Effect of a cylindrical shroud on particle conditions in high velocity oxy-fuel spray process

A. Dolatabadi, J. Mostaghimi*, V. Pershin

Department of Mechanical and Industrial Engineering, University of Toronto, 5 King’s College Road, Toronto, Ont., Canada M5S 3G8

Received 14 December 2001; revised 30 January 2002; accepted 30 January 2002

Abstract

Simulations of solid particles in a highly compressible gas flow in the high velocity oxy-fuel (HVOF) process are presented. The Eulerian formulation is used for the gas flow, and the particle phase is modeled by the Lagrangian method. Effects of attaching a cylindrical shroud to the end of the supersonic HVOF nozzle on gas and particle flows are analyzed. We found that the shroud significantly reduces the oxygen content in the field by protecting the supersonic jet from ambient air entrainment. The validation experiments were performed for the majority of process parameters such as shock formation, particle conditions, and coating oxygen content. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: High velocity oxy-fuel; Cylindrical shroud; Supersonic jet

1. Introduction

Thermal spray coatings are formed by the impact and solidification of a stream of molten or semi-molten particles on a surface. The process combines particle acceleration, heating, melting, spreading and solidification in a single operation. Extensive use is made of thermal spraying in the aerospace, power generation and more recently in automotive industries to provide protective coatings on components that are exposed to heat, corrosion, and wear. High velocity oxy-fuel process (HVOF) has demonstrated to be one of the most efficient techniques to deposit high performance coatings at moderate cost. In this process, a mixture of fuel and oxygen ignites in a high-pressure combustion chamber and the combustion products are accelerated through a converging–diverging nozzle (Fig. 1). As a result, injected particles attain high velocity (above 400 m/s) at relatively low temperature (less than 2000 °C). High particle kinetic energy upon impact leads to formation of a dense, well-adhered coating; whereas low temperature prevents the particles from extensive oxidation. Due to the low flame temperatures, HVOF cannot be used for ceramic coatings. It is primarily used in spraying metals or carbides with metallic binders.

Any thermal spray process in the ambient atmosphere is accompanied by air entrainment into a jet which results in in-flight metal particle oxidation. It is important to minimize oxidation during coating operation which results in improvement of overall coating performance [1,2] Vacuum plasma spraying (VPS) allows us to eliminate oxygen in spraying region and provides oxide-free coatings, but this process is expensive, time consuming and has restriction on the size of coated parts by the size of the vacuum chamber. Compared to other spraying processes, oxidation rate during the HVOF spraying is one of the lowest and under certain conditions, it is comparable with that of the VPS coatings [3]. In order to use the HVOF process as a technological alternative to the cost intensive VPS process, air entrainment should be minimized.

Attaching a protective shroud to the end of the HVOF nozzle in order to delay the jet mixing with air may be a good solution [4]. In an attempt to reduce the oxygen content in the HVOF coatings, Moskowitz et al. [5] tested a cylindrical shroud with gas injection. They claimed that the shrouded nozzle produces poor-oxide coatings. Pershin et al. [6] analyzed the effect of this type of shroud on in-flight particle conditions and coatings formation. Their experiments, similar to the claim of Moskowitz et al. [5], showed that attaching the shroud produces coatings with lower oxygen contents compared to that of the unconfined jet. On the other hand,
shrouding, as the results showed, increased coatings porosity because particle velocities were lower than that without the shroud.

The goal of this work is to get a better understanding of the spraying process by employing a numerical model of the HVOF process in the presence of a cylindrical shroud attachment. Having known the gas–solid particles flow parameters for the configurations with and without a shroud, we can provide a process optimization footpath to minimize the entrainment of ambient air into the main stream. This can also help us to propose the optimum shroud configurations which will minimize the observed negative effects of the shroud attachment. Finally, the numerical results will be validated with the experimental data for the same operating conditions.

2. Methodology

The schematic of the interior of a typical HVOF gun is shown in Fig. 1. The internal flow is characterized by a release of thermal energy from the oxy-propylene combustion and, as a result, the gas pressure reaches to about 6 bar with a temperature of around 3000 K in the converging section of the nozzle. The pressure due to the chemical reaction should be high enough to choke the flow at the throat and then accelerate it to supersonic speed ($Ma \approx 2$) as the gas expands through the diverging zone. An over expanded nozzle produces a jet that undergoes a sequence of shocks and expansions, which are referred to as ‘shock diamonds’ (Fig. 1). Particles are injected through the center port with nitrogen as carrier gas. The main objective of the process is to transfer kinetic and thermal energy from the gas to the particles with a high degree of efficiency. In general, numerical modeling of this process involves complex physical phenomena of turbulent combustive multi-phase flow. In addition, the flow regime varies from incompressible (with very low Mach numbers) to highly compressible flow ($Ma \lesssim 2.0$).

Recently, several computational fluid dynamics (CFD) analyses of the HVOF process have been performed. Oberkampf and Talpallikar [7,8] modeled the internal and external flow of a sonic nozzle. They assumed the flow was axisymmetric and used Eulerian and Lagrangian formulations for the gas and particle phases. Combustion was modeled by an approximate equilibrium chemistry model that accounts for the dissociation of the combustion products. A $k\-\epsilon$ turbulence model was used for turbulence phenomenon. Sinha et al. [9] used a methodology analogous to that implemented for solid propellant rocket propulsion and plume/launcher impingement to simulate the HVOF process. A Lagrangian stochastic model was used by Yang et al. [10] to predict particle trajectories and temperature history as a function of particle size and other coating parameters. A three-dimensional aircap similar to the Metco diamond jet rotating wire torch was simulated by Hassan et al. [11]. They concentrated on the gas dynamics of the three-dimensional fields. Dolatabadi et al. [12] considered the effect of a gas shroud attachment to the HVOF spray gun and compared the flow characteristics with the standard HVOF process.

In this paper, in continuation of the previous work, the shrouding effect on the gas flow, particle characteristics, and

![Fig. 1. Schematic of a typical HVOF nozzle.](image)
coating oxygen content are studied. Finally, the simulations are compared with the experimental results.

2.1. Governing equations

In this study, a particle-laden flow in an HVOF nozzle is analyzed. The Eulerian formulation is used for the gas flow, whereas the particle motion is described by the Lagrangian particle tracking method.

2.1.1. Gas phase

The governing equations are the continuity, momentum, energy, and ideal gas state equations for viscous, compressible, and turbulent flow. The volume fraction of the particulate phase is assumed negligible. The two-way coupling between the two-phase of gas–solid particles is provided by source terms in the momentum and the energy equations. The equations are expressed in Cartesian tensor form with the Einstein summation convention

\[ \frac{\partial p}{\partial t} + \frac{\partial}{\partial x_j} (p u_j) = 0 \]  
\[ \frac{\partial}{\partial t} (p u_j) + \frac{\partial}{\partial x_j} (p u_j u_l) = - \frac{\partial}{\partial x_j} \left( \lambda \frac{\partial T}{\partial x_j} + \nu \frac{\partial^2 u_j}{\partial x_l \partial x_l} \right) + S_{\text{u}} + \frac{\partial}{\partial x_j} \left( \mu _{\text{eff}} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} \mu _{\text{eff}} \frac{\partial u_l}{\partial x_l} \frac{\partial u_j}{\partial x_j} \right) \]  
\[ p = \rho RT \]

where \( \mu _{\text{eff}} = \mu + \mu _e \), \( H = h + 1/2 (u_i u_i) + k \), \( \lambda \), \( k \), and \( S \) are effective viscosity, total enthalpy, thermal conductivity, turbulent kinetic energy, and source terms, respectively.

The standard \( \kappa - e \) turbulence model of Launder and Spalding [13] is considered, where\( \kappa \) is the turbulent kinetic energy and \( e \) is the rate of its dissipation. Local values of \( k \) and \( e \) are obtained from the solution of the following transport equations:

\[ \frac{\partial}{\partial t} \left( \frac{\rho k}{\rho} \right) + \frac{\partial}{\partial x_j} \left( \frac{\rho u_j k}{\rho} \right) = \frac{\partial}{\partial x_j} \left( \Gamma _k \frac{\partial k}{\partial x_j} \right) + P_k - \rho e \]  
\[ \frac{\partial}{\partial t} \left( \frac{\rho e}{\rho} \right) + \frac{\partial}{\partial x_j} \left( \frac{\rho u_j e}{\rho} \right) = \frac{\partial}{\partial x_j} \left( \Gamma _e \frac{\partial e}{\partial x_j} \right) + \frac{\xi}{k} (c_1 P_k - \rho c_2 e) \]

Two reaction mechanisms are considered to represent the characteristics of the flame. The first reaction describes the process of fuel cracking which is necessary to obtain hydrocarbon intermediates that may be oxidized. The remaining three steps describe the process of converting hydrocarbon intermediates to combustion products.

The constant values in the model are: \( c_1 = 1.44 \); \( c_2 = 1.92 \); \( \sigma _k = 1.0 \); \( \sigma _e = 1.3 \).

\( T_k \) and \( T_e \) are diffusion coefficients given by: \( T_k = \mu + (\mu / \sigma _k) \) and \( T_e = \mu + (\mu / \sigma _e) \). The product rate of turbulent kinetic energy \( P_k \) is given by

\[ P_k = \mu \left( \frac{\partial u_l}{\partial x_j} + \frac{\partial u_j}{\partial x_l} \right) \frac{\partial u_l}{\partial x_l} - \frac{2}{3} \left( \rho k + \mu _{\text{eff}} \right) \frac{\partial u_l}{\partial x_l} \frac{\partial u_j}{\partial x_j} \]  

where the eddy viscosity, \( \mu _e \), defined as \( \mu _e = \rho c_\mu (k^2 / e) \), and \( c_\mu = 0.09 \). This provides the coupling of the turbulence model to the Navier–Stokes, energy, and reacting flow equations.

To model the combustion process tractable, a multi-reaction eddy dissipation model (EDM) is used. The EDM is appropriate in modeling industrial scale flames where reaction kinetics is fast. The progress of such reactions is controlled by the rate at which fuel and oxidant are mixed. Experimental observations of the HVOF spraying process agree with this assumption. The four-step reaction mechanism considered to represent the characteristics of the flame is listed in Table 1. Assuming air is composed of only \( \text{N}_2 \) and \( \text{O}_2 \), the chemistry model involves eight gas species: \( \text{C}_2\text{H}_6 \), \( \text{O}_2 \), \( \text{CO} \), \( \text{H}_2 \), \( \text{CO}_2 \), \( \text{H}_2\text{O} \), \( \text{OH} \), \( \text{N}_2 \).

The first reaction describes the process of fuel cracking which is necessary to obtain hydrocarbon intermediates that may be oxidized. The remaining three steps describe the process of converting hydrocarbon intermediates to combustion products.
considered (lumped capacitance system). The volume occupied by particles is also negligible.

The equation of motion for a particle in the gas flow is as follows \[14\]

\[
m_p \frac{d\vec{V}_p}{dt} = \frac{1}{2} \rho_g A_p C_D (\vec{U}_g - \vec{U}_p) \left| \vec{U}_g - \vec{U}_p \right| + \vec{F}
\]  

(8)

where \(m_p\) is the mass of particle, \(\vec{U}_p\) and \(\vec{U}_g\) are instantaneous particle and gas velocities, respectively. \(\rho_g\) is the gas density, \(A_p\) is the particle cross-sectional area and \(\vec{F}\) denotes external forces such as gravitational force.

The drag coefficient, \(C_D\), depends on several parameters such as the particle Reynolds number, the particle Mach number (calculated based on the relative velocity between gas and particle), and the particle surface roughness, and the rotation of the particle. The most important parameter, in the regime of interest, is the local or particle Reynolds number defined as

\[
Re_p = \frac{\rho_g |\vec{U}_g - \vec{U}_p|}{\mu_g d_p}
\]  

(9)

where \(d_p\) is the particle diameter and \(\mu_g\) is the viscosity of the gas. The correlations to calculate the drag coefficient and the corrections used for a moderate particle Reynolds number \(0.01 < Re_p < 260\) are [15]

\[
C_D = \begin{cases} 
1 + 0.1315(Re_p)^{0.82-0.05\alpha} & \text{for } Re_p < 20 \\
1 + 0.1935(Re_p)^{0.6305} & \text{for } Re_p > 20
\end{cases}
\]  

(10)

where \(\alpha = \log(Re_p)\). Integrating the equation of motion for a particle, results in the particle velocity (assuming the gas velocity is constant over the time of integration). Another integration over the time step will result in the particle position.

Using a lumped capacitance system and neglecting the radiative heat transfer, the energy equation for a single particle is given by

\[
m_p C_p \frac{dT_p}{dt} = A_p h_c (T_g - T_p)
\]  

(11)

where \(C_p\) is the specific heat of the particle, and \(h_c\) is the convective heat transfer coefficient which can be expressed in terms of the Nusselt number

\[
h_c = \frac{Nu \lambda}{d_p}
\]  

(12)

The Nusselt number is a function of the Prandtl and particle Reynolds numbers, given by [16]:

\[
Nu = 2.0 + 0.6 Pr^{0.33} Re_p^{0.5}
\]  

(13)

Integrating the energy equation for a particle, results in the particle temperature.

2.2. Numerical technique

This work uses TASCflow version 2.7.3 computer code, which is commercially available from AEA Technology [17]. A collocated finite volume method for predicting flows at all speeds is employed. The primary variables are the Cartesian velocity components, pressure and temperature.
Density is linked to pressure via an equation of state. The computational domain is subdivided into a number of quadrilateral control volumes. All dependent variables and fluid properties are stored in the control volume center (cell-centered arrangement). The data structure is a multi-block, structured grid. Integrating the conservation laws over each control volume results in systems of non-linear algebraic equations which are solved simultaneously.

2.2.1. Geometry

The nozzle geometry is similar to that of the DJ-2700 HVOF torch (Sulzer-Metco Inc., Westbury, NY, USA), which is basically a converging–diverging (de Laval) nozzle (Fig. 1). Through the central stream, solid spherical particles are injected with nitrogen as the carrier gas. The premixed propylene and oxygen is injected through eight 1.2 mm diameter tubes at an angle of $12^\circ$ toward the centerline. The oxy-fuel injection ports are considered as an annular inlet with the equivalent area. The third stream represents nitrogen used as a coolant to protect the nozzle walls from over heating. The torch geometry is composed of converging, cylindrical, and diverging zones as shown in Fig. 2.

The shroud attachment design was based on the aforementioned work [5] and includes two main parts: a gas manifold and a constraining cylinder. Pershin et al. [6] concluded that compared to the case without a gas injection injecting nitrogen into the shroud (gas shroud case) results in lower particle velocities and temperatures without any reductions in the coating oxygen content. Our primary numerical and experimental studies also show the same trend. Therefore, during the experiments the gas manifold was removed and in this analysis only the constraining cylinder is modeled. The water-cooled cylindrical shroud attachment is fitted coaxially to the nozzle (Fig. 2).

2.2.2. Boundary conditions

Boundary conditions are shown in Fig. 3. Computational domain is only a slice with an azimuthal angle of $6^\circ$. Periodic boundary conditions are applied on the side planes. There are three inlets and the mass flow rates used in the simulation are based on the measurements performed during our experiments as presented in Table 2. All gas inlet temperatures are assumed to be at 313 K. The walls are smooth and have a constant temperature of 350 K. Pressure is assumed to be one atmosphere at open boundaries.
2.2.3. Discretization

The computational grid inside the torch is composed of 30 radial and 80 axial nodes. Outside the torch, the computational grid is composed of 50 radial and 650 axial nodes. The grid is highly clustered in the axial and radial directions outside the torch. In supersonic flows, the axial grid should be fine enough to accurately capture the sharp shock diamonds. Outside the torch in the axial direction, the first 40% of the simulation area contains 610 clustered grid points. The next 60% contains a clustered grid with a cell length ratio of 18 to 1. In the radial direction, there are 30 equally spaced grid points from the centerline to the exit radius of the torch. Above the exit radius of the torch there is a clustered grid with a cell height ratio of 15 to 1. In the azimuthal direction three equally spaced grid points are considered.

2.3. Experimental technique

For validation of the numerical model a series of experiments were performed to characterize main process parameters such as shock formation, particle conditions and coating oxygen content. Experimental setup is shown in Fig. 4.

Experiments were carried out using DJ-2700 HVOF torch (Sulzer-Metco Inc., Westbury, NY, USA) with propylene as a fuel. The cylindrical, water-cooled shroud was attached to the torch (Fig. 4b). The coating material was MCrAlY (Co; 32Ni; 21Cr; 8Al, 0.5Y) powder, with a particle size distribution from 11 up to 38 μm; the carrier gas was nitrogen. Experiments were carried out with the standard setup and with a gas shroud attached to the nozzle. In-flight particle conditions such as velocity, temperature and size were measured with a DPV-2000 monitoring system (Tecnar Ltee, Montreal, Canada) [18]. The measurements were performed at standoff distances of 152, 203, 254, and 305 mm from the DJ torch nozzle exit. The high speed CCD camera (SensiCam from Opticon Corp., Kitchener, Ont., Canada) was used to capture the shock diamonds shape and location. Coatings microstructures were examined on polished cross-sections under a scanning electron microscope and image analysis was employed to estimate their porosity. Oxygen concentrations of the initial powder and coatings were measured using a LECO TC-136 (Leco Corp., St Joseph, MI, USA) oxygen analyzer.

3. Results

3.1. Gas phase

General characteristics of the flow are shown in Figs. 5a–c and 6a. Combustion of the premixed oxy-fuel near the injection port causes the combustion products temperature and pressure reach to about 3000 K and 6 bar in the beginning of the converging section of the nozzle. The flow accelerates in the de Laval nozzle. At the end of the converging section of the nozzle, the Mach number is around 1 (Fig. 6a). As the sonic flow expands in the diverging section of the nozzle, a supersonic flow develops.
in this region. Finally, the high-speed gas leaves the nozzle with an average Mach number of 2. A supersonic over-expanded flow (i.e. the gas pressure is higher than the isentropic exit pressure but lower than the ambient pressure) produces shock diamonds, which are basically a series of oblique shocks and expansion fans (Prandtl–Meyer fans). The shock dies away as the shock strength is attenuated by turbulent shear layers. The expansion and compression regions associated with the supersonic jet exiting the HVOF nozzle can be seen in the plot of pressure distribution along

---

**Fig. 6.** Mach number contours (a) without shroud, (b) with shroud.

---

**Fig. 7.** Location of the first shock (a) experimental and (b) numerical.
the centerline (Fig. 5c). Four or possibly five shock diamonds can be observed before the flow stabilizes at atmospheric pressure.

Fig. 5a shows the temperature profile along the nozzle centerline. The gas temperature increases in the converging part of the nozzle and reaches its maximum value at the nozzle throat. Within the diverging part, the expansion causes the velocity to increase to about 1800 m/s while temperature decreases to less than 2000 K (Fig. 5a and b). Just outside the nozzle exit, shock diamonds form and the gas temperature rises significantly right after each oblique shock. In this important region, more heat can be transferred from the gas flow to the particles. Therefore, capturing shock diamonds accurately is a key point to predict the particle temperatures outside the nozzle.

In order to validate the numerical results, location of the first shock diamond captured by the CCD camera is compared with that of the model prediction in Fig. 7. The first shock is chosen because the oblique shock and the Mach stem can be identified clearly from the image. Fig. 7a shows the supersonic over-expanded flow exiting the HVOF nozzle. The adjustment to the ambient pressure for this flow starts with an oblique shock. Then the shock waves reflect from the axis of symmetry as a Mach reflection. Gas goes through the reflected shock and is compressed with a pressure above the ambient pressure. This causes a sudden temperature jump flow.

To compare the numerical and experimental results, the gas temperature profile along the nozzle centerline predicted by the model is plotted in Fig. 7b. Distances are measured from the nozzle exit plane. The gas flow leaves the nozzle with a temperature slightly less than 2000 K. Temperature remains almost unchanged until the gas flow goes through the Mach stem. Passing through the shock causes a sharp temperature rise in the gas flow, which is well predicted in the numerical results. Temperature reaches from less than 2000 to over 2600 K (before and after the shock, respectively) in less than 1 mm.

The numerical results presented in Figs. 6 and 8 provide comparison of the flow parameters for configurations with and without the shroud. Although the gas velocity is lower in the shrouded case compared to that of the unconfined jet, shrouding effect on reducing the oxygen concentration is noticeable by comparing Fig. 8a and b. The oxygen concentration at the spraying position reduces from about 20% for the case of free jet to less than 5% for the case with the shroud attachment. The reduction in oxygen concentration results in smaller oxygen content within the coating. Experimental results for the same operating conditions show the oxygen content in the MCrAlY coating for the free jet case is about 0.4% (by weight), and that of the shrouded case is reduced to 0.12%. Therefore, protecting the main stream from entrainment of the oxygen in the ambient air can significantly reduce the oxide formation in the coating.

Fig. 9 compares the microstructure of the coatings produced with standard configuration and with the gas shroud attachment. The two microstructures are very similar. Estimation of the coating porosity (OPTIMAS image analysis software) for the two cases shows a slight increase in porosity, from 4.8 to 5.6%, as a counter effect of employing the shroud attachment. Particle impact velocity has an important effect on the porosity formation, and will be discussed in Section 3.2.
3.2. Particulate phase

Figs. 10 and 11 show the temperature and velocity of a single MCrAlY particle with a diameter of 15 μm, specific heat of 450 J/kg/K, and density of 7900 kg/m³ modeled for cases with and without the shroud. The particle temperature and velocity inside the nozzle for both cases are almost the same. The small differences are due to the nature of the stochastic modeling of the flow.

As shown in Fig. 10, the particle temperature rises inside the nozzle. After leaving the nozzle, in the supersonic region where the shock diamonds appear, the particles are still heated by the thermal shocks in the field. The shrouded nozzle generates higher particle temperatures compared to that of the free jet. Using the shroud prevents entrainment of the low temperature ambient air into the jet. Therefore, particles in this case are surrounded by the gas with higher temperatures.

Experimental results at different standoff distances shown in Fig. 10 are averaged over particle temperatures (more than 20 particles). Although the particle temperatures measured experimentally are higher than those of the numerical results, the experimental results confirm that shrouding the nozzle results in higher particle temperatures. One of the reasons that the model underestimates the particle temperature can be explained by this fact that the particle oxidation is not considered in the model. Oxidation of particles is an exothermic reaction and causes particles to gain more thermal energy and reach higher temperatures.

The velocity history of a particle as it travels throughout the domain is shown in Fig. 11. The initial particle velocity is 25 m/s. In comparison to the gas flow which essentially accelerates near the nozzle throat and in the first half of the divergent section of the nozzle, the particles are locally retarded and do not respond quickly to the variation of the

Fig. 9. Cross-section of MCrAlY coating (a) without shroud, (b) with shroud.

Fig. 10. Comparison of particle temperature with and without shroud.
gas velocity. Therefore, particle velocity rises at a lower rate compared to that of the gas flow within the de Laval nozzle. The gas velocity in the free jet within a distance of 10 cm from the nozzle exit is higher than the particle velocity, thus, acceleration of the particles continues in this region. Finally, particles decelerate in the region where the gas velocity is lower than the particle velocity.

Compared to the experimental results, the numerical model predicts a lower particle velocity. The reason is that for highly compressible flows the relative velocity between gas and particle can be greater than the local sound speed. In this case, the compression shocks forming in front of the particles can accelerate the particle to higher velocities. In fact, for this flow regime the drag coefficient is a function of the particle Reynolds number and the particle Mach number [19,20].

Although the gas velocity outside the nozzle is lower for the shrouded case compared to that of the free jet, the particle velocity predicted by the model for both cases is almost the same. As explained above, the drag coefficient in the model for a wide range of Reynolds number is almost constant (i.e. form drag). In addition, the relative velocity between gas and particle does not have a considerable influence on the particle acceleration or deceleration. This can be described by evaluating the particle Stokes number, which is the ratio of particle response time to a time characteristic of the fluid motion. For a typical HVOF process, MCrAlY particles with a density of 7900 kg/m³, particle sizes from 10 to 90 μm, gas flow velocities from 100 to 2000 m/s, and torch throat diameter 7 mm as the length scale, the Stokes number would be in the order of $10^2-10^3$. With such high Stokes numbers, particles do not respond quickly to the variation of the gas velocity field [20]. Because of this, in the shrouded case, the lower gas velocity outside the torch does not have a significant effect on the particle velocity.

4. Conclusion and future work

The effect of a shroud attachment on air entrainment and coating oxidation during HVOF spraying has been studied. The results of the numerical simulation were presented for the gas velocity, pressure and temperature. The oxygen concentration, particle velocity and particle temperature which are the most important parameters for coating formation are solved for the cases with and without the shroud. It is shown that by adding the shroud, the penetration of the ambient air into the jet will be significantly reduced. This will minimize in-flight oxidation of the powders, resulting in low oxide coatings.

The use of the shroud can increase the particle temperature because the high temperature zone outside the nozzle is extended in this case. On the other hand, the shrouded nozzle results in lower particle velocities since the gas velocity outside the nozzle in this case is lower than that of the free jet. This is mainly due to the large re-circulating flow that occurs at the beginning of the shroud. In future the re-circulating flow inside the shroud will be minimized by proposing the optimum shroud geometry.

Acknowledgments

The authors would like to thank Dr M. Ivanovic for his advice on TASCflow simulations. This work was supported by NSERC, MMO, and VAC AEORO International Inc.
References

[1] W. Brandl, D. Toma, J. Kruger, H.J. Grabke, G. Matthaus, The oxidation behaviour of HVOF thermal-sprayed MCrAlY coatings, Surface and Coating Technology 94–95 (1997) 21–26.

[2] E. Lugscheider, C. Herbst, L. Zhao, Parameter studies on high-velocity oxy-fuel spraying of MCrAlY coatings, Surface and Coating Technology 1087–109 (1998) 16–23.

[3] D. Toma, W. Brandl, U. Koster, Studies on the transient stage of oxidation of VPS and HVOF sprayed MCrAlY coatings, Surface and Coating Technology 120–121 (1999) 8–15.

[4] L.N. Moskowitz, Application of HVOF thermal spraying to solve corrosion problems in the petroleum industry, Proceeding of the International Thermal Spray Conference and Exposition, Orlando, FL, USA (1992) 611–618.

[5] Moskowitz L., Lindley DJ. US Patent 5,019,426.

[6] V. Pershin, J. Mostaghimi, S. Chandra, T. Coyle, A gas shroud nozzle for HVOF spray deposition, Proceeding of the International Thermal Spray Conference, Nice, France (1998) 1305–1308.

[7] W.L. Oberkampf, M. Talpallikar, Analysis of a high velocity oxy-fuel (HVOF) thermal spray torch. Part 1. Numerical formulation, Journal of Thermal Spray Technology 5 (1) (1996) 53–61.

[8] W.L. Oberkampf, M. Talpallikar, Analysis of a high velocity oxy-fuel (HVOF) thermal spray torch. Part 2. Computational results, Journal of Thermal Spray Technology 5 (1) (1996) 62–81.

[9] N. Sinha, B.J. York, A. Hosangadi, S.M. Dash, First-principles-based computational fluid dynamic (CFD) model of thermal spray deposition process, Proceeding of the 8th National Thermal Spray Conference, Houston, TX (1995) 199–206.

[10] X. Yang, S. Eidelman, Numerical analysis of a high-velocity oxygen-fuel thermal spray system, Journal of Thermal Spray Technology 5 (2) (1996) 175–184.

[11] B. Hassan, A.R. Lopez, W.L. Oberkampf, Computational analysis of a three-dimensional high-velocity oxygen-fuel (HVOF) thermal spray torch, Journal of Thermal Spray Technology 7 (1) (1998) 71–77.

[12] A. Dolatabadi, J. Mostaghimi, M. Ivanovic, Numerical modeling of particle laden flow in HVOF torch with gas shroud, Proceeding of the International Thermal Spray Conference, Montreal, Que., Canada (2000) 105–113.

[13] B.E. Launder, D.B. Spalding, The numerical calculation of turbulent flows, Computer Methods in Applied Mechanics and Engineering 3 (1974) 269–289.

[14] C. Crowe, D. Stock, A computer solution for two-dimensional fluid-particle flows, International Journal of Numerical Methods Engineering 19 (1976) 185–196.

[15] C.T. Crowe, M.P. Sharma, D.E. Stock, The particle-source-in-cell (PSI-CELL) model for gas-droplet flows, Journal of Fluids Engineering 99 (Ser.1, No. 2) (1977) 325–332.

[16] F.P. Incropera, D.P. DeWitt, Fundamentals of Heat and Mass Transfer, third ed., Wiley, New York, 1990.

[17] AEA Technology Engineering Software Ltd, Waterloo, Ont., Canada.

[18] C. Moreau, P. Gougeon, M. Lamontagne, V. Lacasse, G. Vaudreuil, P. Cielo, On-line control of the plasma spraying process by monitoring the temperature, velocity and trajectory of in-flight particles, Proceeding of the 7th NTSC, Boston, MA, USA (1994) 431–437.

[19] M.J. Walsh, Drag coefficient equation for small particles in high speed flows, AIAA Journal 13 (11) (1975) 1526–1528.

[20] C.T. Crowe, M. Sommerfeld, Y. Tsuji, Multiphase Flows with Droplets and Particles, CRC Press, Boca Raton, FL, 1998.

[21] W.E. Mallard, F. Wesley, J.T. Herron, R.F. Hampson, NIST chemical kinetics database 17, NIST Standard Reference Data, Gaithersburg, MD, 1994.