Cold Spray

Literature Review - Nozzle

Week - 2,3

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May 10, 2021

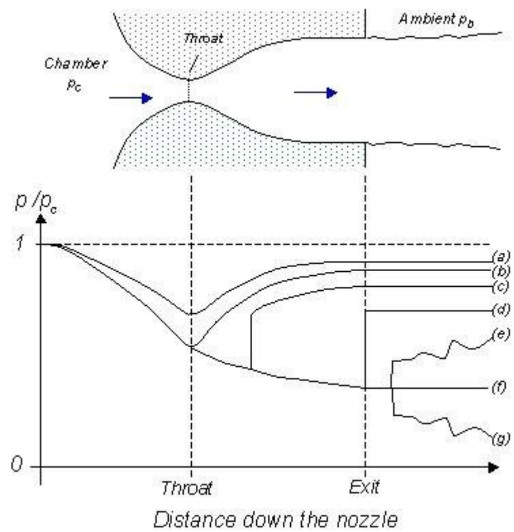
Contents

1 Introduction

This report postulates a short description of the science behind the nozzle which is one of the important factors that affects the DE (Deposition efficiency) of the particles. A typical nozzle has a convergent section where the area and pressure are decreasing while the velocity increases as we move towards the throat section. The highest value of velocity and lowest value of pressure are attained at the throat section. In the diverging section, the area and pressure are increasing as a result the velocity increases. This report is an understanding of the science behind the nozzle and the geometry of the nozzle which affects the flow inside and outside the nozzle. A set of equations are given which postulates the governing equations of the nozzle and also the provided the right geometry for the optimized results.

2 Process Parameters affect the Manufacturing

The flow inside the nozzle happens when the backpressure or ambient pressure is considerably reduced so that the flow from the convergent section moves to the diverging section. There are limitations to reducing the backpressure to maintain the flow inside the nozzle. By reducing the backpressure, we are making the flow near the throat as choked flow where Mach number is 1, which is sonic condition. As this condition provides that the velocity is equal to the sound velocity which makes the flow particles move at the speed of sound, as a result, we might achieve the condition of exceeding the critical velocity of the particle. But the problem with this is that as we keep reducing the backpressure higher than a considerable amount, we would get a normal shock inside the divergent section which might reduce the flow properties as well as the DE. After this point as we keep on reducing the backpressure, at a certain point the condition where exit pressure of the nozzle will come equal to the backpressure of the nozzle. This is the point where the last changes might happen inside the nozzle. After this point, if reduction of back pressure occurs will result in changes in the flow outside the nozzle exit.



From the above picture, we can see point C where there is a formation of shock as we reduce the backpressure to a considerable amount. Point D represents the condition where me met exit pressure is equal to the outside pressure. That is the last point where the changes inside the nozzle happen. Point E and G represent the over-expanded flow and under-expanded flow respectively. There are several parameters rather than the pressure changes in the nozzle which are given below. Processing parameters include nozzle moving speed, spray distance, spray angle, scanning step and nozzle trajectory play an important role in CSAM and CSR [2].

2.1 Nozzle Moving Speed

The coating thickness is affected by the nozzle moving speed. A high rate of nozzle movement results in the coating as a graded coating. An extreme case is a single-particle deposition where the nozzle speed is so high that individual splats are not in contact with each other [2]. According to fluid dynamics theory, the particle velocity and the consequent deposition efficiency at the central zone are higher than that at the outer zone. Low nozzle movement may result in proper DE on the substrate by increasing the subsequent temperature of the bonding surface.

2.2 Nozzle Scanning Step

The nozzle scanning step refers to the movement of the nozzle over the substrate in a horizontal way, which influences the coating thickness, uniformity, and surface morphology [2]. The scanning step can be done in two ways, small scanning step and large scanning step.

2.3 Nozzle Trajectory

The basic principle of trajectory definition is to maximize the coating homogeneity and quality. When spraying on a flat surface, a simple round-trip trajectory is mostly applied to maximize coating homogeneity. However, for a complex curved surface that could be experienced in CSAM and CSR applications, trajectory definition should maintain the constant spray distance, spray angle, nozzle speed, and other processing parameters over the target surface to avoid the in-homogeneity of coating [2].

2.4 Nozzle Design

Several numbers research papers have been published on nozzle design for the cold spray process, yet still, the optimization of perfect nozzle design has been taking place because of the rising demand of this process in additive manufacturing. In this report, three research paper of nozzle design has been discussed. The three papers have optimized the nozzle and provided the results for the better acceleration of particles.

Every simulation is done by using three steps in which it follows:

- Mathematical Modelling.
- Geometric Modelling.
- Simulation of Developed Model.

3 Mathematical Modelling

The governing equation which is used in the flow is slightly modified for the nozzle and provided with a different set of equations that are used inside the nozzle geometry.

Continuity Equation:
According to the law of conservation of mass, the total time rate of change of mass in a fixed region is zero. The conservation equations used for turbulent flow are obtained from those of laminar flow using a time averaging procedure commonly known as Reynolds averaging. It can be stated as [3].

$$\left(\frac{\partial}{\partial x_j} \left(\rho_g v_j \right) \right) = 0$$

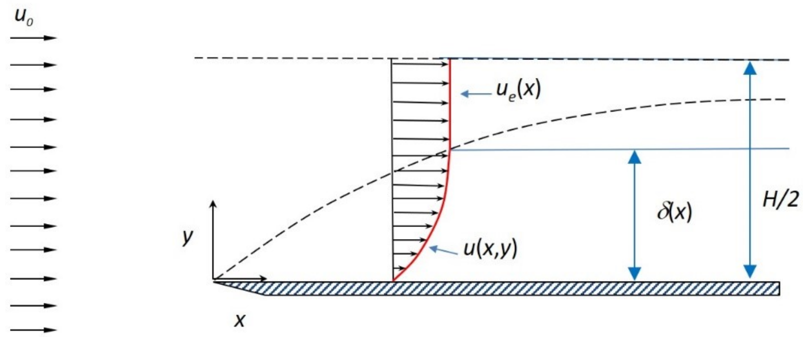
Where,
$\rho - densityofthegas$
$vj - velocityvectorinthejthdirection.$

Momentum Equation:
The law of conservation of linear momentum states that the total time rate of change of linear momentum is equal to the sum of the external forces acting on the region [3].

$$\rho_g \left(\frac{\partial V_i}{\partial t} + v_j \frac{\partial V_i}{\partial X_j} \right) = -\frac{\partial p}{\partial x_j} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho_g g_i$$

Where,
$\tau - Stress$
$gi - Gravitationalacceleration$

These are some basic equation which should be considered before modeling the nozzle geometry. Now that we have looked at the basic governing equation of the nozzle, but the motion of gases is given in one of the papers which are described below. The important factor of providing better efficiency is by taking care of the kinetic energy of the particles and gases inside the nozzle. But as per Fluid Dynamics if a fluid moves alongside a wall boundary wall thickness (boundary layer) is created alongside the nozzle wall. This is a major effect that was addressed in one of the research papers. The boundary layer thickness is given by the distance which can be achieved from the boundary of the surface to the 99 percent of the free stream velocity. This can be widely classified as displacement thickness and momentum thickness.



From the figure we can see that near the boundary wall the velocity is reducing as of the free stream velocity this forms a void in front of the displacement. The decrease in mass flow rate is given by:

$$\delta_1(x) = \int_0^{H/2} \left(1 - \frac{u(x,y)}{u_e(x)}\right) \mathrm{d}y$$

4 Geometric Modelling

To get the perfect optimizing solution, different types of nozzle dimensions should be drawn and simulated. To accelerate the particle up to the gas velocity, it is necessary to increase the nozzle diverging length. However, as the nozzle length increases boundary layer thickness increases, this reduces the gas velocity at the exit of the nozzle [1]. For N1 the outlet velocity and pressure are 945 m/s and 1.5 bars respectively. For N2 the outlet velocity and pressure are 510 m/s and 1.2 bars, which clearly shows that the length of the diverging section is longer in N2 rather than in N1 which provided proper mixing of powder particles with the carrier gas. Both the nozzles were set with the same initial conditions [2]. The expansion ratio of the nozzle influences the particle velocity in the Cold Spraying method. It is the ratio of the area of the exit to the throat. In one of the research papers, the exit dimension of the nozzle is changed to 7 different cross-sectional areas and the results are observed. Nitrogen(N2) and Helium (He) is used as driving gases. The gas pressure was changed from 1 to 3 MPa, and the gas temperature ranged from 27 to 600 – degrees [4]. The governing equations are set in the FLUENT condition and the model K – $\epsilon turbulenceisused.$

5 Simulation of Developed Models

The simulation is set on the outside of the nozzle. The space between the nozzle exit and the substrate and the effect of nozzle exit diameter plays an important role in the acceleration of the particles in the carrier gas. It has been shown that at a given condition there exists a certain value for the nozzle exit diameter where the velocity of different particles has reached a maximum value. It also shows that there is a formation of shock region outside the nozzle which should be taken care of while designing the nozzle, but as per studies, the shock appears to be normal to all the nozzle which is out in the industry. This shock provides a better heat transfer to the particles which is useful for some applications.

6 Conclusion

This report validates that the nozzle design is an important factor in increasing the DE of the particles. By reducing the back pressure, we can increase the mass flow rate inside the nozzle. Because the boundary layer formation in the wall region produces turbulence in the flow.

References

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