Abstract: The aim of this work is to investigate by means of a 3D time-dependent numerical model a particle stream inside a DC non-transferred arc plasma torch for plasma spraying, in order to analyze the influence of the plasma jet cold gas entrained eddies on the particle behavior and to understand the mechanisms that can lead to a fluctuating and non homogeneous heating of the particle stream.

Keywords: Thermal Plasma, Plasma Spraying, Modeling, Particle

1. Introduction

Thermal plasmas are widely used for spraying applications, due to the high temperature that can be reached inside the arc, the strong heating of the injected powders and their high velocity [1-3]. The DC non-transferred plasma torches are the most common plasma sources used in this kind of application. The inlet cold gas is heated by passing through a nozzle in which a plasma arc is generated between the cathode and the anode. Plasma torches of this kind are characterized by strong fluctuations of the arc due to the anode reattachment phenomena that occur inside the nozzle, due to the flow drag of the anode arc root. This phenomena are clearly time-dependent and three-dimensional. Numerical modeling has been commonly used for understanding and predicting plasma arc properties for this kind of application [4-6], but in order to be able to full predict the spraying process, these models must be improved with powder trajectory and thermal history calculations.

This paper is intended to be a first step in the direction of a fully integrated approach to modeling of the plasma spraying process; results will concern not only the plasma arc characteristics but also the powder characterization in terms of thermal histories and spatial spread and velocity in the post-nozzle region. In order to reduce the computational effort, that in the case of LES is remarkable, loading effects have not been taken into account.

The most accurate numerical approach for particle tracking in an unsteady environment would imply the use of the same time step for particles trajectory calculation and for flow field calculation. Nevertheless, this approach needs a strong computational effort that makes it not suitable for parametric studies on particle heating, since a change on a single parameter (e.g. diameter or material type) would imply a complete restart of the LES simulation. In order to reduce the computational effort, trajectories and thermal histories are calculated using “frozen” fields at every time step. In this way it is possible to check and tune the powders operating parameters using the simplified and less time consuming approach here presented, and leaving to a future deeper investigation the use of an unsteady particle tracking model.

2. Model Description

2.1 Model Assumptions

Our model is based on the following assumptions: plasma gas is pure argon, plasma is uncompressible, in LTE and chemical equilibrium, n.e.c. approach is used for evaluating radiation losses, gravity, Hall current and viscous dissipation are negligible, turbulence can be described by means of a Large Eddy Simulation model.

Torch geometry is sketched in Fig. 1, together with the outside region. The current is set to 200 A and the argon gas is injected at room temperature with a mass flow rate of 4·10^-4 kg/s and a 30° swirl angle.

2.2 Plasma Equations

The model equations includes the conservation of mass and of momentum:

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{u} = 0
\]

\[
\frac{\partial \mathbf{u}}{\partial t} + \nabla \cdot \mathbf{u} = - \frac{1}{\rho} \nabla p + \mathbf{f}
\]

where \( \rho \) is the density of the fluid, \( \mathbf{u} \) is the filtered velocity of the fluid (see next paragraph), \( p \) is the pressure, \( \mathbf{f} \) is the sub-grid scale (SGS) stress tensor; the last term is the Lorentz force.
due to the interaction of the conductive fluid and the electromagnetic field.

The energy equation is solved without taking into account the viscous dissipation:
\[
\frac{\partial h}{\partial t} + \rho \mathbf{u} \cdot \nabla h = \nabla \cdot k \nabla T + \frac{5}{2} \frac{k_b \rho}{e} (j \cdot \nabla h) + Q_j - Q_r
\]
where \( h \) is the enthalpy of the fluid, \( k \) is the thermal conductivity of the fluid, \( k_b \) is the Boltzmann constant, \( e \) is the electron charge and \( j \) is the current density. The second term on the right-hand side of the equation represents the enthalpy transport due to the stream of the conductive electrons. Finally, \( Q_j \) is the energy dissipated in the discharge by Joule effect and \( Q_r \) represents the radiative losses.

Electromagnetic field is evaluated using the vector potential approach:
\[
\nabla \times \mathbf{A} + \mu_0 \mathbf{j} = 0 \\
\nabla \cdot \sigma \mathbf{E} = 0
\]
with \( j = \sigma \mathbf{E} \), \( \mathbf{E} = -\nabla \phi \) and \( \mathbf{B} = \nabla \times \mathbf{A} \).

Cathode sheath is neglected and the current density is imposed on cathode surface using a parabolic profile with a maximum value of \( j = 1.4 \times 10^8 \text{A} / \text{m}^2 \). The anode wall is set at zero potential without any external imposition on the location of the restrike; the model itself predicts the restrike frequency and dynamics. Thermodynamic and transport coefficients used for numerical simulations are those given in [7].

2.3 Turbulence LES model

A Smagorinsky-Lilly Large Eddy Simulation (LES) approach has been used in this work, since the averaging of the physical quantities in LES is space-based instead of being time-based (as in classic RANS methods), as previously done by the authors in [4,5]. The main advantage of LES is that the entrainment of every single cold eddy can be taken into account in the simulation, so allowing the calculation of particle trajectories using non-average flow and temperature fields. In this way it is possible to investigate the effects of cold eddies on the particle trajectory.

2.4 Particle model

A lagrangian model for particle trajectory and heating evaluation has been implemented in the model. Stochastic evaluation of the particle trajectory has been used in order to take into account particle dispersion. Details on the model are omitted here for the sake of simplicity and can be found in [8]. Loading effects have not been taken into account in order to reduce computational effort, making the hypothesis of a sufficiently low particle feed rate. Particles are ideally ejected on the axis of the injection probe, which is located 1 mm downstream the nozzle exit at a radial distance of 5 mm from the axis of the torch, whose nozzle is 8 mm in diameter. The carrier gas is argon injected at 10 m/s. Alumina (Al₂O₃) particles of 30 µm have been injected in the plasma tail at the same velocity of the carrier gas. Melting temperature is taken equal to 2326K. Details on powders properties can be found in [8].

![Fig. 2 Temperature slices [K] of the arc discharge at different time steps in logarithmic scale, cropped at T = 600 K, with superimposed particle stream colored by temperature [K]. The side plot on the right shows the radial coordinate [mm] of a single test particle during its in-fly time [ms].](image-url)
3. Results
The effects of the fluctuations on the particle stream between two arc anode reattachments have been investigated using arc temperature and flow fields predicted from simulations. $t = 0\ s$ is the reference time of the first reattachment.

Discharge temperature is shown in detail in Fig. 2 for different time steps using slices perpendicular to the torch axis inside and outside the nozzle, together with the superimposition of ten particle streams colored by particle temperature. In Fig. 2 a side plot shows the radial coordinate of a test particle stream, in order to give an idea of the off-axis location of the stream during its flight time.

A stream of 30 $\mu$m alumina particles has been injected in the plasma tail in order to show the particle temperature fluctuations as a function of time. Three different particle thermal histories due to turbulent dispersion are shown in Fig. 3 for different time steps, together with the corresponding plasma temperature as seen by the particles in their track. Results show that turbulent dispersion has only a limited effect on particle heating when compared with the influence of the arc shape fluctuations. Temperature of the alumina particles exiting from the domain can range from 1700 K to 2400 K, depending on the instant of injection during restrike.

Fig. 4 shows temperature slices, on planes perpendicular to the torch axis, of the arc discharge at $t = 0.70\ ms$, with superimposed particle streams for 20 $\mu$m, 30 $\mu$m and 80 $\mu$m diameter, respectively. The 20 $\mu$m particle streams fail to penetrate the plasma tail and reach a maximum temperature below 1000 K. The 30 $\mu$m particle streams penetrate deeply in the plasma tail and their trajectories remain near the torch axis. Finally, the 80 $\mu$m particle streams pass through the plasma tail due to the high particle inertia, with short residence time in the hot gas region.

4. Conclusions
In this paper a simple but effective approach for the evaluation of the effects of arc fluctuations on the particle histories and trajectories has been presented and applied to the case of alumina particles of 30 $\mu$m injected in a 200 A argon DC non-transferred plasma.
spraying torch. The use of a LES approach is needed in order to predict fluctuations and cold gas entrainment in the plasma fields in the post-nozzle region, where particles are injected. Results show particle temperature fluctuations up to 700K at the exit of the domain, for this particular spraying torch configuration. Future developments of this work will be directed towards a physical-mathematical model for statistically evaluate several hundreds of particle trajectories and thermal history at every time step for different restrike cycles, in order to predict more realistically the mean particle fluctuations. Loading effect of the particle stream which cools down the plasma will be also investigated. Unsteady particle tracking model, using the same time step for particles and plasma fields, will also be the subject of future investigations.

References