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Investigation of a dual-stage high velocity oxygen fuel thermal spray system

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HIGHLIGHTS

- Computational study of a dual-stage combustion assisted spray system for coatings.
- Dual-stage thermal spray system can be used for temperature sensitive materials.
- Combustion chamber dimensions affect the particle velocity and temperature.
- The particle temperature can be controlled by varying the mixing chamber length.

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ABSTRACT

The high velocity oxygen fuel (HVOF) thermal spray coatings are used to protect the surfaces from deterioration. The base material surface properties can be modified to achieve the longevity of the product. Besides spraying material, the coating quality depends greatly on the gas and particle dynamics. The coating quality is also affected by the particle temperature, particularly for the materials which are temperature sensitive such as titanium and copper. As the gas phase temperature is high, the material gets melted and oxidized before it reaches the substrate. To avoid this problem, a dual-stage thermal spray system, has been developed for coating temperature sensitive materials. This process involves making coatings by high velocity impact of powder particles heated to temperatures below their melting point. The advantages of a dual-stage thermal spray process include an easy control of particle oxidation and production of various coating structures by controlling the particle velocity and temperature. The particle temperature can be controlled by varying the coolant flow rate in the mixing chamber.

The present study investigates the effect of various geometric parameters of a dual-stage thermal spray system by developing a comprehensive mathematical model. The objective is to develop a predictive understanding of various design parameters. Conservation of mass, momentum and energy of reacting gases were taken into account in developing the model. Due to low particle loading, the particle phase was decoupled from the gas phase. The results demonstrate the advantage of dual stage system over single stage system especially for the deposition of temperature sensitive materials.

1. Introduction

In many industrial applications, components are subjected to heat and corrosion and may require surface finish and protection from the environment. To achieve these, coatings of different materials are applied on the components using different coating methods. High velocity oxygen fuel (HVOF) thermal spray process is one of these techniques, which is used in various engineering applications, particularly in aerospace and automotive industries. Titanium and titanium alloys are excellent coating material candidates for aerospace applications owing to their advantages of light weight, very high strength and high corrosion resistance [1]. Biocompatibility and osseointegratability of titanium within human body also make it highly useful in biomedical implants [2]. In spite of being costly, the above mentioned properties and applications make titanium a valuable material within engineering and surface coating industries [1,3–6].

Titanium being a temperature sensitive material has a strong affinity towards oxygen [7]. Therefore, titanium cannot be used with a conventional HVOF thermal spray since the temperature generated during the process is above 3000 K. This high

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Nomenclature

A	empirical coefficient in eddy dissipation model
A_p	particle cross-sectional area
B	empirical coefficient in eddy dissipation model
c	turbulent model constant
C_D	drag coefficient
C_p	specific heat at constant pressure
d_p	particle diameter
$\bar{F}$	external force
h_c	convective heat transfer coefficient
H	overall enthalpy
k	turbulent kinetic energy
m_p	mass of particle
Nu	Nusselt number
p	gas pressure
P_k	production rate of turbulent kinetic energy
P_r	Prandtl number
R	gas constant
R_F	volumetric fuel consumption rate
Re	Reynolds number
S	source term
t	time
T	temperature
u_i	velocity in the i-direction
$\bar{U}$	instantaneous gas velocity vector
x_i	spatial coordinate in the i-direction
Y	fluctuating dilation in compressible turbulence to the overall dissipation rate

Greek variables

α	Inverse effective Prandtl number
ε	rate of turbulent kinetic energy dissipation
λ	thermal conductivity
μ	molecular viscosity
μ_{eff}	effective viscosity
Γ_k	diffusion coefficient of k
Γ_ε	diffusion coefficient of ε
ρ	density
σ	turbulent model constant

Subscripts

F	fuel
g	gas
O	oxidant
p	particle
P	combustion product
t	turbulent

temperature will melt the particles completely before they reach the substrate resulting in a low quality coating [2]. The melted particles undergo oxidation during the flight and the oxidation increases exponentially when the particle is heated beyond 900 K [8]. Hence, the control of particle temperature and the oxidation becomes important. This could be achieved by using a cold gas dynamics spray (CGDS) [9], however, this method results in a low deposition efficiency and high porosities in the coating due to the low temperature [2], which hinders the plastic deformation of the particles. The void in the safe operating temperature range from both high velocity oxygen fuel system and the cold spray system was overcome by a recently developed technique called dual stage thermal spray system, which is also called as warm spray system. This was first patented by Browning [10] and later developed by many researchers [11–14]. The schematic of a dual stage spray gun is shown in Fig. 1.

The gas phase temperature in the dual stage spray system can be controlled in the range of around 1000–2500 K depending on the feed material while maintaining the range of particle velocities similar to that of HVOF process. This system has a combustion chamber followed by a convergent nozzle. A mixing chamber is introduced between the convergent nozzle and the converging–diverging nozzle followed by a barrel. The temperature is controlled by varying the nitrogen mass flow rate in the mixing chamber. The combustion products mix with nitrogen in the mixing chamber and get accelerated by a converging–diverging nozzle. The gas mixture leaves the barrel with a supersonic speed. The particles are injected at the upstream of the barrel. The particles get heated by the gas and are accelerated to high speeds in the downstream direction. After exiting the barrel, the particles hit the substrate with a high impact velocity and adhere to it forming coating.

With the involvement of turbulence, combustion, multiphase flow, heat transfer and supersonic/subsonic flow transitions, the thermal spray processes become highly complex [15]. These processes can be modeled in two parts: modeling of the gas phase and modeling of the particle phase. Due to low particle loading, the particle and the gas phases can be decoupled because of the insignificant effect of the particle phase on the gas phase. Hence, the gas phase can be modeled independent of the particle phase. Many computational fluid dynamic simulations have been performed for both gas fueled and liquid fueled single stage spray systems [16–18]. On the other hand, very few computational studies have been performed on the dual stage spray system. Tabbara et al. [2] have modeled the titanium particles in a liquid fueled dual stage spray system by considering a two way gas-particle interaction. The focus of their work was to study and control the particle temperature by varying the coolant mass flow rate. The present study is performed by employing a central cooling chamber concept developed by Kawakita et al. [12,18,19] and the modeling process similar to that developed by Dolatabadi et al. [20]. The modifications used for modeling the dual stage system are listed in the subsequent section. The model has been modified in order to predict the results close to experimental results which would help in understanding the processes more accurately.

The processes occurring in the dual stage gun affects the performance of the spray and consequently, the quality of the coating. The physical properties and the microstructure of the coatings in turn depend greatly on the particle condition at the substrate. The particle phase is governed by the gas dynamics and parameters such as the particle size, oxygen/fuel ratio, particle injection method, and gun design [21]. The current study investigates the influence of important geometric parameters on the gas and particle phases in a dual stage thermal spray system particularly when using temperature sensitive materials like titanium.

2. Model development and mathematical formulation

Due to low powder particle loading, the gas phase is decoupled from the particle phase. Hence, the particle phase does not affect the gas phase. The model includes the continuity, momentum, energy, turbulence and equilibrium chemistry. The solution obtained for the gas phase is used to solve the particle phase model

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