Simulation and experimental studies for plasma spraying applications

M. Baeva, T. Zhu, H. Testrich and R. Foest

Leibniz Institute for Plasma Science and Technology, Greifswald, Germany

Abstract: This work gives an overview of the simulation and experimental studies related to plasma spraying of Al_2O_3 particles employing the plasma torch F4MB-XL (Oerlikon Metco), which is operated in Ar and Ar/H_2. Results in the plasma torch obtained by means of a magneto-hydrodynamic modelling, a particle tracing in the plume region of the torch, and a model of a particle impingement onto the substrate surface are presented along with those from electrical and thermal measurements, and monitoring.

Keywords: Torch, simulation, particle tracing, deposition, measurements.

1. Introduction

The deposition of protective and functional coatings is hugely important to many applications. Such coatings are produced in a great part by plasma spraying. Their quality and properties are closely related to the components of the production chain: the operation conditions of the plasma torch and the characteristics of the electric arc and the generated plasma jet; the feeding of the powder material; the motion and the heating of injected particles in the jet plume; the deposition of the molten particles on the target.

This work is concerned with an overview of the simulation and experimental studies that have been carried out to cover these areas. We present results related to the plasma parameters inside the torch and in the torch plume, the behaviour of the injected material in the plasma jet, as well as the parameters on the substrate surface.

2. Characterization of the plasma torch

A magneto-hydrodynamic (MHD) model along with electrical and thermal measurements have been employed to characterize the direct current (DC) plasma torch F4MB-XL [1] in a steady operating mode. The model couples the La-W cathode and its nonequilibrium boundary layer (NEBL) to the arc plasma, which is considered to be in the state of local thermodynamic equilibrium (LTE). An almost complete description of the model is given in [2] so that here only the main features are presented. The description of the NEBL involves the solution of the balances of energy and electric current density. These balances are solved for a series of values (T_w,U) corresponding respectively to the temperature on the cathode surface and the voltage drop in the NEBL for given the pressure and the work function of the cathode material. The output from this model provides the temperatures of heavy particles and electrons in the NEBL, particle densities, current densities and energy fluxes. These quantities are used to express the heat flux to the cathode surface and the normal current density at the cathode surface j_{wc} as functions of (T_w,U). The model of the cathode and its NEBL solves the heat and current transfer in the cathode for a given total DC current applying the transfer functions $q_c(T_w,U)$ and $j_{wc}(T_w,U)$ as boundary conditions on the edge between the cathode and the arc plasma. The obtained electron temperature and current density along the plasma edge serve as boundary conditions to the MHD model of the arc plasma. The latter solves the Navier-Stokes equations for the conservation of mass, momentum, and energy of the arc plasma in terms of a one-fluid description along with the Maxwell equations for the electromagnetic field. The model provides the distributions of the plasma parameters inside the torch: in particular these are the plasma temperature, the flow velocity, the electric current density and potential, the temperatures in the electrodes. It was found that an appropriate description of the gas flow for Mach numbers beyond 0.3 is essential for the predictive capability of the model.

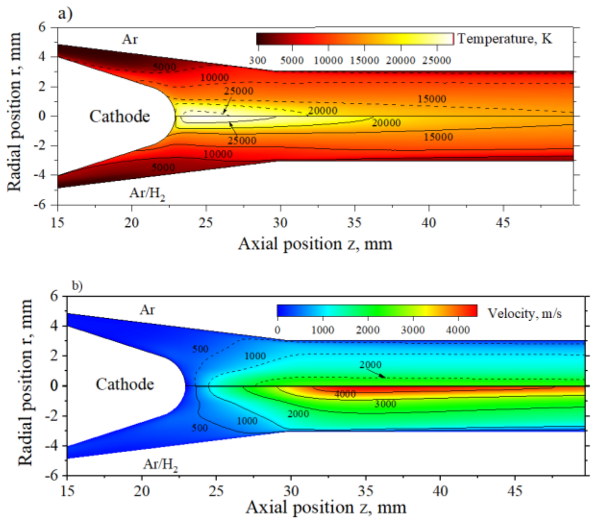

Fig. 1. Distribution of the plasma temperature (a) and flow velocity magnitude (b) in the plasma torch in Ar (40 NLPM) and Ar/H_2 (40/14 NLPM) for a current of 600 A.

Results in Figures 1a), 1b) show respectively the computed plasma temperature and the flow velocity magnitude in the plasma torch for the operation in pure Ar and in an Ar/H_2 mixture (40/14 NLPM, normal litter per minute) for an DC arc current of 600 A. The MHD model predicts a more extended hot region in the jet in axial and radial directions, and a significantly higher velocity magnitude on the jet axis in the presence of hydrogen. The axial jet velocity at the torch exit in the Ar/H_2 mixture is by a factor of about 1.7 higher than in pure argon. This effect might be not quite obvious since the admixture of hydrogen increases the flow rate by a factor of 1.35. However, the mass density of the mixture decreases in the Ar/H_2 mixture. The arc voltage and the thermal efficiency of the plasma torch are shown in Fig. 2 as a function of the gas flow rate. Notice that the total arc voltage includes the voltage drop

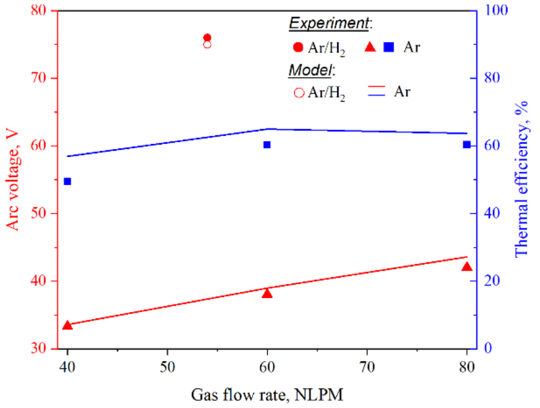

Fig. 2. Arc voltage and thermal efficiency of the plasma torch as a function of the gas flow rate for a current of 600 A from modelling and experiment.

in the NEBL, which amounts to slightly above 8 V at the current value of 600 A. Experimental and modelling results agree well. Notice the significantly higher voltage in presence of hydrogen. As a result, the electric power of the torch increases in comparison to the operation in pure argon at the same current level. The admixture of hydrogen increases the plasma enthalpy due to the dissociation of hydrogen molecules.

Experimental studies related to the process of erosion of the cathode have indicated a mass loss of about (0.7-0.8) mg per one hour of operation. Modelling studies on the transport of tungsten atoms released from the cathode have been carried out [3]. They show that the ionization of tungsten atoms occurs in a distance of a few micrometers from the cathode surface. The tungsten ions are driven by the electric field towards the cathode. The removal of tungsten species from the ionization layer of the cathode needs a mechanism that works beyond the edge of the ionization layer. Such mechanism is provided by reversal of the electric field.

3. Behaviour of the injected particles in the jet plume

The plasma jet in the plume region in pure Ar differs from those in the mixture Ar/H_2. In particular, the decrease of the temperature along the jet axis is steeper in the mixture. The temperature decrease is caused by the large increase in the effective thermal conductivity of the mixture Ar/H_2. The axial component of the jet velocity in the mixture is higher than that in pure argon over the whole distance.

The behaviour of the powder material injected into the plume of the plasma jet is studied by means of a particle tracing model along with a turbulent model of the plasma jet in the plume region [4] and monitored with the Tecnar Accuraspray-g3c system [5] to obtain the temperature and the velocity of the injected particles. This system provides an accurate and reliable observation of the spray plume. The data is collected on a real-time basis and undergoes a computer processing that enables both a real-time and an offline analysis. Particles made of Al_2O_3 are injected into the plasma jet. Their size distribution has been measured applying the static light scattering technique combined with a Mie scattering model. A normal distribution with a mean value of 52.9 µm and a standard deviation of 20.5 µm is adopted for use in the model of particle tracing.

This model solves the equation of motion of particles with the account for the drag, gravity, and the thermophoretic forces. Each particle is released from a randomly chosen position on the injector exit under a randomly chosen polar angle in the range (-10°, 10°), and a velocity expressed as a function of the average velocity of the carrier gas and the injector radius. The trajectories of the particles injected into the plasma jet are followed until their impact onto the substrate surface, which is placed in a distance of 12.3 cm from the torch exit. The velocity and the position of a particle are obtained by integrating the equation of motion. The temperature is obtained by solving the heat balance of a particle with the account for the convective heat transfer between the particle and the fluid, and the radiative heat transfer further afield from the particle.

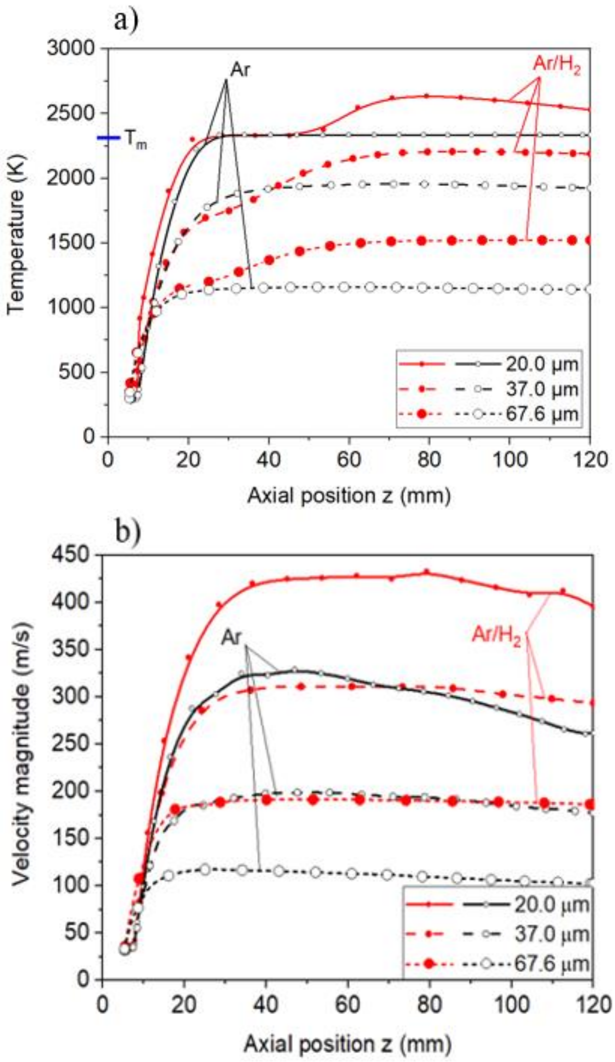

Fig.3. Temperature (a) and velocity magnitude (b) of particle of various size injected into the plasma jet along the jet axis in Ar and in Ar/H_2.

Fig. 3 shows respectively the computed temperature (a) and velocity (b) of particles of different size (small, middle, large) as a function of the axial position in Ar and Ar/H_2. The operating conditions in the plasma torch are those in Fig. 1. Small particles are rapidly heated. Their temperature reaches the melting point T_m (2327 K) in both Ar and Ar/H_2. Once T_m is reached, the temperature remains constant but start to rise in Ar/H_2 due the effect of fluctuating heating [4]. The heating of the injected particles is dominated by the convective heat transfer between the particles and the fluid. The radiative heat loss is of minor importance. The convective heat source exhibits a well pronounced spatially fluctuating structure due to the enhancement of the thermal conductivity resulting from dissociation and ionization in temperature range of 2500–4000 K and 13000–14000 K, respectively. Small particles undergo a repeated heating in Ar/H_2 in contrast to pure Ar. The temperature of particles of a middle and a large size do not reach the melting point neither in Ar nor in Ar/H_2. Furthermore, the less inert small particles reach larger velocities than particles of a middle and a large size. Downstream the plasma jet, the jet velocity start to decrease that leads to a direction change of the drag force. As a result, the particle velocity also decreases. This effect is stronger pronounced in Ar. The computed temperature and velocity of the particles injected into Ar/H_2 agree well with the data shown in Fig. 4, which is obtained by means of monitoring during an operation time of 40 hours.

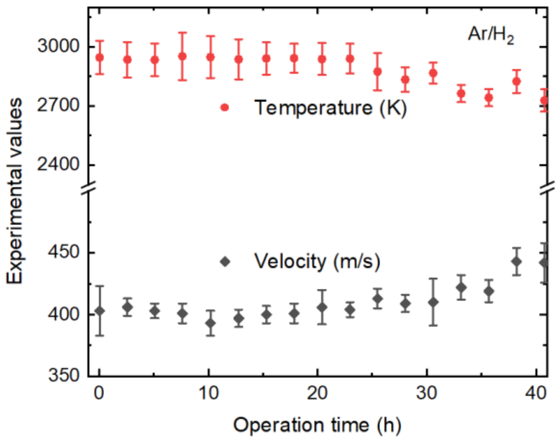

Fig. 4. Temperature and velocity of particles obtained by monitoring with the Tecnar Accuraspray-g3c system.

4. Deposition and build of the coating

The particle trajectories ending on the substrate surface indicate the conditions for deposition. The K-Sommerfeld number is evaluated accounting for the diameter, the mass density, the incident normal velocity, the surface tension, and the viscosity of the particle. The values of the K-Sommerfeld number are used to characterize the conditions on the surface of the substrate according to the established classification: a rebound with $K < 3$, a deposition with $3 < K < 57.7$ and a deposition with splashing $K > 57.7$.

The distributions of the K-Sommerfeld number on the substrate plane under the operation conditions with Ar (40 NLPM) and Ar/H_2 (40/14 NLPM) for a current of 600 A are shown respectively in Figures 5a) and 5b). The values of the K-Sommerfeld number in pure Ar are lower than those in Ar/H_2. In both cases, however, conditions corresponding to a deposition with splashing are predicted for (x,y) positions, which are close to the jet axis.

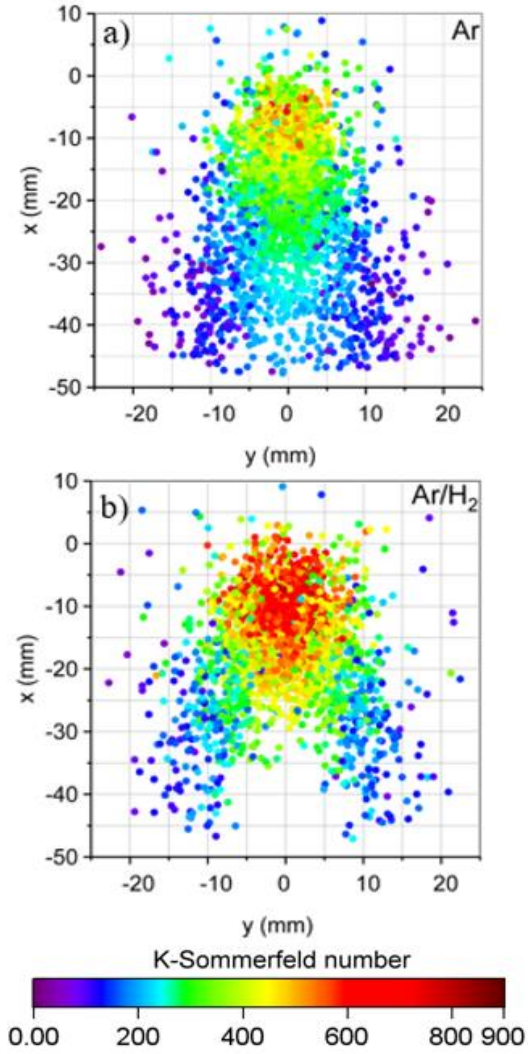

Fig. 5. Distributions of the K-Sommerfeld number on the substrate plane in a) pure Ar (40 NLPM) and in b) Ar/H_2 (40/14 NLPM) for a current of 600 A.

A model of a particle impingement on the substrate is developed that applies the results of the particle tracing model for the particle position, temperature, and velocity. In this model, specific accumulator boundary condition is applied to account for the growth and formation of the coating under the conditions in the Ar and Ar/H_2 plasma jets. The accumulator feature transmits data from the particle to the boundary crossed. The accumulator defines a specific variable in the boundary elements assigned to the surface of the substrate. This variable is discretized by means of a shape function to take a constant value within a mesh element, but the value is allowed to change in the neighbour elements. Every time a particle collides with a boundary element, the value of the accumulating variable in that element is raised in accordance with the amount of the user-defined source term for the incident particle. In order to estimate the coating thickness resulting from a single droplet, the impingement of single droplet on the substrate has been simulated applying the level set method, which traces the shape change and the free interface evolution between the liquid and the gas phases. The model has been validated by a comparison of the spreading factor and the apex height with reported measurements for a published case. The model provides the information of the coating thickness caused by a single droplet and applies it as a source term for the next released particles. The release of 3000 particles is found to represent statistically significant results. A modelling of the coating building layer by layer that presumes a change in the model's topology is out of the scope of the present work. The predicted coating buildings corresponding to the operating conditions presented in this work are shown in Fig. 6. They correlate with the results in Fig. 5. The particles injected and molten in the Ar jet plume reaching the substrate occupy a larger area and build a coating with a smaller thickness than in the operation in the gas mixture Ar/H_2.

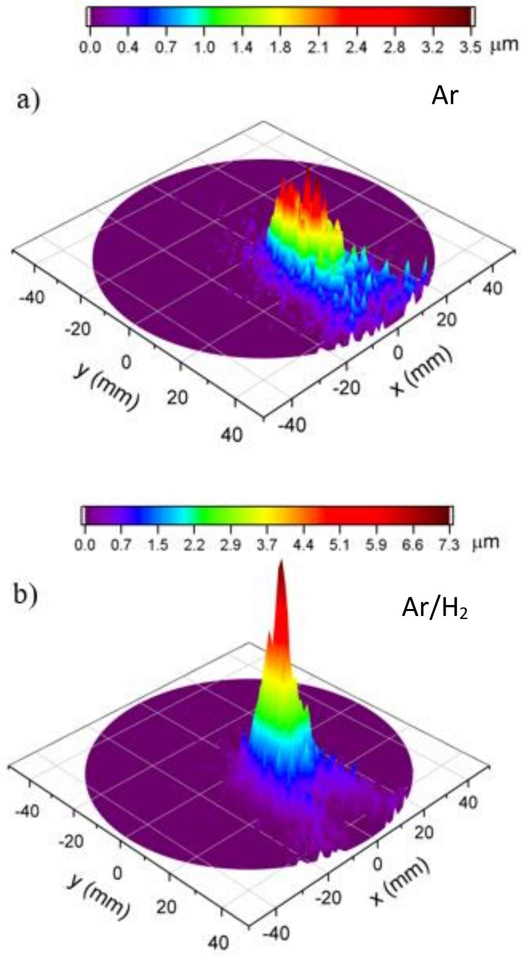

Fig. 6. Computed coating building in a) Ar (40 NLPM), b) Ar (40NLPM) /H_2 (14 NLPM).

5. Conclusions

The plasma parameters, the electric and thermal characteristics, and the erosion of the cathode of the DC plasma spray torch F4MB-XL have been studied. Results based on a model coupling the cathode and its NEBL and the plasma in the state of LTE agree well with experimental findings concerning the electric and thermal characteristics of the torch. A more extended hot region in the jet in axial and radial directions, and a significantly higher velocity magnitude on the jet axis are obtained in the Ar/H_2 mixture in comparison to pure Ar.

The presence of the molecular gas (H_2) leads to a higher jet velocity, in particular at small distances from the torch exit, and a steeper decrease of the plasma temperature beyond the torch exit in comparison to pure Ar. The temperature decrease is caused by the large increase in the effective thermal conductivity of the mixture Ar/H_2.

The behaviour of Al_2O_3 particles injected into the plume region of the plasma jet and their impingement on the substrate surface have been studied in the framework of a particle tracing and a particle accumulation models. Based on the temperatures and velocities of the particles reaching the substrate, the K-Sommerfeld and the thickness of the coating are computed. Close to the torch axis, a regime of a deposition with splashing is predicted both in Ar and in Ar/H_2. The covered area in Ar is larger but the thickness of the coating is smaller than in Ar/H_2.

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7. References

[1] F4MB-XL BRO-0006.6 Atmospheric Plasma Spray Solutions (2016) Oerlikon Metco, Switzerland.

[2] M. Baeva, T. Zhu, T. Kewitz, H. Testrich, R. Foest, Journal of Thermal Spray Technology, **30**, 1737 (2021).

[3] M. Baeva, M. S. Benilov, T. Zhu, H. Testrich, T. Kewitz, R. Foest, Journal of Physics D: Applied Physics, **55**, 365202 (2022).

[4] T. Zhu, M. Baeva, H. Testrich, T. Kewitz, R. Foest, Plasma Chemistry and Plasma Processing, **43**, 1 (2023).

[5] Thermal spray monitoring solution (2022) Montreal, Canada.

[6] C. Escure, M. Vardelle, P. Fauchais Plasma Chemistry and Plasma Processing, **23**, 185 (2003).