New powder port holder geometry to avoid lump formation in APS.

I. Choquet[1], S. Björklund[1], J. Johansson[2], J. Wigren[2]

[1]*Department of Technology, Trollhättan/Uddevalla University, Trollhättan, Sweden*

[2]*Volvo Aerospace Corporation, Trollhättan, Sweden*

Abstract

A new geometry of the powder port ring holder used in atmospheric plasma spraying has recently been designed to avoid lump formation, and successfully tested for a set of process parameters associated with Ni-5Al powder used in production to form bond coat [1]. But with ZrO_2 powder used to made top coat, improvements were not enough satisfactory. Here, we investigate numerically the cause of the remaining defects, and further improve the ring geometry to prevent lump from forming in any part of the coating.

Keywords

1. Introduction

During atmospheric plasma spraying (APS), powder is injected into a plasma jet, melted and deposited onto a substrate. Under standard operation conditions, a back-stream of powder may return to the spray gun, leading to clogging of the nozzle wall. Under certain operation conditions a dramatic increase of clogging frequency can be observed [2]. Typically, this occurs when the carrier gas flow rate is increased above some limit to built-up coatings with enhanced tensile bond strength. When clogging occurs during operation (see figure 1a), the powder clogged on the nozzle or on the end piece of the spray gun aggregates in larger droplets, which are liquid due to the high wall temperature. The droplets are pulled by gravity, get loose and are ejected into the plasma jet. They cause disturbances in the spraying process, resulting in blisters and lumps being generated in the coating (see figure 1b). As these coating defaults are unacceptable, the damaged work-piece must be stripped and re-coated.

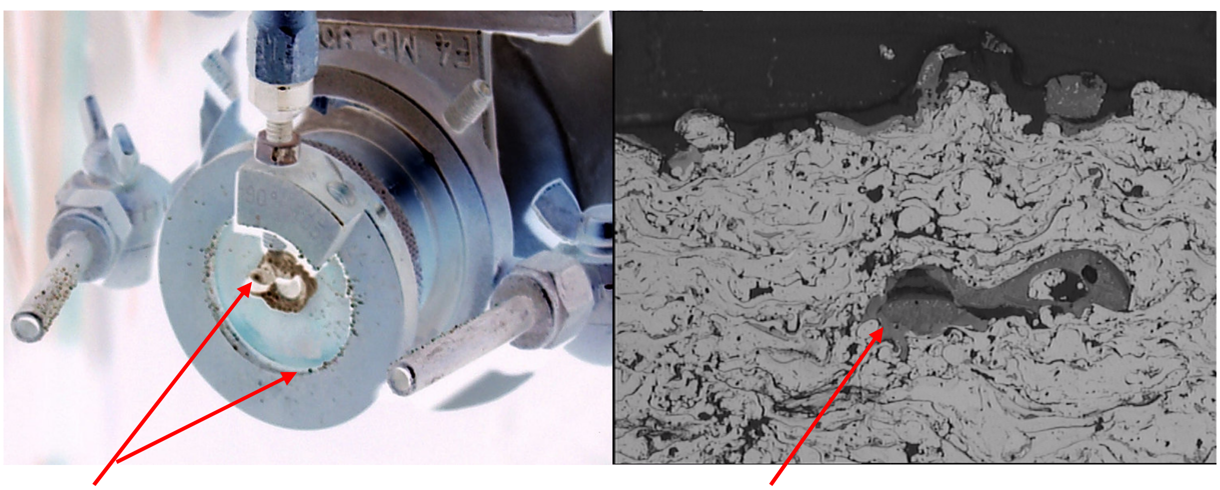

Fig. 1: a) Nozzle wall of a spray gun with traces of clogging that can be observed after operation. **b)** Optical microphotographs; 768x576 µm. Microstructure for a ZrO_2 top coat sprayed with 32 slpm of argon through the powder port ring holder.

A previous study was focused on the understanding of the cause of lump formation, and the development of a solution for avoiding it [1]. The coating baseline used in this investigation was a standard Ni-5Al one used in Volvo Aero production, operating with an F4 atmospheric plasma spray gun manufactured by Sulzer Metco Ag (Wholen Switzerland). This spray gun is equipped with a Sulzer Metco annular holder ring with one or two threads for assembly of up to two powder injectors, figure 2a. The ring is fixed at the nozzle exit; the powder is thus injected downstream the nozzle.

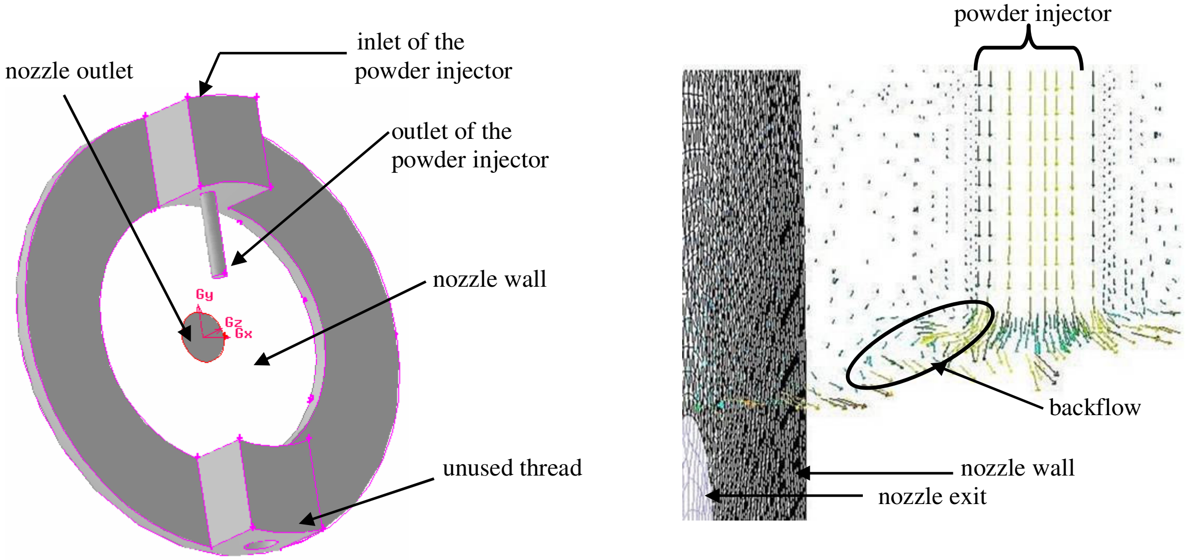

Fig. 2: **a)** CAD representation of a ring with two powder port holders, only one powder port injector, **b)** velocity vectors (calculated numerically with Fluent 6.1) showing the carrier gas backflow at the powder pipe outlet (the plasma flow is not plotted here).

Numerical simulations showed that beyond some critical value of the carrier gas rate, the carrier gas starts expanding towards the nozzle as it exits the injector, figure 2b, and entrains some powder particles. The solution proposed in [1] to prevent this backflow of powder from clogging the nozzle wall consisted in applying a screen between the nozzle wall and the powder pipe injector. The intention was to divert from their path the small fraction of powder flowing backwards, while keeping the coating quality. For this purpose, a new geometry of the powder port ring holder has been designed. It allows the injection of a gas through the ring to form a protective layer in the vicinity of the nozzle wall. When properly formed, this gas layer prevents the powder back-stream from reaching the nozzle wall and thus from initiating lump formation.

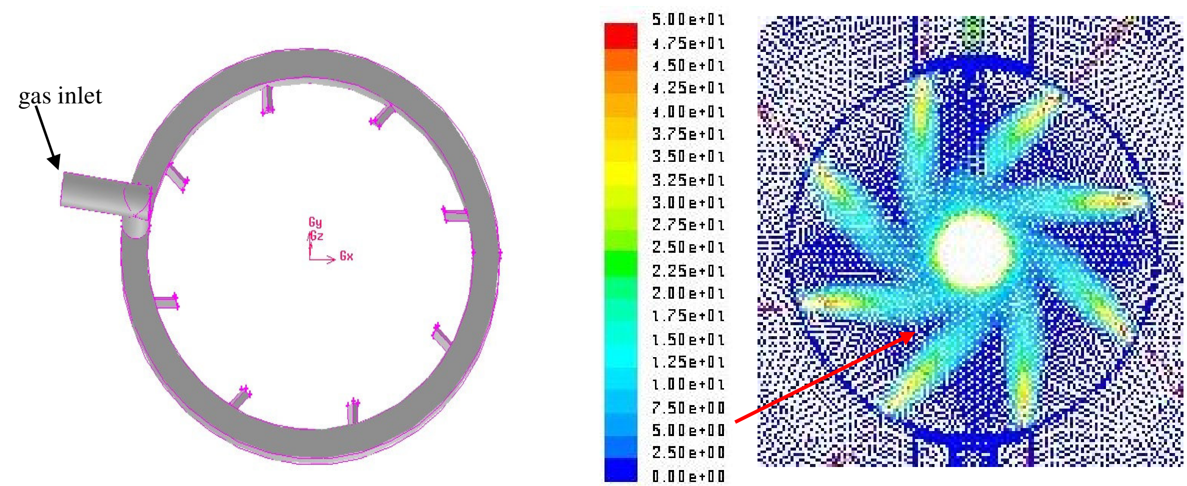

Fig. 3: **a)** CAD representation of the channels allowing to inject the protective gas layer through the powder port ring holder, **b)** velocity vectors of the protective gas layer formed at the nozzle wall (calculated numerically with Fluent 6.1) showing areas (red arrow) hat should be further protected (the plasma flow is not plotted here).

The new ring has been designed in [1] starting from a standard annular powder port ring holder. It has been made by milling grooves in a Sulzer Metco ring with two threads, figure 2a, to form a path for the gas layer injection. When sealing the ring on the nozzle exit, the grooves result in channels, plotted figure 3a. They link the pressurized gas inlet, via a circular channel of rectangular section (1 mm x 3 mm), to eight gas channels of triangular section (right isosceles of base 1.8mm) opening on the inner radius of the ring. The eight inner gas injection channels are evenly angularly distributed along the circumference of the ring. They are oriented along a non-radial direction, such that the injected gas flows in the close vicinity of the outer periphery of the plasma jet, as illustrated by the velocity vectors of figure 3b. This orientation allows avoiding any direct interaction between the gas injected through the ring and the plasma jet. So the protective gas layer should: *i*) prevent from lump formation in the coating, *ii*) not modify the properties of the powder particles prior to impact on the substrate (velocity, temperature, oxidation, etc.) and thus *iii*) preserve the coating quality.

These properties have indeed been successfully verified experimentally when spraying a bond coat on Titanium coupons with the commercially available powder NiAl Amdry 956 from Sulzer Metco, [1]. No lump was observed when using the new ring with a gas rate of 32slpm to form the protective layer. No difference was noticed when using a protective gas layer of argon or air. The measured properties of the coating microstructure remained within the required quality range.

Other experimental tests have been carried out building the top coat with the commercially available powder ZrO_2 Amperit 827.873 from HC Starck. When sprayed with a standard ring, this powder leads to more severe clogging problems than NiAl Amdry 956. Using the new ring and the same gas flow rate as for the bond coat, a significant reduction of the number of lumps was reached. But this improvement was not sufficient since lumps could still be observed in some coupons, as illustrated figure 1b. ZrO_2 Amperit 827.873 is characterized by particles of smaller size than NiAl Amdry 956. Plotting the protective gas layer formed at the nozzle wall (such as the velocity vectors calculated numerically with Fluent 6.1, figure 3b) we can observe, in the vicinity of the plasma jet, areas of the nozzle wall that are poorly protected by the gas layer. So we assumed that the finest powder particles could still find a path through these weakly protected areas. The purpose of this study was thus to further optimize the geometry of the channels through the ring in order to prevent lump from forming in the coating when spraying powder lots containing very small particles. The two constraints we fixed are: to maintain the quality requirements for the coating and design a solution based on a standard annular powder port ring holder.

2. Simulation model

APS processes are composed of three separate sub-processes: the plasma generation by an arc discharge [3], the plasma/powder particle interaction, and the formation of the coating [4]. In this work the plasma generation was modeled by imposing profiles at the nozzle outlet, and the plasma/powder particle interaction was calculated up to the substrate location. The models used to simulate both the atmospheric plasma and the powder particles are summarized in [5]. They have been widely studied and validated by comparisons with experimental data; related references are also given in [5].

Three species were taken into account in the calculations: the plasma gas, the surrounding air and the carrier gas. The plasma gas was formed by the ionization of a mixture of argon and diatomic hydrogen (here 24.5% of H_2 in volume). The carrier gas was pure argon. The gas used to form the protective layer at the nozzle wall was either argon or air. Each of these gases was supposed to be in local thermal and chemical equilibrium.

The system of equations governing these fluids was the complete set of turbulent Navier-Stokes equations. The turbulence closure was a k-epsilon model in its RNG formulation, supplemented by a corrective term for the k-conservation equation [6]. Quantities such as the transport coefficients were derived from kinetic theory as in [7]. This system was solved using a finite volume method (Fluent 6.1, [8]) and numerical schemes of second order accuracy in space.

The computational domain was 3-dimensional and started from the wall at the exit of the plasma gun. It included the powder port ring holder fixed at the nozzle outlet. The geometrical dimensions were the same as in [1].

The boundary conditions at the nozzle exit were imposed profiles of temperature, velocity, turbulence kinetic energy and dissipation rate. Their expressions are detailed in [1]. The maximum temperature was $T_{\max} = 12575$ K and the maximum velocity $U_{\max} = 2167$ m/s. These quantities were derived from the

operating conditions of the arc generator, as explained by Nylén [5]. The boundary equations for the turbulent kinetic energy and the dissipation rate are also reported in [5].
Pure argon was injected through the inlet of the powder injector. This boundary condition was set assuming a constant temperature of 300 K and a parabolic velocity profile corresponding to an average velocity of 26.2 m/s for the figures presented here. Concerning the hole of the ring that was not occupied by a powder port, the boundary condition was, as for the surrounding, air at rest and 300 K. The wall of the nozzle was assumed to be at a constant temperature of 1000 K.
The powder feed rate was 54 g/min. The particles were modeled as described by Nylén [5]. However, the calculations did not account for all phenomena involved such as vaporization or oxidation of the particles. This powder feed rate is low enough to avoid any loading effect. A weak coupling between plasma and powder particles was thus retained: heat and momentum were transferred from the plasma to the particles, but the effect of the particles on the plasma was neglected.

5. Numerical results

The first change we did to obtain a more extended protective gas layer around the plasma jet at the nozzle wall was to increase the number of triangular channels (from 8 to 16), reduce their section area by two, and keep the same total inlet gas flow rate. As illustrated by the argon mass fraction, and the argon velocity vectors, figures 4a and b, the evenness of the protective gas layer gets worst than with only 8 triangular channels. Similar disappointing results are obtained with air rather than argon to make the gas layer.

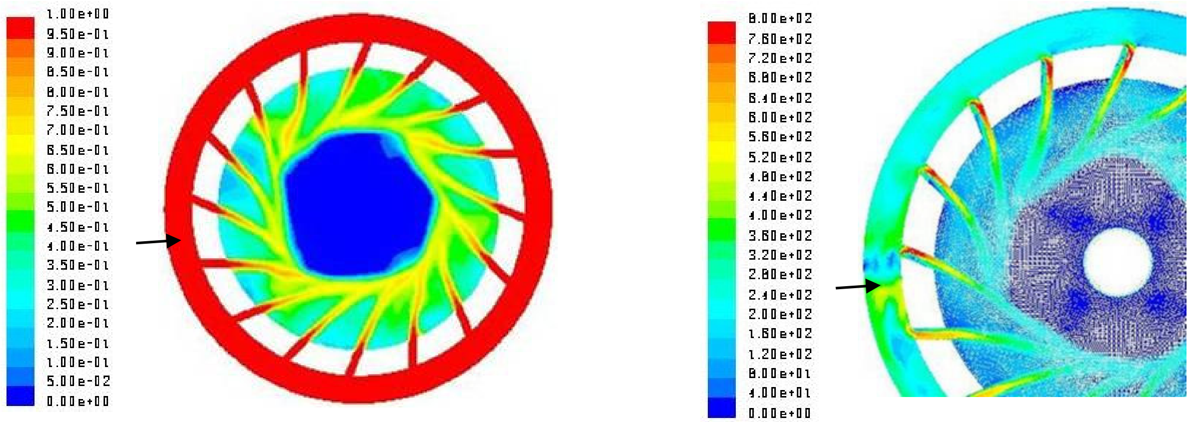

Fig. 4: Protective gas layer made of argon at the nozzle wall (calculated numerically with Fluent 6.1) with 16 triangular channels. The arrow indicates the location of the gas inlet. **a)** argon mass fraction, **b)** velocity vectors (zoom; the plasma flow is not plotted here).

We observe that the gas layer is far away from the plasma jet. The gas jets leaving the triangular channels vary significantly from one channel to the next. This non-uniformity is already important at the junction between the circular channel and the triangular ones.
So we did a second change: inject the gas through two inlets rather than only one. The gas inlets are located on the circular ring, symmetrically, each being equidistant from two neighboring triangular channels. This modification results in the gas flows at the exit of the triangular channels being more similar. Then, the central area (i.e. at the center of the nozzle wall) that is not covered by the protective gas layer becomes circular, as required. However its radius is twice larger than the nozzle exit, so the screen extension is not sufficient to prevent powder particles from reaching the nozzle wall.
A part of the kinetic energy given to the gas at the inlet is indeed lost on the way through the ring. This loss is here too large to form an efficient protective gas layer. The channels used here are short. Many changes occur along the gas path though the ring: in direction, in shape, and in size. The minor losses are thus more important than the major ones. But they can be reduced at various levels. For instance by changing the bending angle of the pipe for gas injection into the circular channel from 90 degrees to 45 degrees, and adjusting properly the distance from the bended edge to the circular channel, figures 5a and b. An additional way to reduce losses is to force the gas to flow mainly along the external radius of the circular channel (which is smooth), rather than the internal one (that contains all the triangular channels inlets). This can be achieved inserting a conical shape in the circular channel, on its internal side, and vertically aligned with the

injection pipe (see figure 6.a). In this way the turbulent flow is confined to the vicinity of the connection between the inlet channel and the circular channel, figure 6.b. Notice that the injection pipe bend angle, the distance from this bend to the circular channel, the size and location of the conical shape are dependent parameters.

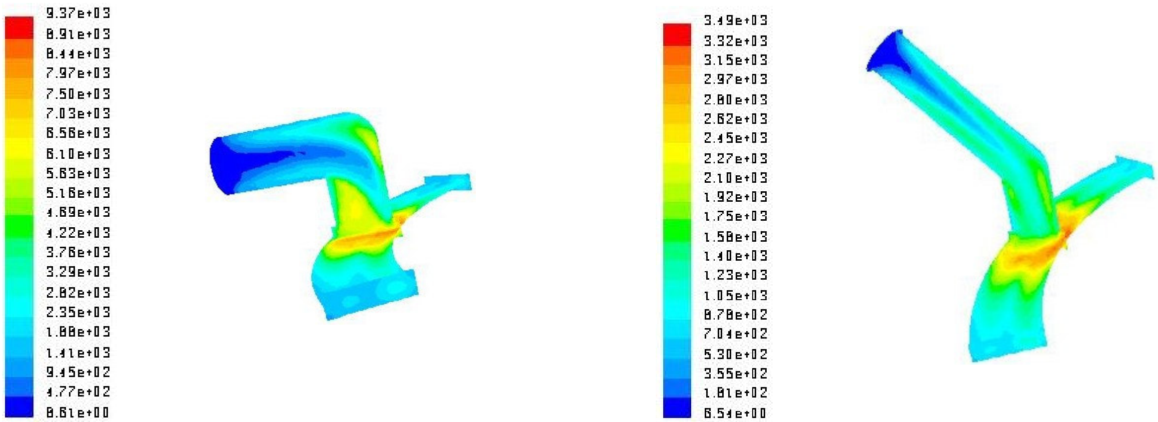

Fig. 5: Turbulence intensity in the pipe for gas injection and a section of the circular channel for a gas injection pipe bended at **a)** 90 degrees, **b)** 45 degrees.

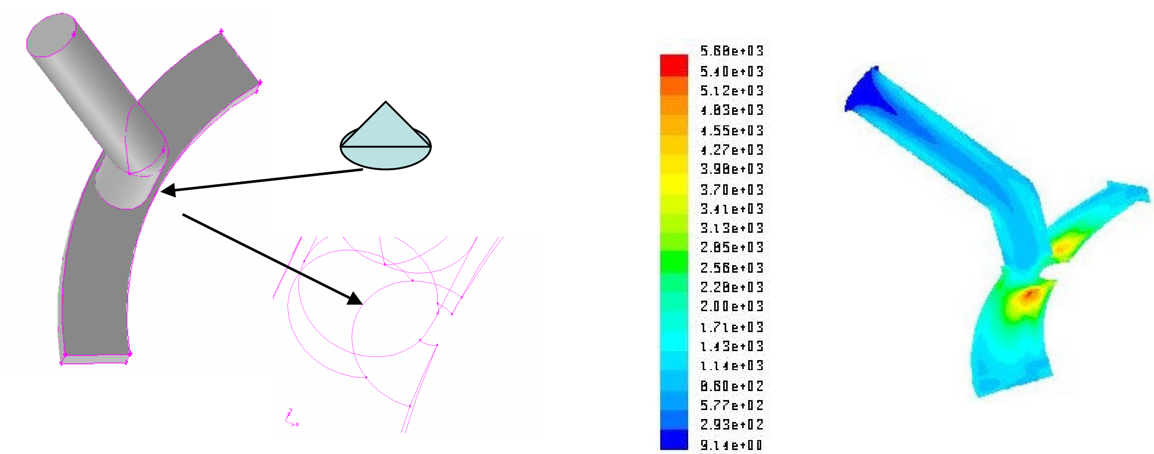

Fig. 6: **a)** Schematic representation of the conical shape inserted at the junction between injection channel and circular channel to redirect the flow, **b)** turbulence intensity in the pipe for gas injection and a section of the circular channel obtained with the channels geometry 6.a.

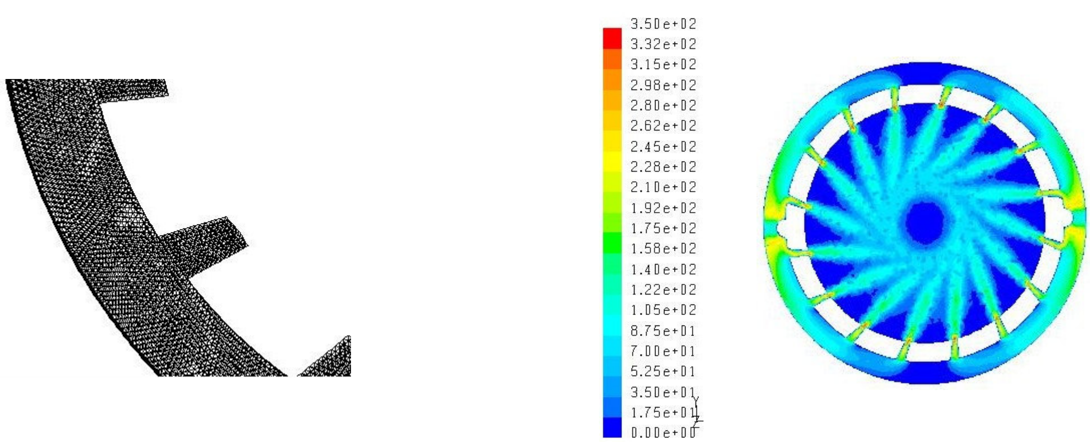

Fig. 7: **a)** A section of the circular channel and a triangular convergent channel, **b)** velocity vectors (zoom; the plasma flow is not plotted here) obtained with the modified geometry.

Unfortunately these changes are not enough to sufficiently reduce the losses. To go further we could also use more than two pipes for gas injection through the ring, but this does not seem to be very convenient. We could also change the section of the circular pipe, from a rectangle to a square, but this is not consistent with our whish to use a standard ring. A thicker ring would indeed be needed. Another source of loss is the large difference in sections between a triangular channel and the circular one. For this reason, the triangular channels are instead modified by increasing regularly their section in the direction of the circular ring. This last modification reduces losses, also accelerates the gas flow since the triangular channels now act as nozzles. As a result, the protective gas layer becomes sufficiently extended to cover the nozzle wall up to the vicinity of the plasma jet, figure 7.b.

These modifications result in a gas layer that better screens the nozzle wall between the powder injector outlet and the plasma jet. The non-radial orientation of the triangular channels is determined so that plasma jet and protective gas layer do not directly interact. The numerical results show that the properties of the powder particles (such as velocity, temperature) prior to impact with the substrate are kept unchanged (when using or not the protective gas layer). During preliminary experiments, no lump formation could be observed in top coats sprayed with the new system of 16 channels through the ring. Other experiments are in progress to further validate this numerical study.

6. Conclusion

The efficiency of the proposed solution to avoid lump formation in coatings built up using APS (with powder injection downstream the plasma nozzle) depends on the evenness of the protective gas layer. To completely eliminate lump formation, a minimum number of channels used to form the screen, and a minimum flow rate through these channels are needed. These minimum values depend on the distribution in size of the powder particles. The solution suited to Ni-5Al Amdry 956 powder from Sulzer Metco used to form bond coat [1] was not sufficient for the finer powder ZrO_2 Amperit 827.873 from HC Starck. The present numerical investigation indicates that a few modifications in the channels geometry designed in [1] are needed to sufficiently improve the screen quality to avoid lump formation with these finer powders. Preliminary experiments with ZrO_2 Amperit 827.873 support this numerical study.

A key issue is also to maintain the coating properties. It has been checked numerically that just prior to impact with the substrate, the average temperature and velocity of the powder particles are kept unchanged when using the new ring (with either argon or air) compared to a standard ring. So the coating quality should not be affected by the injection of gas through the ring. Experiments are in progress to confirm this last point.

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