ. Plasma gas is superheated by the electric arcs in the arc chamber and expands as it exits the throat in the convergent/divergent plasma nozzle. As the plume expands, thermal energy is rapidly converted into kinetic energy. This rapid expansion results in rapid cooling of the plume where the powder particles are injected [5]. Therefore, the particles are exposed to high temperatures initially and tend to cool as the plume expands beyond the nozzle exit. As the particles accelerate their thermal energy state between the surface and the core is significantly different [1].

1st stage DoE diagnostic measurements of the particle temperatures suggested that the particles themselves required less heat input to match the HVC coating characteristics. However, the results of this study clearly indicate that the particles require higher temperatures to achieve more desirable coating properties. This could be due to the fact that while the DPV2000 (as well as other existing in-flight particle diagnostic technology) is very accurate in its determination of particle velocities, it relies on thermal emission from the surface of the particles to describe the particle temperature. While this is a fair indication of the surface temperature, it does not accurately describe the actual thermal energy present in the particle and may suggest why the HVP sprayed coating results required higher particle temperatures to achieve acceptable coating qualities.

The fact that the HVP process induces a high initial thermal exposure also may limit the ability to achieve optimal results in terms of ideal coating stress conditions. Achieving the desired microstructure required elevated surface temperatures, which in turn increased tensile stresses in some of the coatings. This may also be an indication that the use of iso-energy curves may not be feasible in process mapping, at least on the first order maps. Further development of HVP nozzles may be able to circumvent this limitation by increasing the particle dwell time at lower plasma temperatures thereby providing a more uniform and linear temperature exposure gradient.

The evaluations completed in this exercise prove that HVP is capable of achieving the necessary particle velocities for the application of good WC coatings. While this is not a true representation of kinetic energy – as it does not account for particle mass – it is possible to achieve the same particle velocity conditions as the HVC process.

Summary and Conclusions

This paper summarizes the development of using design of experiment techniques to generate process maps to explore the feasibility of applying tungsten carbide coatings using state of the art high velocity plasma technology.

Important conclusions are summarized below:
1. The use of DoE techniques and process maps afford the ability to establish key parameter relationships quickly and effectively;
2. The use of particle diagnostic tools is essential in defining the particle conditions within the spray stream and using these conditions to characterize coating qualities;
3. High velocity plasma is capable of operating within particle condition regimes previously unattainable by conventional plasma spray methods;
4. High velocity plasma applied carbides can exhibit similar coating properties to high velocity combustion processes.

Further work is scheduled to understand the relationship of other parameter variables of the HVP process. Using 2nd and 3rd order process mapping techniques, a greater understanding of process variables including particle morphology, thermal conductivity and application characteristics can be used to evaluate their interaction in the coating build-up process. The effect of nozzle design, particle injection and further parameter development is also scheduled.

References