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Modelling and simulation of plasma spraying process with a use of Jets&Poudres program

S. Kotowski*, J. Sieniawski, M. Góral
Rzeszow University of Technology,
Al. Powstanców Warszawy 12, 35-959 Rzeszów, Poland
* Corresponding e-mail address: skot@prz.edu.pl

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Analysis and modelling

ABSTRACT

Purpose: Plasma spraying is one of the basic methods of coating deposition used in many branches of industry, especially in aviation and power industry. The process is applied in the aircraft engineering for obtaining the sealing coats, anti-abrasive coatings and, above all, metallic layers, ceramic layers as well as thermal barrier coatings. The comprehensive characterisation of the plasma spraying process requires taking into consideration 50-60 parameters, which confirms its complexity. The purpose of this article is to describe the functioning of the program, presentation of its simulation capabilities, including the parameters of the plasma spraying process, which can be controlled in the program.
Design/methodology/approach: The authors present in the article the model of plasma spraying process and describe the simulation of the process with a use of Jets&Poudres software. It is based on the GENMIX code (GENral MIXing) developed by B. Spalding and S. Patankar for analysis of the two-dimensional, parabolic flows characterized by large values of Reynolds and Péclet number.
Findings: Jets&Poudres enables tracking the current position, velocity and the fusion process of powder particles as well as conducting the basic analysis of obtained coating formed during the plasma spraying process.
Practical implications: Jets&Poudres enables determination of parameters of plasma spraying process in order to obtain better coating thickness distribution and improve the coating efficiency - ratio between the weight of the spray pattern deposited on a big flat plate and the weight of powder injected.
Originality/value: Jets&Poudres is one of few available tools based on comprehensive model of plasma spraying under atmospheric pressure which makes possible to perform simulation of the whole process.
Keywords: Plasma spraying; APS; LPPS; Modelling; Simulation; Jets&Poudres

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1. Introduction

Plasma spraying is one of the basic methods of obtaining protective coatings - mostly high temperature resistant - in many branches of technology, especially in aviation and power industry. The process is applied in deposition of sealers, anti-abrasive high temperature resistant protective layers, metallic layers and thermal barrier coatings. The plasma spraying process is characterized by a number of significant factors (50-60) which have influence on performance and quality of formed layer [2].

Taking into consideration the physical basics of the process and selection of those factors which significantly influence its kinetics and the coating characteristics is important for development of the process model. Simulation of the plasma spraying process consist in application of those numerical methods which enable solving the equations resulting from the used model.

The availability of the software dedicated to simulate the whole plasma spraying process is limited. One of those tools is Jets&Poudres (available in the Internet for free [1]). The program was created in the SPCTS facility (Science des Procédés Céramiques et de Traitements de Surface) in France on the basis of the GENeral MIXing (Genmix) algorithm developed by B. Spalding and S. Patankar for the analysis of two-dimensional, parabolic flows characterized by large Reynolds and Péclet numbers (Re > 20, Pe > 50) [3].

2. Modelling of plasma spraying method

In this section it is necessary to present in details assumptions and course of own researches to such an extent that a reader could repeat those works if he was going to confirm achieved results. In short papers those information should be given in as short a version as possible.

Characterisation of plasma jet created in plasma gun is one of most significant factors necessary for development of the comprehensive model of plasma spraying process. The simulation of plasma plume is based mainly on the theory of viscous flows. Behaviour of such fluid is described by Navier-Stokes equations:

$$\rho\frac{Dv}{Dt} = \nabla\cdot\boldsymbol{\sigma} + \boldsymbol{f}, \qquad \frac{D}{Dt} := \frac{\partial}{\partial t} + v_1\cdot\frac{\partial}{\partial x} + v_2\cdot\frac{\partial}{\partial y} + v_3\cdot\frac{\partial}{\partial z}, \tag{1}$$

where: ρ - fluid density, $\mathbf{v}=[v_1,v_2,v_3]$ - fluid velocity vector, D/Dt - Stokes operator, $\boldsymbol{\sigma}$ - stress tensor, **f** - term related to other forces in the body, t - time, x, y, z - space coordinates.

Jets&Poudres program applies the two-equation turbulence models (K-ε and K-ω) for description of plasma jet during the plasma spraying process. Those models are based on time-averaged Navier-Stokes equations (Eq. 1). Two additional equations are used for characterization of fluid (plasma) flow; equation describing transport of turbulence kinetic energy (K) and respectively, dissipation rate of turbulence kinetic energy ε (K-ε models) or specific dissipation rate of turbulence kinetic energy ω (K-ω models). The K-ε models are one of the most popular methods of description of turbulent fluid flows [4-11]. The equations constituting K-ε models (Standard K-ε, RNG K-ε, Realizable K-ε) and K-ω models (SST-K-ω, Wilcox model) are presented and described on „CFD Online" Web page [12].

The next important elements of model development of the plasma spraying process are the characterization of in-flight powder particles and their description after impingement on the base material. In order to achieve that, it is necessary to determine the velocity and trajectory of powder particles as well as analyse the process of heat exchange with the plasma jet and the change of state of the powder particles.

Momentum and energy transfer are the basic interaction mechanisms between powder particles and plasma jet. The firs type of interaction can be used for calculating the velocity and determination of the trajectory of powder particles. The analysis of the energy transfer between the powder particle and plasma jet can be applied for description of temperature- and phase changes of powder particles.

Analysis of forces which act on the in-flight powder particles and significantly influence their motion make possible to describe the momentum transfer between powder particles and plasma jet.

$$m_{Part}\cdot\frac{dv_{Part}}{dt} = F_{Drift} + F_{Grav} + F_{Mass} + F_{Rot} + F_{Basset} + F_{Th} \tag{2}$$

where: $\mathbf{v}_{\mathbf{Part}}$, m_{Part} - velocity and mass of powder particles, $\mathbf{F}_{\mathbf{Drift}}$ - drift force, $\mathbf{F}_{\mathbf{Grav}}$ - gravitational force, $\mathbf{F}_{\mathbf{Mass}}$ - added-mass force, $\mathbf{F}_{\mathbf{Rot}}$ - force created by particle rotation, $\mathbf{F}_{\mathbf{Basset}}$ - Basset force, $\mathbf{F}_{\mathbf{Th}}$ - force created by temperature gradient in the plasma plume, t - time.

Interaction between powder particle and plasma jet can be divided into four stages: heating up the solid particle, fusion of the particle, heating up of melted particle and evaporation of its material. The temperature of powder particle before fusion (T_{Part}), melting mass fraction ($X_{Part,Liquid}$) and particle diameter during evaporation process (D_{Part}) are described by following equations:

$$\begin{cases} \dfrac{dT_{Part}}{dt} = \dfrac{6\cdot Q}{\pi\cdot D_{Part}{}^3\cdot C_{S,Part}\cdot\rho_{Part}} & (3)\\[2ex] \dfrac{dX_{Part,Liquid}}{dt} = \dfrac{6\cdot Q}{\pi\cdot D_{Part}{}^3\cdot\Delta H_{Melt}\cdot\rho_{Part}} & (4)\\[2ex] \dfrac{dD_{Part}}{dt} = \dfrac{6\cdot Q'}{\pi\cdot D_{Part}{}^3\cdot\Delta H_{Vapour}\cdot\rho_{Part}} & (5) \end{cases}$$

where: T_{Part}, D_{Part}, ρ_{Part}, $C_{S,Part}$ - temperature, diameter, density and specific heat of powder particle, $X_{Part,Liquid}$ - melting mass fraction ($X_{Part,Liquid}$ = 0 - the particle is solid, $X_{Part,Liquid}$ = 1 - particle is fully melted), Q - energy required for heating up the particle, it is a conduction - convection heat energy, Q' - thermal energy lost when vaporizing the particle, ΔH_{Melt}, ΔH_{Vapur} - latent heat of fusion and evaporation for powder particle, t - time [13,14].

At first the process of heating up the powder particle in solid state is described by equation (3). When the particle temperature reaches its melting point, a part of particle material changes its state to liquid - the liquid fraction can be estimated using equation (4). When investigating the process without evaporation of powder material, the molten particles are heated up and its temperatures changes according to equation analogical to eguation (3). When the powder material reaches the boiling point, it can be assumed that the whole heat absorbed by the particle is transformed to latent heat of the phase change process. The decreasing particle diameter during evaporation process can be determined using the equation (5). Reduction of powder particle diameter and mass during the evaporation process influences its acceleration and trajectory.

The model concerning article behaviour and properties used in Jets&Poudres program is based on following assumptions:

1) powder particles have spherical shape,

2) powder particles don't influence the characterisation of plasma plume,
3) only the drift force and gravitational force have significant influence the behaviour of powder particles in plasma jet,
4) powder material is melted but not evaporated in plasma plume.

3. Simulation of plasma spraying method

The models of plasma spraying process implemented in the Jets&Poudres software take into account the spray distance, chemical composition, flow of plasma gases, power and efficiency of plasma gun, diameter of plasma gun nozzle as well as chemical composition material properties and initial movement parameters for powder particles. There is a possibility of selecting the model assuming laminar flow or applying models of turbulent flow of plasma jet (e.g. K-ε and K-ω models). The program allows to calculate i.a. temperature field (Fig. 1a), pressures field and velocity field (Fig. 1b) in plasma jet.

a)

b)

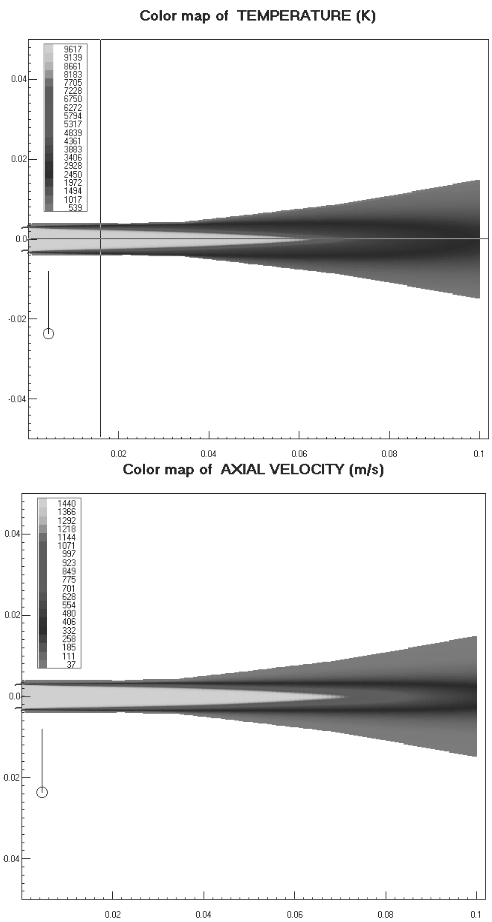

Fig. 1. The exemplary results of temperature field (a) axial velocity field (b) simulation performed with a use of the Jets&Poudres program

Jets&Poudres is able determine the trajectory and velocity in each point, for single powder particle introduced into the plasma jet during the plasma spraying process (Fig. 2). The program calculates also the percent of molten material of the powder particle. It allows to assess if the in-flight particle was completely or partially melted - it influences the splat morphology.

a)

b)

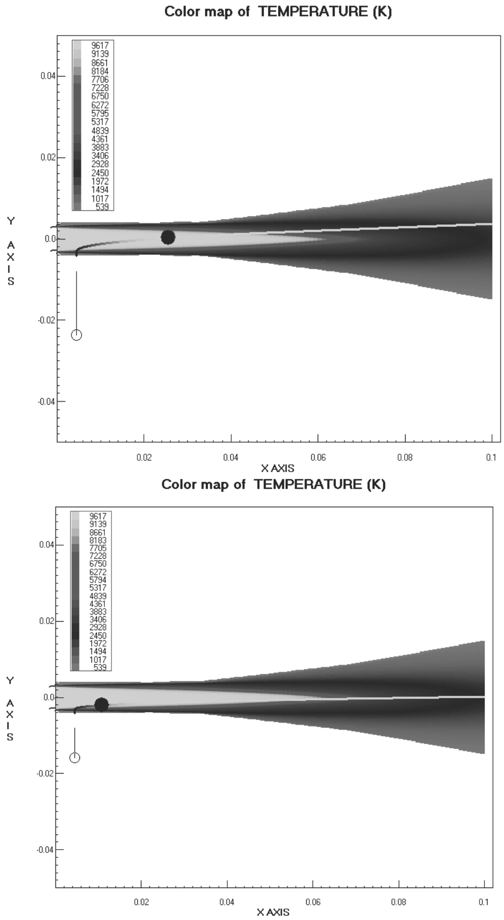

Fig. 2. The exemplary simulation results of movement of Al_2O_3 particle introduced into the plasma jet with velocity of v= 40m/s (a) and v=20 m/s (b) perpendicularly to the jet axis during the plasma spraying process

The simulation of the plasma spraying process with a use of Jets&Poudres program allows to determine suitable material properties and particles size as well as conditions of introducting them into the plasma jet in order to increase the deposition efficiency and reduce the material costs of the process. The authors performed the simulation of single particle movement (v=40 m/s, Fig. 3a) and determined the optimal velocity (v=20 m/s, Fig. 3b) of introduction of the Al_2O_3 powder particle with diameter of and initial temperature of into the plasma plume. The powder particle introduced with this velocity into the plasma jet was deposited in the intersection of jet axis with substrate surface. For velocities lower than and greater than the particle didn't reach the base material. The obtained results allowed to determine the velocity and diameter distribution of powder particles in order to reach optimal deposition efficiency (ratio between the weight of the spray pattern deposited on a big flat plate and the weight of powder injected).

Apart from movement and properties of single powder particle there is a possibility of simulation of the multiple particle deposition process on the surface of base material. There is also possibility of defining the angles under which the powder particles are introduced into the plasma jet as well as the diameter distribution and material properties of particles.

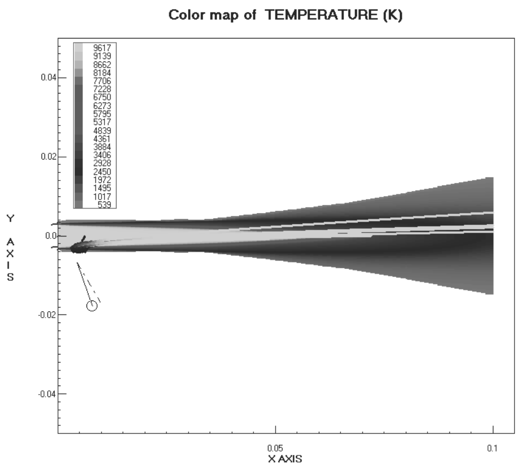

Fig. 3. The result of simulation of multiple Al_2O_3 powder particles introduction into the plasma jet

Authors simulated the deposition process of 1098 Al_2O_3 powder particles on flat substrate surface. Normal distribution of powder diameters was assumed. Jets&Poudres is able to calculate the thickness distribution of obtained coating. The result of preformed simulation is presented on Figure 4.

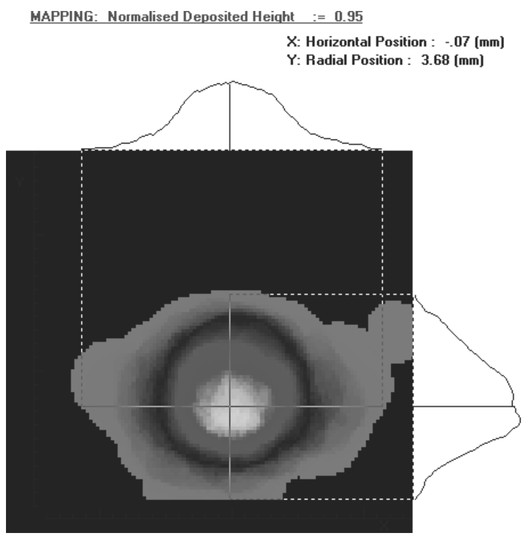

Fig. 4. The result of simulation of introducting 1098 Al_2O_3 powder particles into the plasma jet. The gaussian diameter distribution for the powder particles was assumed

4. Conclusions

Jets&Poudres is one of few available tools based on comprehensive model of plasma spraying under atmospheric pressure which makes possible to perform simulation of the whole process. The additional advantage of the program are open licence (Jets&Poudres is available on-line for free) and simulation speed - the calculation time for single powder particle was of approx. 1 s, and for 1098 powder particles - approx. 8 min. Jets&Poudres enables determination of parameters of plasma spraying process in order to obtain better coating thickness distribution and improve the coating efficiency - ratio between the weight of the spray pattern deposited on a big flat plate and the weight of powder injected.

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