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Size-dependent distributions of particle velocity and temperature at impact in the cold-gas dynamic-spray process

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ABSTRACT

A mathematical model, which describes the particle velocity and temperature of impact in the cold-gas dynamic-spray process and accounts for varying drag and heat transfer coefficients, is developed and validated. Using the proposed model, the distributions of impact velocity and temperature as function of particle diameter are predicted and their dependence on process parameters, standoff distance and the particular trajectory of the particle in the jet is analyzed. These distributions must be taken into account if a correct description of the required impact conditions for successful deposition in cold-gas spraying is to be understood and modelled.

1. Introduction

The cold-gas-dynamic-spray (CGDS) process is a coating method developed in the mid-1980s at the Institute for Theoretical and Applied Mechanics in the Soviet Union by Papyrin et al. (2007). It is a high-rate deposition method where fine particles are accelerated through a converging–diverging nozzle by a preheated compressed gas to velocities usually ranging from 500 to 1000 m/s. Directed towards a target surface, the incident particles undergo a massive plastic deformation, which generates the intimate contact essential for a successful bonding to the substrate. The prevailing theory for cold-spray bonding asserts that the plastic deformation of the particle occurs by means of an adiabatic shear instability mechanism, which is activated only if the impact velocity is higher than a threshold value, called critical velocity. Indeed, Grujicic et al. (2004a) showed that the minimal impact particles velocity needed to produce shear localization at the particles/substrate interface correlates quite well with the critical velocity for particles deposition in a number of metallic materials. However, besides this mechanism, Grujicic et al. (2003) argued that an interfacial instability inducing the formation of interfacial roll-ups and vortices can play a significant role in attaining the interfacial bonding necessary for deposition. Due to the extremely high pressure and stress level at the particles/substrate interface, Grujicic et al. (2003) treated the material adjacent to the interface as a viscous "fluid-like" material, so that they can use the Yih interfacial instability analysis (this permits the introduction of kinematic viscosity, Reynolds number and viscosity differences, on which the Yih's theory is based). On this basis, it was found that a 1 μm-wavelength perturbation is unstable and can grow during collision events in CGDS and that perturbations with smaller wavelengths will grow more rapidly.

The facts established by the scientific community about CGDS are below summarized:

(1) The critical velocity is function of the particle diameter and impact temperature. To this regard, Schmidt et al. (2006a) firstly found the experimental correlation between the critical velocity and the particle diameter proving that for copper and 316L steel particles with diameter larger than 10 μm the critical velocity decreases with the increase of the diameter. Similarly, Schmidt et al. (2006b) demonstrated that the critical velocity can be reduced if the impact temperature is increased using a heating prechamber. In this case, a clear increase of the deposition efficiency was observed using a heating prechamber meaning that a higher impact temperature reduces the impact velocity needed for the successful bonding of the particle.
(2) The velocity and temperature of the particles, both at impact and in the free-jet flow, are function of the diameter. At the same time, there is a proven scattering of the velocity and temperature related to the radial position from the jet centerline. For example, Gilmore et al. (1999) experimentally observed the in-flight velocity distribution as function of the radial position

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General symbols

u	axial velocity component [m/s]
m	mass [kg]
d	diameter [m]
T	temperature [K]
p	pressure [Pa]
ρ	density [kg/m^3]
Cp	specific heat [J/(kg K)]
H	enthalpy [J]
μ	viscosity [Pa s]
Y	mass fraction of the working gas in the discharging jet
A	nozzle cross-sectional area [m^2]
k	thermal conductivity [W/(m K)]
W	molecular or atomic weight [kg/mol]
h	heat transfer coefficient [W/(m^2 K)]
F_D	drag force [N]
R	gas constant, 8.314 [J K^{-1} mol^{-1}]
x	axial coordinate [m], see Fig. 1
r	radial coordinate of the axially symmetric problem [m], see Fig. 1
x_0	axial coordinate at the nozzle inlet
x_*	axial coordinate at the nozzle throat
x_j	axial coordinate at nozzle exit
$x_{\text{core}\_u_m}$	core region for the velocity of the emerging jet
x_{core_T}	core region for the temperature of the emerging jet
x_{core_Y}	core region for the mass fraction of working gas in the emerging jet
r_0	nozzle radius at the inlet [m]
r_*	nozzle radius at the throat [m]
r_j	nozzle radius at the exit [m]
$r_{i\_q_m}$	radius of the core region of the generic gas-dynamics quantity q [m]; q can be either u, Y or T
$r_{5\_q_m}$	radius where the generic gas-dynamics quantity q becomes one-half its centerline value [m]
SoD	standoff distance [m]
l_{st}	height of the stagnation bubble [m]

A-dimensional quantities

γ	ratio of the constant-pressure and constant-volume specific heats
M	Mach number
Re	Reynolds number
C_D	drag coefficient
Nu	Nusselt number
Pr	Prandtl number

Subscripts

g	quantity referred to the working gas inside the nozzle
p	quantity referred to the particle
e	quantity referred to the external ambient atmosphere, usually still air at room condition
m	quantity referred to the mixture of working gas and external atmosphere created by the turbulent mixing outside the nozzle
y	quantity referred to the generic fluid acting the dragging force, the working gas inside the nozzle and a mixture of working gas and ambient atmosphere outside
st	quantity referred to the fluid inside the stagnation bubble

from the nozzle axis and showed that the mean particle velocity drops off sharply away from the central axis. Similarly, Lee et al. (2007), using a CCD camera equipped with a high power pulsed laser diode to illuminate the particles, found a distribution of particle velocity around the nozzle centerline. However, the origin of these distributions and of the particle scattering have not been analyzed in their complete development during the CGDS process.

(3) A bow shock, generating a stagnation bubble, decelerates the sprayed particles at the impingement of the supersonic jet onto the substrate. About this point, Grujicic et al. (2004b), using computational analysis, described the flow field in the impinging zone and showed that the stagnation bubble contains a re-circulating fluid with relative low velocity which causes the deceleration of the impacting particle. Pattison et al. (2008) experimentally observed the stagnation bubble and measured its dimensions by means of the Schlieren imaging technique at different SoD.

The role of the stagnation bubble and related bow shock is very important considering that the in-flight and impact velocity of a particle are tightly correlated. Indeed, the impact velocity distribution with particle diameter at a given SoD is the result of the application of the bow shock deceleration to the velocity distribution calculated at the same distance in the free-jet condition. Previous works of modelling fail to consider the SoD as an influential factor for the dimensions of the stagnation bubble and, as a consequence, for the deceleration capability of the bow shock. Grujicic et al. (2004b) and Assadi et al. (2011) proposed the most important works of modelling in this field. By means of fluid dynamic arguments and using the Lambert W function to resolve the Newton's second law applied to the particle, however, under simplified conditions, i.e. constant drag coefficient, Grujicic et al. (2004b) found an analytical solution for the particle velocity at the nozzle exit as function of particle diameter and process parameters. The distribution of impact velocities was, then, obtained applying to these velocities the bow shock deceleration. These results are to be considered valid only for a substrate very close to the nozzle, since the influence of the SoD is not implemented in the model. Assadi et al. (2011), following a parametric approach, introduced an analytic expression for the impact velocity of the particle, but similarly, the starting point was the particle velocity at the nozzle exit, and no deceleration or acceleration of the particle outside the nozzle was taken into account, neither the SoD influence over the bow shock deceleration.

However, a couple of studies suggests that the SoD influences the dimensions of the stagnation bubble and that the impact of the supersonic jet onto the substrate occurs with complete absence of bow shock for sufficiently large SoD. For example, Pattison et al. (2008) showed that the bow shock disappears at large SoD, without negative effect on the deposition; on the contrary, at small SoD, the bow shock deceleration strength is high and the deposition efficiency is reduced. Yet, the meaning of small and large SoD is not explored in this work. In the same way, Li et al. (2008) found a maximum in the deposition efficiency of copper particles in dependence of the SoD, meaning that the SoD strongly affects the deceleration of the impacting particles.

The possible cause of variation of bow shock size with the SoD should be traced to the turbulent mixing between the discharging jet and the external atmosphere. The final effect of this mixing is that, with the increase of the SoD, the jet reduces its velocity at impingement, while its density, temperature and composition tend progressively to that of the external atmosphere. One of the aims of the present study is to model the influence of the SoD on the bow shock height and, as a consequence, on the distribution of particle impact velocities. Additionally, the distributions of particles